Appendix C CRSP Modelling

Colorado Rockfall Simulation Program (CRSP) Modelling

Background

The Colorado Rockfall Simulation Program (CRSP) was developed to provide a statistical analysis of probable rockfall behaviour at any given site and to be used as a tool to study the behaviour of rockfalls, to determine the need for rockfall mitigation, and to aid in the design of rockfall mitigation. The numerical model simulates rockfall events at a site from data describing slope geometry, and rock properties such as type, surface roughness and block size. The model applies equations of gravitational acceleration and conservation of energy to describe the motion of the rock. Empirically derived functions relating velocity, friction, and material properties are used to model the dynamic interaction of the rock and slope.

The statistical variation among rockfalls is modeled by randomly varying the angle at which a rock impacts the slope within limits set by rock size and slope irregularities. The program provides estimates of probable velocity and bounce height at various locations on a slope.

Program Assumptions

On a natural slope, the parameters in Table 1 will have a wide range of values and would be cumbersome to analyze as independent variables. CRSP reduces the number of variables by means of the following simplifying assumptions:

- The slope profile should follow the most probable rockfall path as established during field investigations. Therefore, all calculations may be in two dimensions.
- Because the rock type does not change during a rockfall and the range of slope material properties is much greater than that of rock material properties, coefficients assigned to the slope material (R" and R1) can account for both the rock and slope properties.
- The worst case scenario is generally that of the largest rock that remains intact while travelling down a slope. Therefore, it is assumed that the rock does not break apart in its fall.
- Rock size and shape are assumed constant for analysis of rockfall from a given source. Values assigned to these parameters are determined by held study of the source area and slope materials.
- For determination of a rock's volume and inertia, a sphere may be used because it yields a maximum volume for a given radius, which will tend toward a worst case. CRSP will also allow the use of discoidal or cylindrical rocks.

Input and Output Data

CRSP requires the following input data:

- A slope profile, input as a series of straight-line segments, referred to as cells, designated by the Cartesian (x, y) coordinates of the endpoints of each line.
- An estimation of the roughness of the slope surface (relative to rock radius) within each cell.
- Coefficients (Rt and Rn) that determine the rock energy loss upon slope impact.
- The size, shape, and starting location of the rocks comprising the rockfall events.

CRSP uses this input data in a stochastic model to produce statistics on probable rockfall velocity, kinetic energy, and bounce height based on a series of rock rolls under identical conditions. The following data is output by CRSP:

- The slope profile showing cell locations and the position of each simulated rock every tenth of a second as it travels downslope.
- The maximum, average, minimum, and standard deviation of rock velocities at each of one to three selected points (analysis points) on the slope.
- The maximum, average, and standard deviation of rock velocities at the end of each cell.

- The maximum, average, geometric mean, and standard deviation of rock bounce heights at each analysis point.
- The maximum and average bounce heights at the end of each cell.
- The maximum, average, and standard deviation of kinetic energies at each analysis point.
- Cumulative probability analyses of velocity, kinetic energy, and bounce height at each analysis point.
- Graphs of the distribution of rock velocities and bounce heights at each analysis point.
- Graphs of the maximum velocities and bounce heights along the slope.
- The number of stopped rocks in each ten-foot or ten-meter slope interval.

Redcliffs School Model – Input Data

Cell Boundary Selection

Cell boundaries are used to define the slope profile and areas of uniform slope and characteristics. Cells are input into CRSP as the (x, y) coordinates of their endpoints. Cells may have any slope, but the beginning x-coordinate must equal the ending x-coordinate of the preceding cell. Cell boundaries are selected where changes in slope occur and/or where the slope material changes. The number of cells to use depends on the length and complexity of the slope.

Figure 1 shows the general input parameters for the model. Part A being rockfalls sourced from the steep face only with a sole analysis point set at the base of the slope.

Figure 2 shows the generalised slope profile used in the CRSP model for Redcliffs School. The cross section shows the existing ground level and the location of the current container line and catch fence. The modeled (design) ground levels are also shown. Figure 3 shows the same intermediate case with 10m of cliff regression is cut back and the resulting infill on the talus slope with bulking factor of 2:1. The data shows scatter paths of bounce trajectories.

