ROCK FALL HAZARD ASSESSMENT ALONG RAILWAYS USING GIS

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ABSTRACT
Railways are exposed to numerous types and magnitudes of natural hazards. Managing these spatial hazards requires enabling technology. Geographic Information Systems (GIS) have many of the features required for a risk management system and were used to analyze approximately 60 km of railway that has a historic database containing 300 rock fall events. In addition to the rock fall database, the GIS model for the track section also contains such parameters as the geology, digital elevation, weather records, vegetation cover, etc. The commercial software *RocFall* was used to interact with the GIS model to analyze the track section for potential rock fall hazards.

RÉSUMÉ
Des chemins de fer sont exposés à de nombreux types et ampleurs de risques naturels. La gestion de ces risques spatiaux exige la technologie appropriée et précise. Les systèmes d'information géographiques (GIS) ont plusieurs des caractéristiques exigés pour un système d'administration des risques et ont été employés pour analyser approximativement 60 kilomètres du chemin de fer qui a une base de données historique contenant 300 événements de chute de pierres. En plus de la base de données de chute de pierres, le modèle GIS pour la section de voie contient également les paramètres comme la géologie, l'élévation digitale, les rapports de temps, la couverture de végétation, etc. Le logiciel commercial *RocFall* a été employé pour agir l'un sur l'autre avec le modèle GIS pour analyser la section de voie pour des risques potentiels de chute de pierres.

1. INTRODUCTION

The railway industry has been exposed to ground hazards since the railways were constructed in the late 1800s. Railways have unusually high exposures because of their great length and grade limitations. In addition, the diversity of soil and rock conditions, the very active geomorphological processes associated with the relative youth of the terrain since glaciation, and climate extremes in both precipitation and temperature encountered along rail corridors, increase their risk to ground hazards. As much of the terrain traversed by Canadian railways is sparsely populated, resources available to mitigate these hazards are usually limited. As a result, in Canada there has been a greater need for objective priority setting for mitigative measures by the railway industry. Traditionally, Canadian railways have relied upon experience and subjective assessment for hazard management. Over the last decade there has been increased focus on the risks these hazards pose to railway operations and the management of those risks. This stems from rising public and employee awareness, greater regulatory scrutiny, increased inter-railway competition, deregulation, reduction of available resources and increased railway traffic.

Rock falls are a natural geomorphologic process that can present a significant ground hazard to the transportation corridors in the Rocky Mountains. Since the early 1990's several risk assessment tools have been developed for evaluating the rock fall hazard along highway corridors. Bunce et al, 1997 developed a methodology for quantitatively estimating rock fall risks on highways. For example Hunt (1992) described slope failure risk mapping, and Pierson et al. (1990) outlined the Rock fall Hazard Rating System (RHRS) developed by the Oregon State Highway Division. A modified version of RHR system was described by Abbot et al. 1998 for CN cut slopes. These highway rating systems were developed for identifying areas of elevated risk and for assigning priorities for carrying out remedial measures. Highways differ significantly from railway lines as trains cannot steer or brake readily and can be derailed by rocks as small as 30 cm. Therefore, a remedial measure that may be used on a highway slope may be not be appropriate for a slope above a railway. (Piteau and Peckover. 1978).

In mountain regions, where large areas can be subject to rock fall hazard, the slope and rock properties controlling the initiation and behaviour of rock falls vary widely (Guzzetti et al. 2002). The significance of a rock fall increases dramatically in local areas of steep gradient and fresh rock exposure and particularly in man-made cuts, where it is the only type of slope movement if these slopes are stable overall (Hungr. 1981). Estimating the potential for rock fall risk is enhanced when a database of rock fall events exists. Such a database facilitates estimating the frequency magnitude of the event in any given location. Between 1940 and 2003, some 500 rock falls were recorded along Canadian Pacific Railway's Cascade subdivision between miles 2.6 to 39.6. This represents 60 km of track through south-western British Columbia. In this paper a Geographic Information System (GIS) is used to analyze these rock fall events.

2. DATABASE AND ROCK FALL EVENTS

CPR's rock fall events database includes the track mileage, weather, time, size, and source location. The rock fall event was recorded by operational staff who are not trained in geotechnical engineering or geology and hence no effort is made to interpret the event in the database, i.e., it is only a record of the event. The location of the event is recorded by track Mileage and this location marker is used in the present study. It should also be noted that the quality of the record keeping is not uniform throughout the life of the database. For example, formal guidelines for recording the event were not introduced until the early 1970's and hence the events recorded between 1940 and 1970 cannot be given the same weight as those being recorded today. This is particularly important when developing frequency magnitude relationships. Nonetheless, because of the 50 years of records this deficiency is not considered to adversely bias the information contained within the database.

