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Logistic regression and neural network classification of seismic records

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ABSTRACT

The identification of seismic records in seismically active mines is examined by considering logistic regression and neural network classification techniques. An efficient methodology is presented for applying these approaches to the classification of seismic records. The proposed procedure is applied to mining seismicity from two mines in Ontario, Canada, and compared based on an analysis of the receiver operating characteristic curve as well as a number of performance metrics related to the contingency matrix. The logistic and neural network models presented excellent performance for identifying blasts, seismic events and reported events in the training and testing datasets for both mining seismicity catalogues. Operated under their respective optimal decision threshold values, the logistic and neural network models, accuracy was higher than 95% for classification of seismic records. In general, the logistic regression and neural network methods had close overall classification accuracies. The ability of the models to reproduce the frequency-magnitude distribution of the testing dataset was used as a signature of classification quality. The logistic and neural network models reproduced the reference distribution in a satisfactory manner. The advantages and limitations pertaining to the two classifiers are discussed.

1. Introduction

Microseismic monitoring is employed in many mining operations in Canada as a tool to identify potential ground control safety hazards to workers. The full-waveform seismic systems employed at these mines provide real-time seismic parameters of seismic records. From these seismic parameters, it is possible to characterize the rockmass response around mining excavations, particularly to the blasting cycle which triggers most of the seismicity as aftershocks. Occasionally large magnitude events are triggered, caused by the interaction of mining and geological structures at depth.

Following large seismic events or blasts there is a short-term increase in levels of seismicity that over time decays to background levels. One of the applications of the microseismic data is to enhance workplace safety by restricting access to the affected zones of the mine for sufficient time to allow this decay of aftershock events. This is the re-entry protocol [1,2].

A key aspect of re-entry policies is the triggering of re-entry incidents, i.e., when should a re-entry protocol be invoked? Based on a survey on current re-entry practices at 18 seismically active mines, it was established that 90% of re-entry incidents are triggered by blasting [3]. Therefore, it is necessary to accurately identify the origin time and location of blasts. The microseismic technologist at the mine has an idea when blasts are scheduled, but exact times are not recorded in blast notices or daily blast logs. It is up to the technologist to manually match blasts to the recorded seismicity; therefore, automating this procedure is an invaluable labour saving device [4].

Some of the guidelines used at the surveyed mines for invoking a re-entry protocol after large magnitude events, measured in the Nuttli magnitude scale (M_n), are:

1. Any seismic event with a $M_n \geq 3.0$, regardless of location and whether or not there was damage to mine excavations.
2. Any seismic event with a $M_n \geq 1.5$ and affecting the main accesses (e.g. ramp, footwall drifts), which could require workers to be confined to underground refuge stations and/or could require the evacuation of workers.
3. Any seismic event with a $3.0 > M_n \geq 1.5$, located within 30 m from mine excavations and/or main infrastructure (e.g. cross-cuts, ramp, refuge station, electrical sub-station, garage, crusher station).

Guidelines such as these, which are based on a correlation between event magnitude and damage, require a history of seismicity and careful calibration. However, large magnitude events are not that frequent in all mining operations in Ontario, and mines that are

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just starting to experience seismicity and rockbursting are faced with the difficulty of having to develop their own guidelines for invoking a re-entry protocol without the benefit of significant local experience. What is needed is an approach that enables the type of seismic record (blast, microseismic event, trigger of a re-entry protocol) to be classified based on the real-time information provided by the microseismic monitoring system.

This paper examines the applicability of logistic regression and neural network-based classifiers for the identification of blasts, microseismic events and events that may trigger a re-entry protocol by using multiple seismic parameters. This linkage implicitly assumes that there is a direct correlation between the seismic parameters of an individual event and the consequences as observed underground.