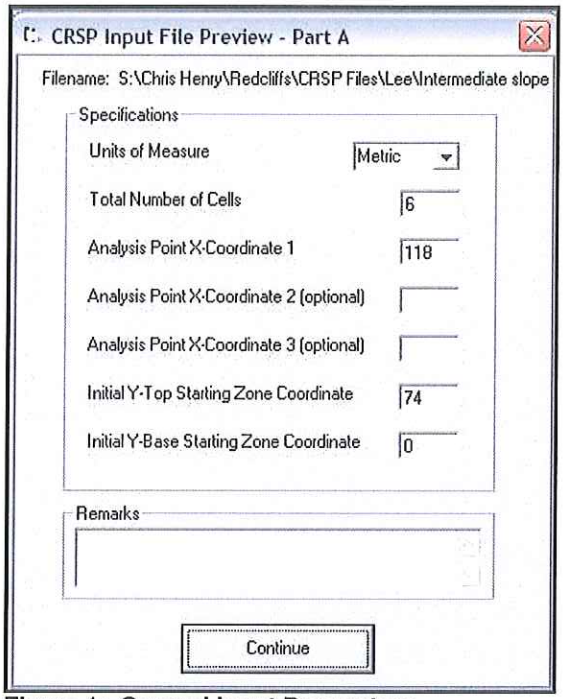
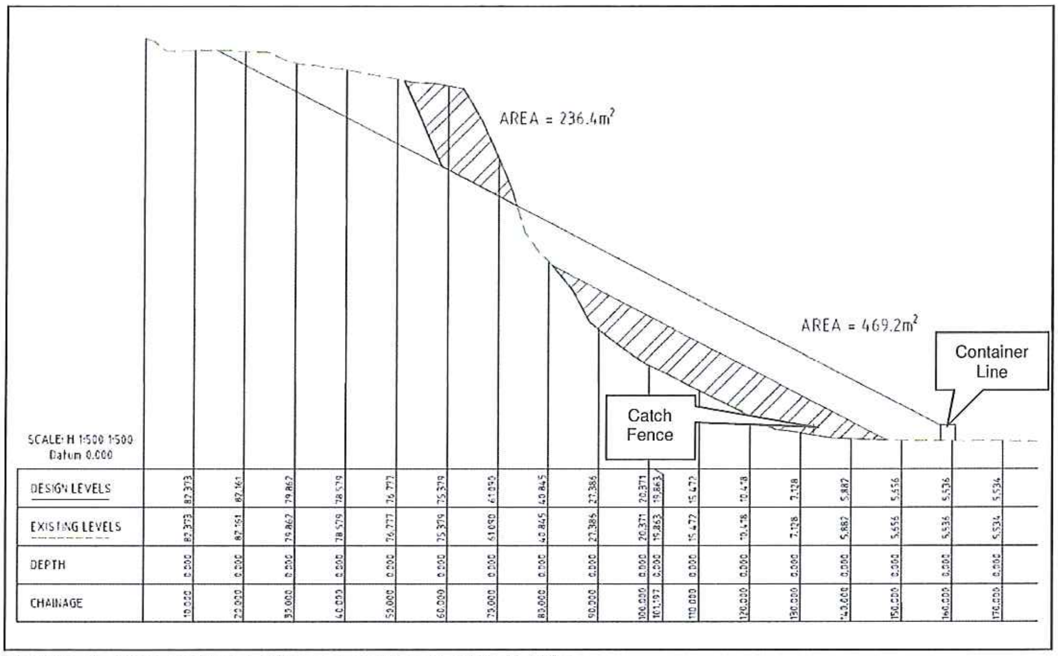


Figure 1: General Input Parameters



DESIGN LEVELS	82.373	82.161	79.862	78.579	76.777	75.379	61.090	40.845	27.386	20.371	19.863	15.472	10.478	7.128	5.887	5.456	5.536	5.534
EXISTING LEVELS	82.373	82.161	79.862	78.579	76.777	75.379	61.090	40.845	27.385	20.371	19.863	15.472	10.478	7.128	5.887	5.456	5.536	5.534
DEPTH	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
CHAINAGE	10.000	20.000	30.000	40.000	50.000	60.000	70.000	80.000	90.000	100.000	101.197	110.000	120.000	130.000	140.000	150.000	160.000	170.000