2.1 Rock fall event statistics

A summary of the 300 events is given in Figure 1. Figure 1b shows that the rock falls are not uniformly distributed along the 60 km (40 miles) suggesting that the physiographical and/or geological conditions vary along railway corridor.

The database indicates that the majority of rock fall material ranges in size from 0 to 3 cubic meters (see Figure 1c). This size of rock fall is sufficiently large enough to have detrimental effects on both the track and the train itself. Note that the frequency of rock falls varies from year to year (Figure 1d) and since 1975 the annual number of rock falls is typically 8 or more. In 1978, 1982, and 1997, more than 50 rock falls were recorded, approximately 6 times the minimum suggesting these years were anomalous. In the next section the records for 1978 and 1982 are examined in detail and compared with the results for 1981.

2.2 Correlation between weather and rock fall events

Rock falls are generally initiated by some climatic or biological event that causes a change in the forces acting on a rock. These events may include pore pressure increases due to rainfall infiltration, erosion of surrounding material during heavy rain storms, freeze-thaw processes in cold climates, chemical degradation or weathering of the rock, root growth or leverage by roots moving in high winds. Piteau and Peckover (1978) suggested that rainfall and temperature were the most likely climate-induced trigger events for rock falls in a Canadian climate. For this preliminary analysis only these two climate-induced triggers are evaluated.

The National Climate Data and Information Archive operated and maintained by Environment Canada, contains climate and weather observations for Canada. Climate data such as, daily temperature, precipitation,