2. Information available from the full-waveform systems

The full-waveform systems commonly used in Ontario mines provide automatic (on-line) calculation of event location coordinates (E, N, D) and the associated vectorial error sum (Δr), origin date-time (t), number of sensors used in the location of the event (N_s) and 13 seismic parameters: uniaxial magnitude (*uMag*), triaxial magnitude (*tMag*)—not applicable if no triaxial sensors were used to acquire the data set, seismic moment (M_o) and moment magnitude (M_w), seismic energy (E_o), S-wave to P-wave energy ratio (E_S/E_P), source radius (r_o), asperity radius (r_a), static stress drop ($\Delta\sigma$), apparent stress (σ_a), dynamic stress drop ($\Delta\sigma_d$), maximum displacement (D_{max}), peak velocity parameter (*PVP*), and the peak acceleration parameter (*PAP*). Table 1 presents a summary of the main formulas and terms involved in the calculation of these seismic parameters. *uMag* and *tMag* are estimates of the strength of an event based on the maximum amplitude of a seismic wave at a particular frequency. M_o, E, E_S/E_P, r_o, $\Delta\sigma$ and σ_a are determined over P-wave and/or S-wave windows using a time-domain methodology [5]. $\Delta\sigma_d$, D_{max}, *PVP* and *PAP* are based on velocity and acceleration waveforms accounting for source-receiver distance.

Generally, the seismic records are classified by mine personnel mainly into three categories: microseismic events (e), blasts (b),

Table 1
Summary of the seismic parameters provided on-line by the full-waveform systems.

Term	Description	
Required parameters and variables	A, B	: Parameters based on local conditions
	R	: Source-sensor distance
	ppV	: Peak particle velocity
	ρ	: Density at the source
	c	: P-wave velocity
	β	: S-wave velocity
	F_c	: Wave radiation coefficient
	K	: Wave source model parameter
	μ	: Synamic shear modulus
	v_{max}, a_{max}	: Maximum velocity and acceleration recorded from the root-mean-square trace
Local Magnitude $uMag \equiv tMag \equiv A\log(R \cdot ppV) + B$	Estimate of the energy release of an event based on measurements of the maximum amplitude of a seismic wave at a particular frequency. It can be calculated using either uniaxial or triaxial sensors: *uMag*: average of the unclipped peak amplitudes of uniaxial sensors *tMag*: average of the unclipped data of the vectorial amplitudes for each component of the triaxial sensors. -9.99 default value if no triaxial sensors	
Squared spectral integrals $S_{D2} = 2\int_0^\infty D^2(t)dt$ $S_{V2} = 2\int_0^\infty V^2(t)dt$	S_{D2} and S_{V2} are integrals of the squared spectral displacement and velocity determined over P-wave and S-wave windows $D^2(t)$ and $V^2(t)$ are calculated by summing the squared double- and single-integrated P- and S-wave train acceleration components	
Corner frequency $f_c = \frac{1}{2\pi}\sqrt{S_{V2}/S_{D2}}$	The frequency corresponding to the intersection of the low frequency spectral level and high-frequency decay in the displacement amplitude spectra of P or S waves	
Low-frequency spectral level $\Omega_0 = \sqrt{4S_{D2}^{3/2}S_{V2}^{-1/2}}$	Flat part of the displacement amplitude spectra prior to the corner frequency	
Energy flux $J = S_{V2}$		
Seismic moment $M_o = \frac{4\pi\rho c^3 R\Omega_0}{F_c}$	Measure of seismic event strength equivalent to the amount of work done to produce the observed displacement over the entire slip surface. Average of P- and S-waves	
Moment magnitude $M_w = \frac{2}{3}\log M_o - 6.0$		
Seismic energy $E_o = 4\pi\rho c R^2 J$	Measure of the total energy contained in the P- and S-waves. The sum of the P and S contributions	
Source radius $r_o = \frac{K\beta}{2\pi f_c}$	Equivalent circular surface over which slip is predicted to occur during a seismic event. Average of P- and S-waves	
Asperity radius $r_a = 1.32\beta\frac{v_{\max}}{a_{\max}}$	Calculated on the S-wave only	
Static stress drop $\Delta\sigma = \frac{7}{16}\frac{M_o}{r_o^3}$	Average difference between initial and final (shear) stress levels over a fault plane associated with slip on that surface	
Apparent stress $\sigma_a = \mu\frac{E_o}{M_o}$	Difference between the average loading stress and the average resisting stress	
Dynamic stress drop $\Delta\sigma_d = 2.50\rho R a_{\max}$	Estimate of the stress release associated with breaking through the strongest part of the source area. Calculated on the S-wave only	
Maximum displacement $D_{\max} = 8.1R\frac{v_{\max}}{\beta}$	Calculated on the S-wave only	
Peak velocity parameter $PVP = Rv_{\max}$	Calculated on the S-wave only	
Peak acceleration parameter $PAP = \rho R a_{\max}$	Calculated on the S-wave only	