Figure 2: Generalised Cross Section for Redcliffs

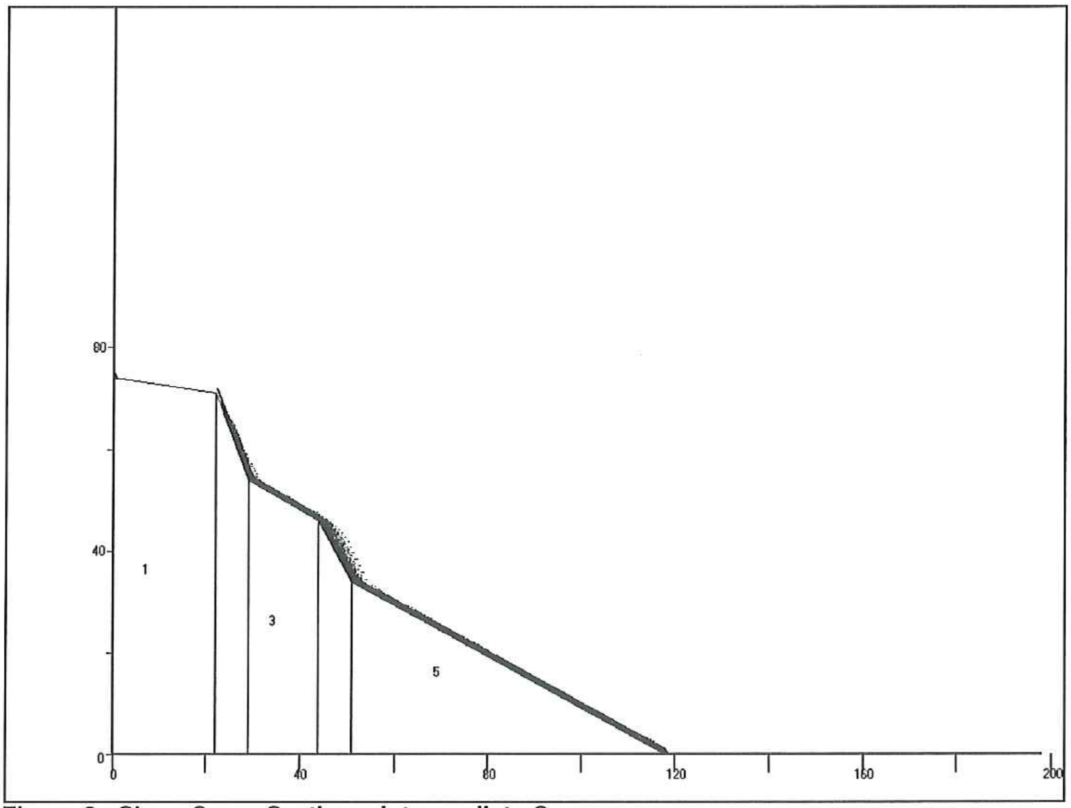


Figure 3: Slope Cross Section – Intermediate Case

Surface Roughness
Surface roughness is a function of the size of the rock and the irregularity of the surface as described by the "CRSP Algorithm" (refer to CRSP manual for details). Surface roughness is an estimation of how much the slope angle may vary within the radius of the rock. Figure 4 shows the method for determining surface roughness.

Figure 5 shows the range of surface roughness values used in the model for Case 1. Standard characteristics have been taken from Tables 4 and 5 of the CRSP manual. Roughness has been calculated in relation to the maximum boulder size of 2.2m, according to Figure 2 of the manual and assuming that voids equivalent to 1.1m diameter exist in the face.

Figure 6 shows the input parameters for sensitivity analysis that was undertaken on the model. Here, the standard characteristics for Tangent and Roughness coefficients were amended to reflect a softer and smoother upper tuffaceous talus slope.