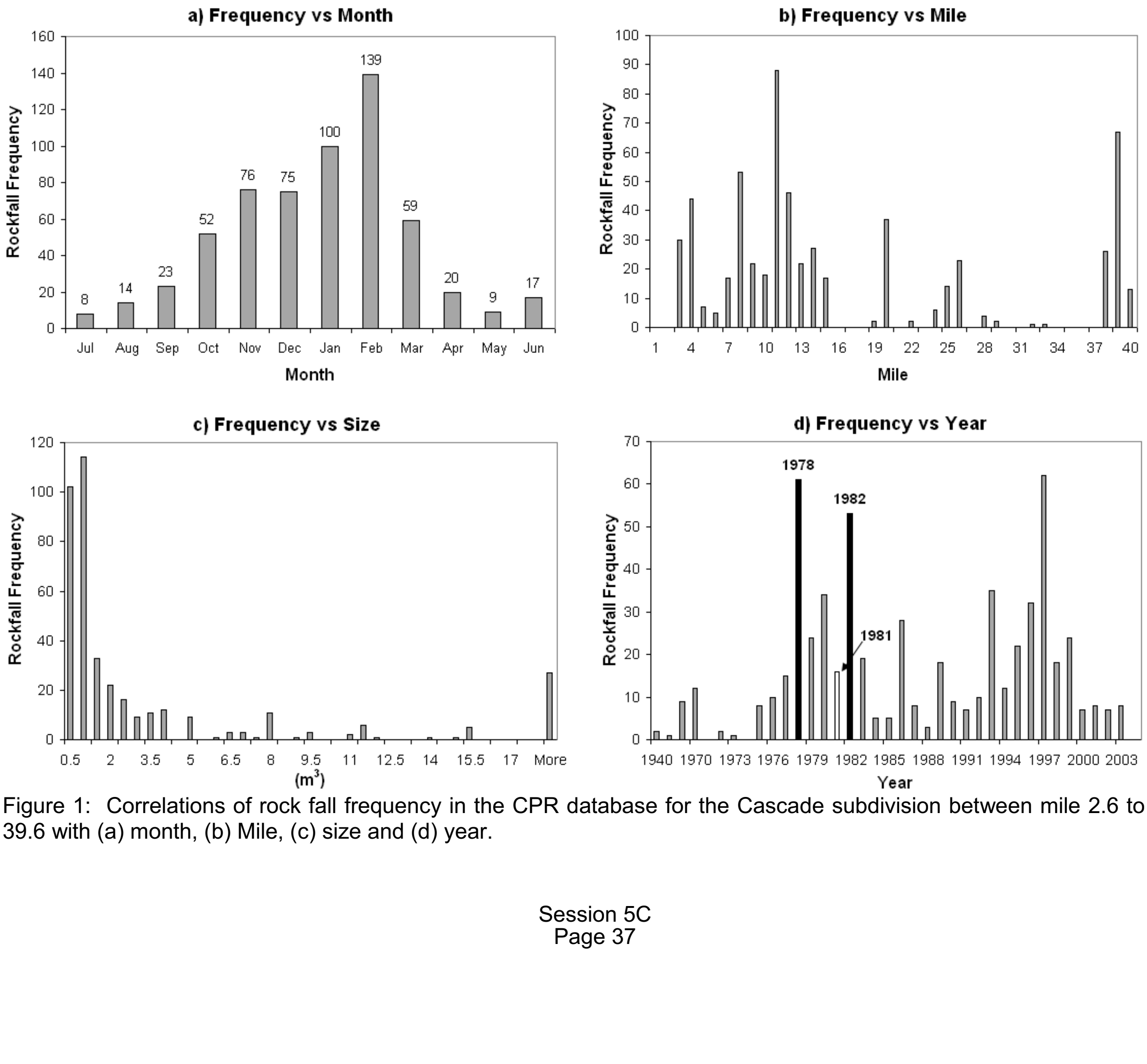

Figure 1: Correlations of rock fall frequency in the CPR database for the Cascade subdivision between mile 2.6 to 39.6 with (a) month, (b) Mile, (c) size and (d) year.

and snow accumulation was compiled for the weather station closest to the Cascade subdivision, at Yale, BC for the period between 1934 until the end of 1995.

Because the summer months contain very few rock fall events all correlations shown in Figure 2 begin in July. The primary (left) y-axis shows the average maximum, minimum temperature and the average daily precipitation including rainfall and snowfall. The secondary (right) y-axis indicates the rock fall frequency represented by the bar graph. A Freezing index defined as the cumulative number of days the average daily minimum temperature remains below freezing during any given year, is identified in the upper right hand corner of each graph. The average freezing index between 1934 and 1995 is 75 days.

Figure 2a shows that September is the first month following the summer dry season with significant rainfall. This month also coincides with an increased frequency of rock fall reports. January typically has the lowest average minimum temperature and is the turning point for increasing temperatures. It is during this period, January to April, when the minimum average temperature rises above the freezing level and provides the greatest potential for freeze-thaw conditions. There is also a steady decrease in the amount of precipitation during this period. The greatest rock fall frequency in Figure 2a does not coincide with either the lowest minimum temperature or the maximum precipitation. Nonetheless there is a better general correlation with the rock fall frequency and the temperature, rather then rock fall frequency and rainfall.

A more detailed correlation between rock fall events and climate conditions was carried out for the years 1978, 1982 and 1981. In 1978 (Figure 2b), the rock fall frequency shows a very different distribution compared to Figure 2a with over ½ the number of events occurring in January. Prior to January there are only 7 recorded events. In this period the precipitation amount is well below average. However, once the temperature begins to increase in January the number of rock fall events increases significantly (Figure 2b). By March when the minimum temperature is above freezing the number of rock falls has decreased to 6 compared to 33 for January. During 1978 the number of days the minimum temperature remains below freezing is 95 compared to the average of 75 in Figure 1a. It appears for 1978 that the number of rock fall events correlates with an increase in the Freezing Index rather than an increase in precipitation.

