Numerical Approach to Interpretation of Acoustic Emission Occurring at Different Scales

Anastasia Dobroskok Alexander M. Linkov
anastasiadobroskok@hotmail.com

Abstract

The paper presents a computer-aided technique based on the unification of passive seismic monitoring with numerical simulations. The paper also discusses the technique application to the interpretation of acoustic emission data at different scales. The technique is based on the joint analysis of two types of data i) geophysical (passive seismic) data recorded in a laboratory experiment or in field and ii) synthetic data simulated using geomechanical approaches. This allows one to match the numerical results with the data of observations. Illustrative examples demonstrate the effectiveness of the approach. Simulated seismicity also serves to compare two methods of seismic data interpretation: the principal component analysis (PCA) currently employed in the industry, and the strip ray scanning (SRS), recently suggested by the authors. Examples indicate that the SRS technique is superior over the PCA on the time steps.

1 Introduction

Acoustic or microseismic emission in materials and structures, being induced by a time-dependent internal process (e.g., damage accumulation, heat transfer, stress redistribution, etc.), can provide useful information characterizing the process. Thus, interpretation of emission can contribute to the solution of such engineering problems as structural health monitoring and characterization of the internal structure of a material or engineering system. In practice emission occurs at various connections: i) in laboratory specimens, ii) in engineering systems (e.g., bridges and subsurface reservoirs), iii) seismicity and rock bursts in mines, and iv) earthquakes in the earth crust.

Interpretation of acoustic emission and seismicity is driven majorally by the growing demand to use non-destructive techniques to characterize engineering systems and their development in time. The idea is not new: data of microseismic monitoring is routinely used for maintaining bridges and safety monitoring in mines. However, in the majority of applications, interpretation of acoustic (seismic) data is limited to statistical analysis. Such analysis does not allow one to make use of deterministic description of the considered system. As a result some features of the considered systems and processes remain unnoticed or misinterpreted.

This paper presents a novel computer-aided technique, based on the unification of seismic (acoustic emission) monitoring with numerical simulations. The paper also discusses the technique application to the interpretation of acoustic emission data at different scales.

2 Background and numerical realization

Analysis of microseismicity in mines often yields the conclusion that microseismisity cannot serve to reliably predict dynamic events (e.g., roof falls, rock bursts). For instance, the study conducted by [1] has shown that there is no direct correlation between elevated microseismic activity and roof falls. This result is in agreement with the study conducted by the authors and is discussed in section 3.1.

Problems with interpreting seismicity in reservoir engineering applications are of different nature. The problem of stability rarely arises in reservoir engineering. Instead, the problems of poor characterization of the subsurface system and of assessing the efficiency of stimulation present significant challenges. Statistical analysis of microseismic data [2] leads to too general conclusions which can be obtained using less sophisticated monitoring techniques.

Similar problems are encountered in other applications. For instance, recording acoustic emission during mechanical testing has become almost a golden standard at least for scientific experiments. Meanwhile, analysis of the recorded data is rarely conducted. In civil engineering microseismic monitoring serves only for warning on severe damage taking place in constructions. However, the most impressive example of underutilization of seismic data is given by earthquake applications: despite continuous monitoring with distributed arrays of accelerometers these data usually serve only for geophysical studies of wave forms.

This paper discusses the approach allowing for more meaningful interpretation of acoustic emission (microseismic) data. The approach makes use of joint analysis of two types of data i) acoustic emission or seismic data recorded in a laboratory experiment or in field and ii) synthetic data simulated using geomechanical approaches.

Numerical simulations utilize approach introduced by Salamon [3] and developed over a few decades. The approach suggests that a single seismic event occurs on a discontinuity (crack, flaw, fault, etc.) instantaneously when the strength of the contact is reached. In this case stability is lost and the discontinuity reaches a new stable state by a jump. The accumulated elastic energy is then released in the form of acoustic (seismic) waves. However, if the imbedding medium is stiff enough, while a fracture surface has sifficient capacity to absorb the elastic energy, the loss of stability does not take place. Instead a different type of event, aseismic slip, occurs [4]. An event runs smoothly without elastic energy excess. Still its characteristic time may be very small if it occurs under a combination of parameters close to a critical value, corresponding to the point of dynamic instability. On the level of the earth crust, such a smooth movement with small characterisitic time appears as a 'silent earthquiake' (see, e.g. the paper [5] and references in it). The elasticity-softening-creep (ESC) model [4] is the simplest model, developed for numerical simulation of the both types of the events, seismic and aseismic; the latter may have arbitrary characteristic times, including those, which are whatever small. The model allows one to distinguish the type of a simulated event and to obtain quantitative data on its features.