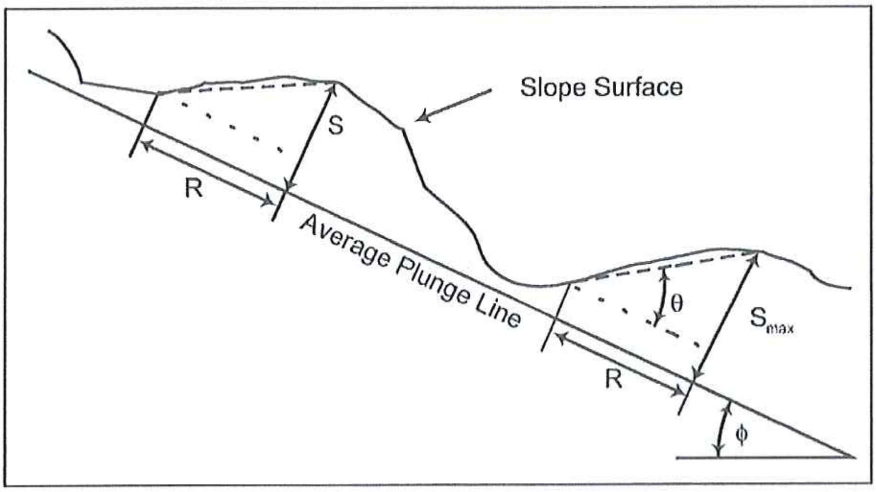
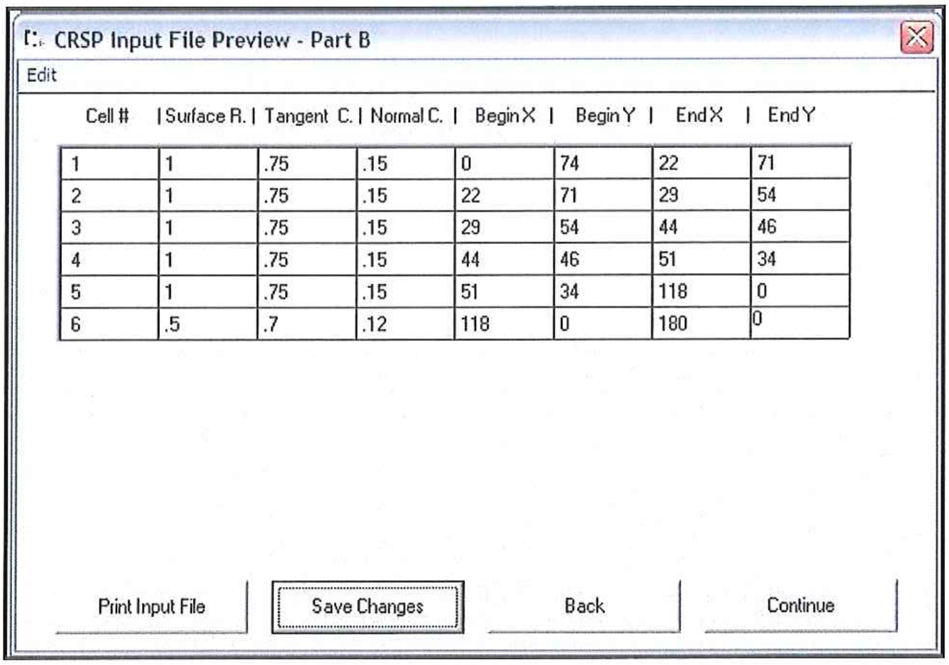


Figure 4: Surface roughness (S) established as the perpendicular variation from an average plunge line (defined by slope angle Φ) over a distance equal to the radius of the rock (R). Maximum slope variation (θ_{max}) is defined by S and R.



CRSP Input File Preview - Part B

Edit

Cell #	Surface R.	Tangent C.	Normal C.	Begin X	Begin Y	End X	End Y
1	1	.75	.15	0	74	22	71
2	1	.75	.15	22	71	29	54
3	1	.75	.15	29	54	44	46
4	1	.75	.15	44	46	51	34
5	1	.75	.15	51	34	118	0
6	.5	.7	.12	118	0	180	0