In 1982, the greatest number of rock falls occurred in

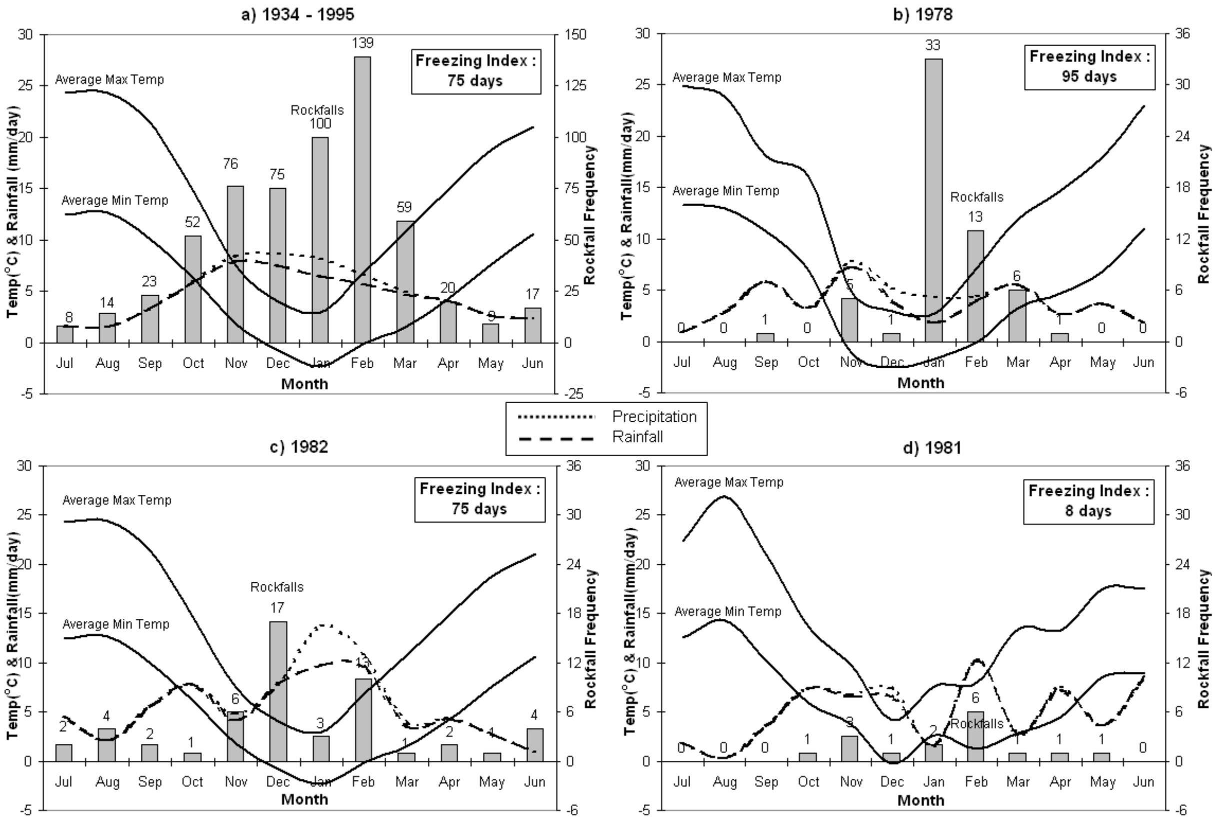

Figure 2: Correlation between weather data and rock fall event frequency for (a) years 1934 to 1995, (b) 1978, (c) 1982 and (d) 1981. The freezing index refers to the cumulative number of days the average minimum temperature remains below freezing.

December (see Figure 2c). During this year the Freezing Index is average (75 days) while the precipitation is above average during the period December through February. The lowest number of rock falls occurs in January (3 events) while the precipitation for this month is well above average. Again there is no compelling evidence that the rock fall frequency strongly correlates with precipitation.

In 1981 only 15 rock fall events were recorded and as shown in Figure 2d, these events are uniformly distributed between October and May. However, as shown in Figure 2d, 6 events were recorded for February a period of significant precipitation. Note that during 1981 the Freezing Index is extremely low (8 days), again suggesting a strong correlation between temperature and rock fall frequency.

From the preliminary analysis it appears that the Freezing Index has a stronger correlation to intense rock fall activity than precipitation. However, when temperatures are above freezing, the frequency of rock falls is relatively low and appears to correlate with precipitation. In the study area, the monthly precipitation is relatively low compared to many other parts of British Columbia and therefore any conclusions relating climate and rock fall frequency may be local to the region. Also no effort was made to consider the location of the slope relative to sunlight, which can have a significant impact on temperature. Nonetheless Piteau and Peckover (1978) also suggested that frequency of rock falls was likely linked to frost action and that this single factor probably directly or indirectly accounts for more rock falls than all other factors combined. Water undergoes about a 9 percent volume increase when it freezes and can exerts significant pressure when it freezes in a confined space. Piteau et al (1977) also found that significant snow fall insulated the ground from freezing and that this can reduce frost-induced movement. In this study area there is little frost protection from snow cover.

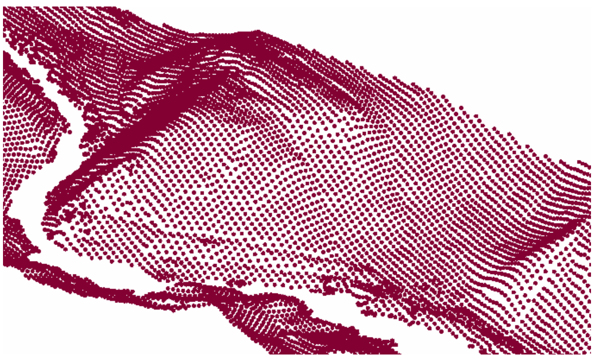

Figure 3. An example of a Digital Elevation Model, visualized in ArcScene, the 3-D visualization component of ArcGIS.

3. GIS VISUALIZATION AND SPATIAL ANALYSIS

Geographic Information Systems (GIS) is an enabling technology that is traditionally used to store spatial information such as the rock fall database. All that is required is the coordinates of each event. In addition to the rock fall database, the GIS model for the study area also contains base layers of geology, digital elevation, weather records, and vegetation cover. This information is created in layers and given various attributes. The GIS technology has advanced significantly in recent years but is still used mainly as a data storage and retrieval system of digital information. However, a significant component of GIS is visualization in both plan view and three dimensional block view. This visualization allows effective communication of complex three-dimensional problems. The GIS analyses in this section were carried out using the commercial software ArcGIS running on a desktop PC.