The ESC-model may be used in frames of any computational method serving to find stresses. To the date, the hypersingular boundary element method (H-BEM) [6] has served as a basis for evaluation of stresses at time steps. Realization of the approach consists of two major components: i) solution of the problem of elasticity by the H-BEM, and ii) statistical procedures to simulate seismicity. The H-BEM serves for tracing changes in stresses occurring due to a time dependent process (e.g., mining steps, pressure or temperature changes following hydraulic or thermal shock, hydraulic fracture propagation, etc.). Subroutines for simulating seismicity allow for a) random seeding of rectangular cracks (flaws), b) detecting the flaws which have reached a critical state and are to produce a seismic or aseismic event, c) distinguishing between seismic and aseismic events, d) accounting for mutual influences of the flaws and tracing chains of seismic and aseismic events on multiple flaws, and e) statistical analysis of simulated seismic and aseismic data. Simulations use Poisson's distribution of sizes and uniform distribution of location and orientation. Specific choice of mechanical parameters of interfaces conforms to the recommendations given in [4].

The workflow employed is as follows. We conduct simulations of seismicity for a numerical model of a considered system. The results of simulations are formulated in terms of seismic quantities. This allows us to match the numerical results with the data of seismic monitoring. History matching requires that the limited number of the parameters of the model be adjusted in iterative steps. After history matching is completed, simulations with the adjusted model may provide the following information: stress and permeability tensors, geometry of the system, pore pressure, etc.

In practice numerical simulations remain unaffected by the technical limitations imposed by the resolution of monitoring instrumentation. Consequently, simulations yield more statistical data and provide more details on the development of the studied system. Synthetic seismic data also serve to compare two methods of seismic data interpretation: the principal component analysis (PCA) currently employed in the industry, and the strip-ray scanning (SRS), recently suggested by the authors. Application of the both techniques to simulated seismicity indicates that the SRS is superior over the PCA on the time steps. The advantage is due to the SRS capability to highlight the features of the considered processes, which are missed when using standard statistical interpretation.

3 Numerical examples

To illustrate the enhancement provided by the joint acoustic emission (seismic) monitoring and numerical modelling, we revisit example considered in [7]. We also discuss some preliminary results of the analysis of acoustic emission recorded in a laboratory experiment.

3.1 Analysis of seismicity in mines

The field data were recorded in the the longwall opening 712-c in the coal seam No. 4 of the Komsomolskaya mine in February 2008. The details of the geological settings are presented in [7]. The total number of seismic events recorded was small (295 events) what prevented substantial statistical analysis. The locations and the energies of the events are the only parameters recorded. Due to the mentioned limitations, the conclusions directly available from the analysis of the field data are not extensive. Analysis of the locations of the events indicated that the majority of the events occurred at a distance of about 20m from the seam plane and were similarly distributed in the mine roof and floor. This clearly indicates that the events are triggered by stress changes in the vicinity of the advancing mining front.

Deeper insight becomes possible when following the workflow outlined in the preceding section. To this end we used the available data on in-situ settings to create an H-BEM numerical model of the considered system. Further adjustment of the model allowed for reasonable agreement between recorded and simulated seismic data. Specifically, the flaws are seeded in a rectangular parallelepiped block with height of 100m in the vertical direction, length of 300m in the direction of strike, and width of 150m in the direction of dip. Number of flaws is N = 20 000 what provides the density of the flaws within the interval recommended in [4]. The average size of flaws is taken 2.2m to agree the average energy of the simulated events with that recorded in mine (1800J); the average cohesion of flaw surfaces is 2.5MPa; the average friction angle is 15 deg.