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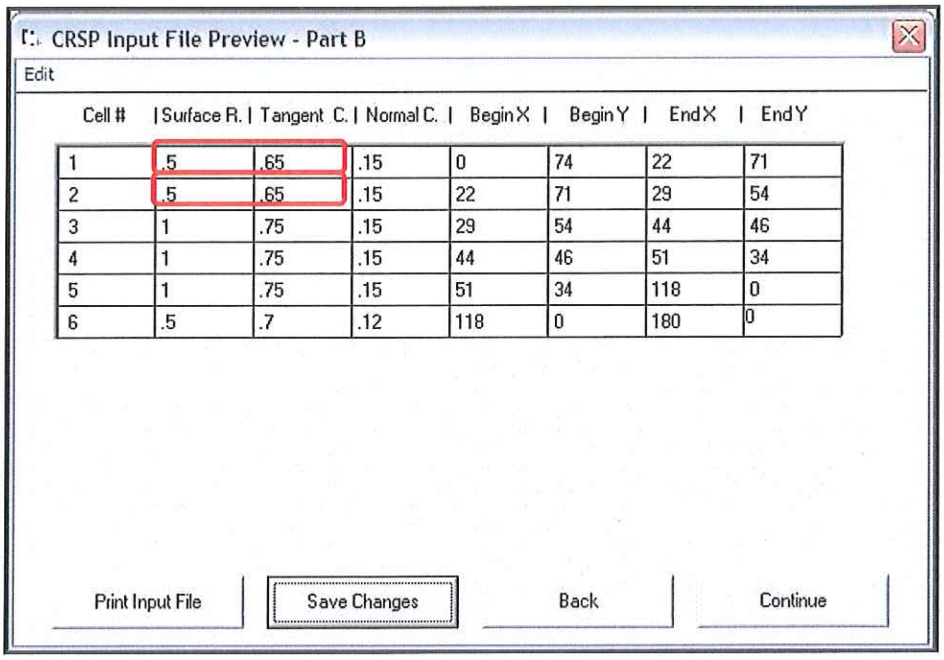
Figure 5: Case 1 Specific Input Slope Geometry and Slope Roughness Characteristics (Part B)



CRSP Input File Preview - Part B

Edit

Cell #	Surface R.	Tangent C.	Normal C.	Begin X	Begin Y	End X	End Y
1	.5	.65	.15	0	74	22	71
2	.5	.65	.15	22	71	29	54
3	1	.75	.15	29	54	44	46
4	1	.75	.15	44	46	51	34
5	1	.75	.15	51	34	118	0
6	.5	.7	.12	118	0	180	0

Print Input File | Save Changes | Back | Continue

Figure 6: Case 2 Specific Input Slope Geometry and Slope Roughness Characteristics (Part B)

Tangential Coefficient

The tangential coefficient of frictional resistance determines how much the component of the rock's velocity parallel to the slope is slowed during impact. Vegetation and, to a lesser extent, slope material, influence the tangential coefficient. A range of probable values should be selected for each cell, for use in a sensitivity analysis of the slope. Suggested ranges of tangential coefficient (Rt) values for various slope materials are presented in Table 1 (from Table 4 Chapter 5 of CRSP manual). The tangential coefficient is significantly less sensitive than the normal coefficient, but the tangential coefficient may become more important for vegetated slopes.

Table 1: Suggested Tangential Coefficient Input Values

Description of Slope	Tangential Coefficient (R_t)	Remarks
Smooth hard surfaces and paving	0.90 – 1.0	-R_t is not very sensitive compared to R_n, but may be important for hard or significantly vegetated slopes -Use lower R_t as the density of vegetation on the slope increases.
Most bedrock and boulder fields	0.75 – 0.95	
Talus and firm soil slopes	0.65 - 0.95	
Soft soil slopes*	0.50 - 0.80	

*Soft soil slope coefficients were extrapolated from other slope types due to lack of data.

Normal Coefficient

The normal coefficient of restitution is a measure of the change in the velocity normal to the slope after impact, compared to the normal velocity before the impact. The normal coefficient is determined by the rigidity of the slope surface.

Table2 (from Table 5 Chapter 5 of CRSP manual) shows the ranges of suggested normal coefficient values for different materials. During the program calibration, it was observed that the normal coefficient appears to be somewhat dependent on slope length, with a longer slope corresponding to a greater value of Rn. Also, the normal coefficient is particularly sensitive compared to the tangential coefficient.

Table 2: Suggested Normal Coefficient Input Values

Description of Slope	Normal Coefficient (R_n)	Remarks
Smooth hard surfaces and paving	0.60 – 1.0	-For short slopes try lower values in applicable range. -If max. velocity/KE* are design criteria, use lower values in range; if avg. velocity/KE* are design criteria, use higher values in range.
Most bedrock and boulder fields	0.15 – 0.30	
Talus and firm soil slopes	0.12 – 0.20	
Soft soil slopes**	0.10 - 0.20	

*KE = kinetic energy

**Soft soil slope coefficients were extrapolated from other slope types due to lack of data.

Rock Size Determination
The CRSP manual states the following:
The size of the rocks involved in rockfall events depends on the size of the blocks in the source area and on the durability of the rocks. While it is conceivable that a rock breaks during descent or a smaller rock could produce a worst case, the worst case is usually for the largest rock that travels the length of the rockfall path. The largest rocks found at the base of the rockfall path that can be identified as having fallen from the source area make a good choice for rock size determination.