3.1 Procedure

In order to visualize the spatial location of the rock falls in the database a digital elevation map of the railway was created. The Digital Elevation Model (DEM) is the simplest digital representation of topography and the most common. Figure 3 shows the DEM data represented by 25 m grid points. The transformation from this vector format to a 3-D surface can be done by constructing a Triangular Irregular Network (TIN) using ArcGIS. Once a 3D surface has been created the vegetation and slope conditions can be imported from airphoto data.

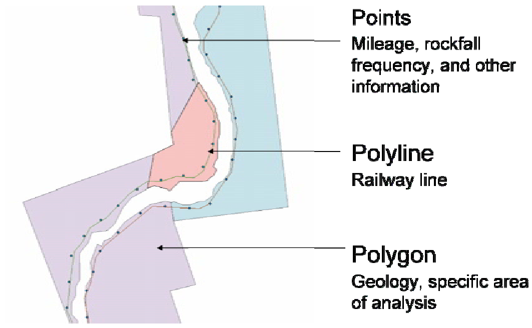

Figure 4. GIS feature types that can be stored in a shapefile.

Vegetation cover and slope condition can be viewed in the DEM by geo-referencing data derived from airphotos to the TIN surface model. This information can then be used to evaluate the rock fall properties of slope surfaces and aid in the characterization of the source of the rock fall events. Georeferencing refers to the process of establishing the relationship between page coordinates (i.e. x, y) of a planar map or image with known real-world coordinates (i.e. longitude/latitude, UTM, etc.). Geo-referencing a raster begins with identifying control points that link known positions on the digital copy of the airphoto to known target data positions in map coordinates. This link information is saved or permanently applied to the image to rectify the raster. Once the raster is rectified to the common project coordinate system, information derived through airphoto interpretation can be captured from the airphotos but creating shapefiles of each data category, such as geology or rock source locations. Shapefiles represent one of the more widely used GIS data formats (Figure 4). Because shapefiles do not have the processing overhead of other GIS data structures, they have advantages over other data sources such as faster drawing speed and edit ability. (ESRI, 1998).

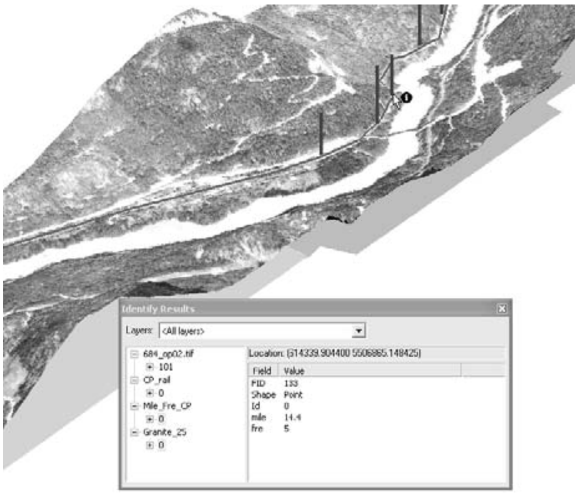

Figure 5: Spatial representation of rock fall frequency and orthorectified airphotos "draped" on a TIN surface.

Figure 5 shows the completed 3D model with the airphoto information geo-referenced and draped on the TIN surface and the rock fall events shown as vertical black bars. The height of the bars corresponds to the number of events. Clearly this form of data visualization is more powerful and useful than the data shown in Figure 1b.

3.2 Spatial analyst

The slope geometry is a vital piece of information required in order to evaluate the hazard of a rock fall. This slope information is inherent in the TIN data model. A grid size of 25 x 25 m was used in converting the TIN slope data to a raster surface using ArcGIS 3D Analyst to honour the data point spacing of the TIN source data. A sensitivity study of the influence of grid size on the calculated slope angle was carried out by Zhou et al. (2003) using grid sizes of 2, 5, 10, 20 and 50 m. They found that slope angle distributions are not changed significantly when the grid size is less than 20 m.

Figure 6 shows the computed slope angles for the 25 x 25 m grid. Figure 6 and Figure 3 are derived from the same source; the former is displayed using the slope raster

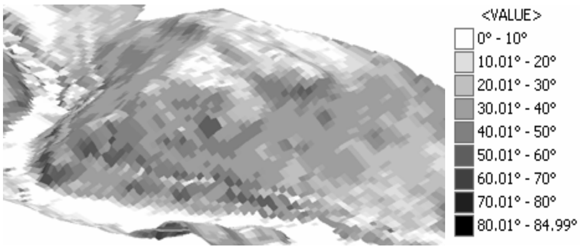

Figure 6. Slope angle distribution determined using ArcGIS.

superimposed on the TIN surface and the latter represents the original source data for the elevation surface.