The adjusted model serves us to delineate zones of increased rock pressure (IRP). These zones are most susceptible to hazardous dynamic events. Calculations indicate that the IRP zone follows the mining front, extending approximately 70 - 80m ahead of the front. The boundary of the IRP zone rounds the area where the majority of seismic events occurred. The numerical model also indicates the existence of the zone of high compressive stresses in the middle plane of the seam ahead of the mining front. Stress state in the zone is almost hydrostatic yielding small shear stresses what results in low microseismic activity in this zone. Nevertheless, due to high magnitude of normal stresses this zone clearly can produce dangerous events. This would not be possible to predict if not conducting geomechanical calculations in addition to the analysis of seismic data. Note that similar effects can underlie the observation of [1] that microseismic activity does not necessarily increase in the areas producing dynamic events. More detailed discussion of the results of joint seismic monitoring and geomechanical modelling for the considered problem can be found in [7]. The results are briefly summarized as follows:

Numerical simulation of seismicity in the considered problem provides more data than seismic monitoring. The number of simulated events is higher than that of the recorded events because numerical simulations are not limited by the resolution of monitoring instrumentation. This allows for more meaningful statistical analysis of the synthetic data. Numerical simulations also provide more geophysical information regarding a single event. As opposed to the field data where only locations and magnitudes were recorded, numerical simulations allow distinguishing between events occurring in tension and in shear, define shear displacements and seismic moments of the events. Other seismic attributes of interest also can be obtained when necessary.

In the considered problem statistical analysis of the orientations of the activated flaws did not reveal any preferential directions. However, further investigations involving a variety of problems are required to provide solid conclusions regarding potential use of the analysis of the orientations.

3.2 Analysis of acoustic emission data recorded in a laboratory experiment

Acoustic emission data were recorded during experiments described in [9]. However, following the request by the authors, Professor Labuz provided the data without the description of the experimental settings. The motivation for the request is that the authors wanted to check which system parameters are readily available from the data of acoustic emission without any a priory knowledge of the settings. While detailed joint geophysical and numerical analysis is a subject of on-going research, this section summarizes the results obtained from statistical analysis of acoustic data. Statistical treatment also outlines a problem which cannot be solved without numerical modeling.

Statistical analysis was conducted using standard principal component analysis (PCA) and strip-ray scanning (SRS) technique recently suggested by the authors. The important feature of the SRS analysis is that the totality of the events is divided into groups. The events are grouped in accordance to their locations so that each group of the events is located within a strip of a fixed width. Initially the orientation of the strip is arbitrary. Further different orientations of the strip within a hemisphere are checked to determine which orientation corresponds to the maximum number of events within the strip. Previous investigations [8], [10] have shown that this orientation of the strip can be associated with the plane containing the source which triggers the events (e.g., hydrofracture plane or mining front). The analysis yielded the following conclusions:

Distribution of the totality of microseismic events allowed for reconstructing geometrical parameters of the tested specimen: it was determined that the region was a rectangle; its width and height were determined with the accuracy of 2% and 0.1% respectively. The length was uncertain, but was estimated to exceed 72.9mm (note that actual length of the specimen was 100mm);

Analysis of the density of the events yielded an estimate of the approximate size of a typical flaw (microcrack). This estimate agrees with a grain size of the specimen;

Distribution of the events within strips of a fixed width indicated that the geometry of the problem did not change during the experiment (i.e. no fracturing has occurred) and that the events were triggered by the changes in the external load. This conclusion coincides with the description presented in [9];

The results obtained by PCA and SRS methods roughly agree. However, the analysis indicates that PCA may serve to estimate the reasonable width W of the strip used in the SRS method. In the meantime SRS seems to provide more accurate interpretation of acoustic data.

The specific grouping of the events cannot be explained in details using only statistical analysis of the events. Thus, joint statistical analysis and numerical modelling may be required for better understanding of the underlying physical process and for more meaningful interpretation of the acoustic data.

4 Conclusion

Unification of statistical analysis of acoustic emission and numerical simulations enhances the understanding of the underlying physical processes. It improves the interpretation of acoustic data and allows for more rigorous inversion of observed microseismicity in well-established terms of solid mechanics.

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Anastasia A. Dobroskok: New Mexico State University; Alexander M. Linkov: IPME, Saint-Petersburg, Russia; Rzeszow University of Technology, Rzeszow, Poland