The size of boulders observed at the base of the cliff and talus slope were measured as part of the rock fragment mapping exercise and used in the model. Three different boulder sizes (0.5, 1.5 and 5 m^3 boulders equivalent spherical diameter of 1.0, 1.4, 2.2 m) were modelled to represent the range of what is considered likely to fall down the slope over the coming months and possibly years. Figure 7 shows the input details for the rockfall simulation.

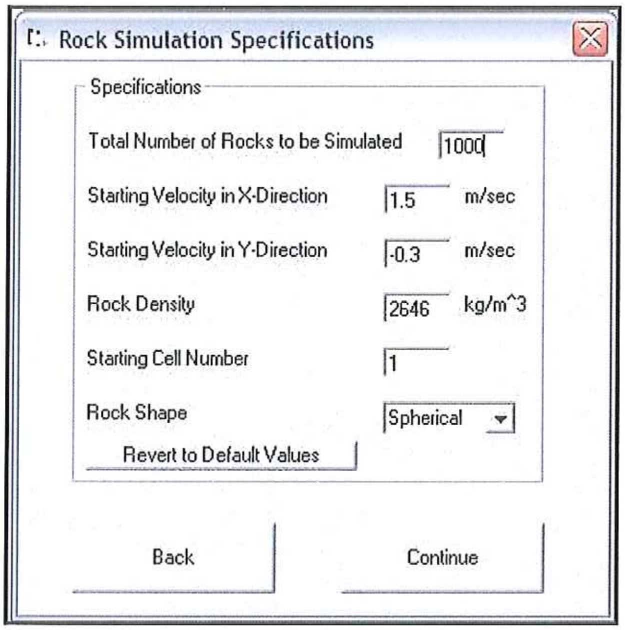


Figure 7: Rock Simulation Specifications (Note: toppling initial velocity of 1.5m/s laterally)

Figure 8 shows the simulation dimensions for the rock whereby a 2.2m diameter block was deemed to be the maximum block size, by inspection of existing blocks towards the base of the talus slope. The 2.2m diameter sized boulder is deemed to be a conservative estimate, given the measured boulders at the base of the slope generally being less than 1.6m diameter.

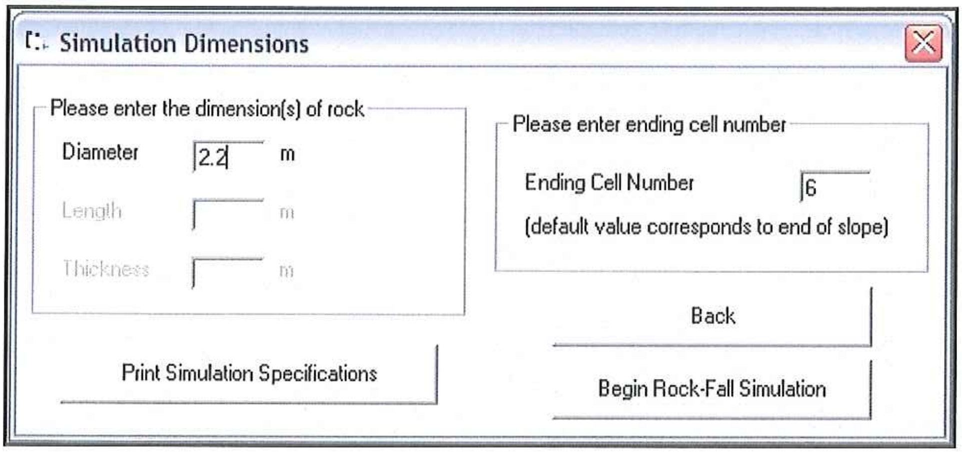


Figure 8: Simulation Dimensions

Site-Specific Calibration

In order to achieve the highest degree of accuracy from CRSP, the program was calibrated to the Redcliffs site. Whereby parameters such as surface roughness, tangential coefficient, and normal coefficient values were adjusted according observations on site. In addition, an evaluation of the sensitivity of various input parameters was undertaken to determine the effect on the results of the model. The results are described below.