Once the slope angles are determined the user can then chose an appropriate classification scheme to suit the application to the problem. The slope classification dialog box within ArcGIS is demonstrated in Figure 7. Three classifications were used to distinguish between slopes that ranged from 6-45°(low), 45-65°(moderate), and 65-85°(high) to identify those areas with the largest slope angle. Once the classes were created, ArcGIS was used to compare the frequency of rock falls with the slope angle classes.

Figure 8 shows the spatial location of the highest slope angle class as black squares and rock fall frequency as vertical bars. The vertical bars in Figure 8 represent rock fall frequencies at every 0.2 miles along the railway. By visualizing rock fall frequency with areas of greatest slope angle in this manner, it is easy to see correlation between the areas of high rock fall frequency with the areas of high slope angles. Similarly, Figure 8 also shows that the areas of low rock fall frequency correspond to areas with lower slope angles. The preliminary findings using a relatively coarse grid are encouraging but additional work is required to establish confidence in the correlations.

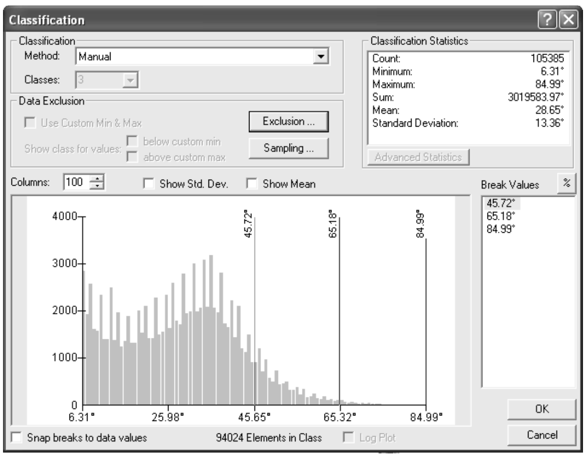

Figure 7. Slope angle classification dialog box in ArcGIS.

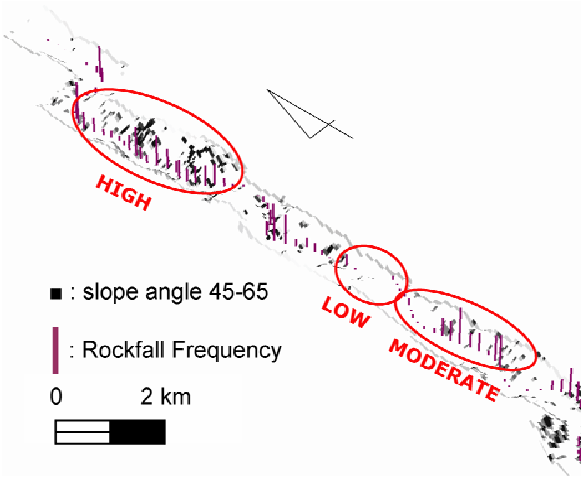

Figure 8. Rock fall hazard assessment of regional scale using slope angle distribution. The columns represent rock fall frequencies at every 0.2 miles along the railway.

4. ROCK FALL ANALYSIS AND PROCESS MODELLING

In transportation corridors, rock slopes must be maintained to an acceptable level of safety. To achieve this engineering analyses are periodically carried out at site specific locations using limit equilibrium or numerical methods. Stand alone computer software to assess Rock fall instability have been developed over the past 20 years to analyze rock fall trajectories, run-out distance, kinetic energies, and the effect of remedial measures. (Pfeiffer and Bowen 1989, Stevens 1998, and Jones et al. 2000). Much of the information required for a rock fall analysis is

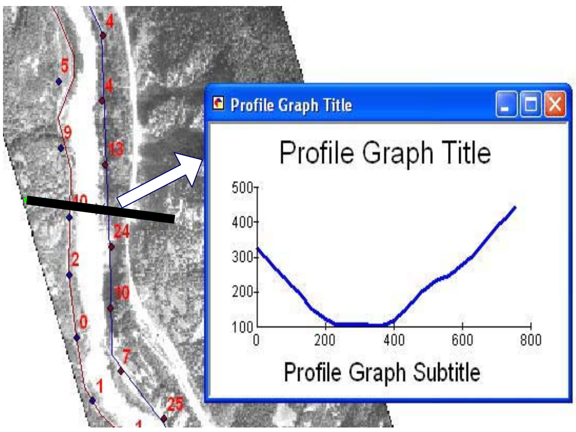

Figure 9. Slope profile that is automatically generated from the DEM model in ArcScene. The profile is exported using the DXF file format.

contained with the GIS database, however the rock fall software does not allow for the importation of the required information from GIS software directly. Hence, there is a need to recompile the GIS information in a form that is suitable for the rock fall software. In addition, for analyzing rock fall risk along transportation corridors there is a need to conduct a large number of analyses at regular intervals. In recent years, GIS has been demonstrated as an effective tool in hazard delineation, but seldom is GIS used for modeling (Chau et al. 2004, Dorren and Seijmonsbergen. 2003, Duarte and Marquinez. 2003). Part of this study attempts to overcome these deficiencies and utilize GIS and the numerical software to develop a process model for rock fall analysis. Ultimately, all the modeling will be conducted within the GIS environment but for this paper the work flow required for the development of the process model is demonstrated.

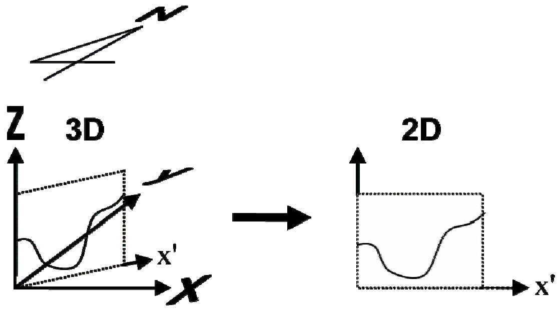

Figure 10. Converting 3D to 2D coordinates.

The numerical program *RocFall* was used to conduct the rock fall analysis in this study. *RocFall* is designed to calculate the bounce/run-out path for rock falls in two dimensions. Energy, velocity and "bounce height" envelopes for the entire slope are automatically determined by the program. It has been designed to predict rock fall trajectories along user defined slope profile and uses probability to take into account the uncertainties and local variation of the input data. Distributions of energy, velocity and bounce-height are also calculated along the slope profile; Distributions can be graphed and comprehensive statistics are automatically calculated.

The *RocFall* program is Windows based and utilizes DXF (Drawing eXchange Format) files to import the slope profile. This format is probably one of the most widely supported vector formats in engineering application today. Hence the slope profile for the *RocFall* analysis must first be extracted from the GIS DEM model.

4.1 Extracting DXF

After zoning the rock fall hazard area in GIS, the slope profile needed as input to the *Rocfall* program can be extracted using built in export functions in ArcGIS. Figure 9 shows the DEM and the profile that can be captured from the 3D DEM information using 3D Analyst once the profile location is specified. At present, this profile is manually located but in the future, the software will automatically generate the profiles at regular intervals. Care must also be taken so that the profile represents the steepest profile possible.

The profile example given in Figure 9 was exported to a three-dimensional DXF file. The three dimensional file must be converted to a two-dimensional DXF file to extract the elevation and distance along the profile for incorporation into *Rocfall* (Figure 10). The coordinate transformation was performed external to both programs.

4.2 *RocFall* Analysis

The single most important parameter in the *RocFall* analysis is the coefficient of restitution as it significantly affects the travel distance and bounce height. The coefficient of restitution is a function of the slope morphology, rock type, vegetation cover, shape of the rock fall, etc. The most reliable means of determining the coefficient of restitution is to conduct back analysis of existing rock fall data. (Chau et al. 2002).

The Rock fall event database contains most of the information necessary to conduct the rock fall back analyses, such as rock fall height, location of run-out zone, slope condition, shape of rock, and size of rock fall.

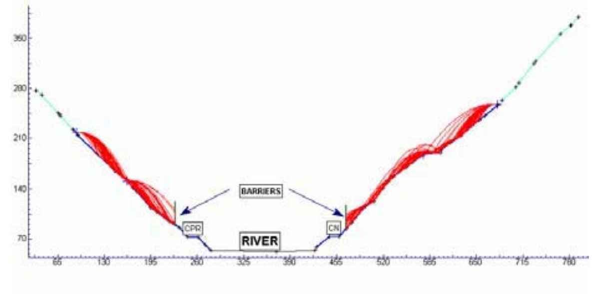

Figure 11. *RocFall* simulation with barriers.

This information will be used to calibrate the properties for shape of rock fall, initial velocities, and coefficient of restitution. The database indicates that the majority of rock falls are less than 2 m^3 and that the majority of rock falls in CPR's records come to rest immediately down slope of the track centerline. It should be noted that the CPR rock fall database reflects only those events that reach the track. Figure 11 is an example of the output from a *RocFall* analysis where a barrier is used to assess its effectiveness in preventing the rock fall from reaching the track.

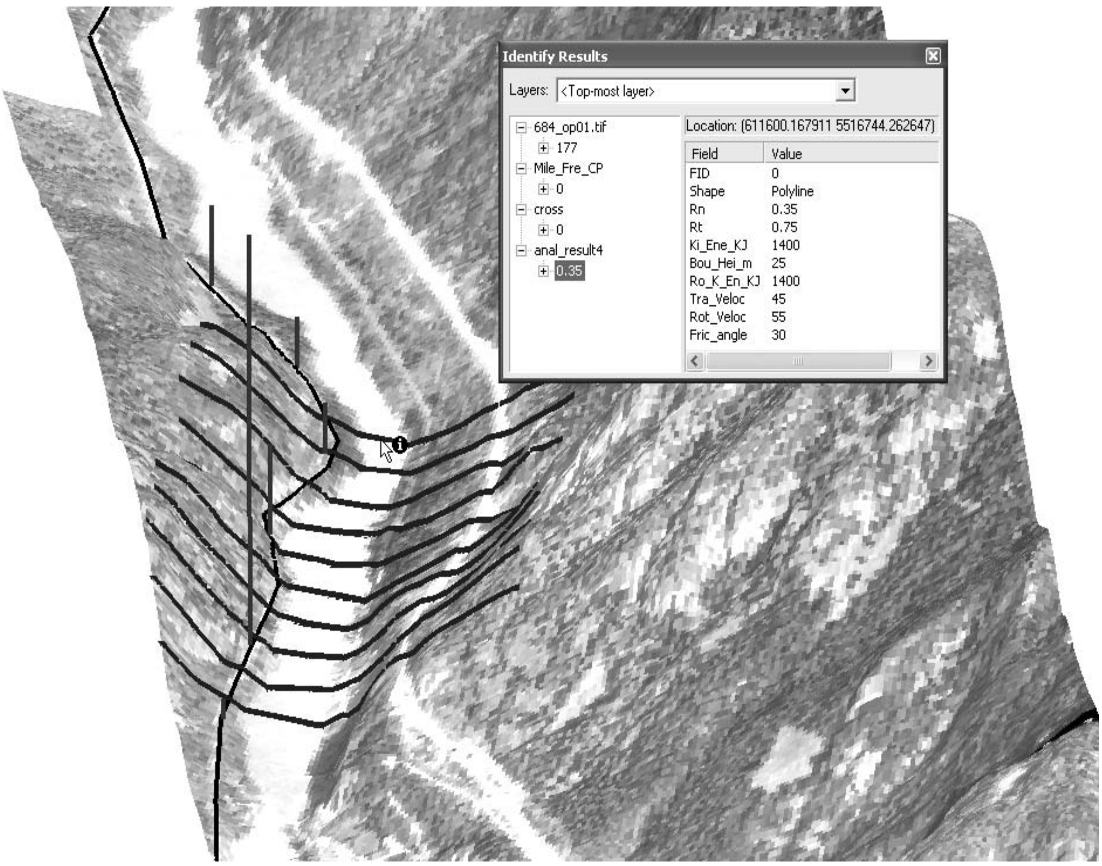

Figure 12. RocFall simulation results displayed in ArcGIS ArcScene.

The *RocFall* analysis results can be transferred back to ArcGIS for presentation and visualization. Figure 12 shows an example of attribute information that can presently be transferred from *RocFall* to ArcGIS. These attributes include normal and tangential coefficient of restitution, related kinetic energies, bounce height, velocities, and friction angle of the slope. Eventually all the statistical information form the *RocFall* analysis will also be automatically displayed in ArcGIS.

5. CONCLUSION

Assessing rock fall hazard over large areas where the rock fall frequency is not uniformly distributed is a challenge. In recent years, GIS has attracted attention for the delineation of natural hazards. However, its role is often restricted to data storage and cartographic presentation. The objective of this work is to utilize GIS to develop a process model for rock falls.

The results from the current work can be summarized as follows.

- A database of 300 rock fall events along a 60 km section of railway has been established.
- Spatial analyses of the database show that the events are not uniformly distributed along the route.
- Temporal analyses show that the majority of events occur between September and May.
- Preliminary analyses suggest that the majority of the rock falls occur when the minimum temperature increases above the freezing point, suggesting that freeze-thaw conditions combined with melting snow may be the most significant trigger mechanism for this location.
- GIS can be effectively used for data capture, input, manipulation, visualization, query, analysis, modeling, and output.
- Slope profiles in the form of DXF files can be obtained from the DEM using GIS tools that currently exist within the software. Although there is a limitation of DEM resolution, one can save the expense and time of a topographic survey by using DEM data.

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