SEISMOACOUSTIC EMISSION FIELD AND ITS APPLICATIONS

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ABSTRACT
Seismoacoustic emission field and its intensity are useful notions when – as usually in practice of mining seismoacoustic observations – acoustic emission (AE) sources are not localized. Given observed (with a few sensors, during a time interval Δt) values of a so-called „conventional (AE) energy" and postulating reasonable parametric form of emission intensity e(x, y), parameters of intensity equation can be estimated allowing – when the sources are not localized – to estimate the physical AE energy emitted during the Δt, what is needed (e.g.) to evaluate the seismic hazard.

KEYWORDS: mining induced seismic hazard, acoustic emission/seismoacoustics, energy estimation, emission field, emission intensity

1. INTRODUCTION

Rockburst-prone Polish coal mines are equipped with seismoacoustic (AE) systems and apply various, involving AE parameters, methods of seismic hazard assessment. If the seismic hazard – during a (t, t+Δt) time interval at a region S of a coal mine – is defined, as we now define it (e.g. Kornowski, 2003a) as the probability of exceedance, by the total seismic energy $E_T = E_T(t, t+\Delta t)_s$ [being the sum of tremors and AE events' energy emitted during the (t, t+Δt) from the S, with lower index „T" for „total"], of some prespecified „safety threshold" E_g (which may depend on local conditions), then energy E_T should be estimated and there are some problems to solve if we do not routinely estimate coordinates of AE sources. It is then assumed here that – as is usual in Polish coal mines – coordinates of AE sources are not estimated (not „localized") and that the computer supervizing the AE system in a coal mine, periodically (every Δt, with e.g. Δt = 1 hour) reports cumulated number of observed events (called „activity") $N = N(t, t+\Delta t)_s$ and cumulated volume of a so-called conventional (AE) energy $E_u=E_u(t, t+\Delta t)_s$, which is (modified) wavefield energy density nearby observing sensor(s). It is assumed also that activity N is high enough to allow statistical considerations, and that the longwall of the length L and of constant height h_L occupies the region [(x, y) with $0 \le x \le L$, $0 \le y \le \infty$, with the longwall face always on the axis y = 0]. These assumptions exclude any reasonable analysis of a single event energy, allowing instead to consider the cumulated AE energy E_{AE} or, equivalently, the mean level $\bar{e} = e_{AE}(t, t+\Delta t)_s$ of energy intensity (called also the „mean field intensity" and defined below) which must, for consistency, integrate (over S and Δt) to E_{AE}.

This way we have introduced an important notion of energy emission field P, characterized by its intensity *e* which, in the simplest (no side information) case, is constant: $e(x, y)=\bar{e}$, or randomly distributed around the constant $\bar{e}$. Emission field P is spanned on the space region where AE sources occur and should not be misidentified with resulting wavefield. Intensity *e*(x, y, z, t), or *e*(x, y) in practice, is the volume of energy emitted from a point (x, y) during the time unit (Δt). The important consistency requirement postulates that, during the consecutive Δt intervals, the estimated [given P-field model and transmittance relations] energy equals, or fits as much as possible (minimimizing mean squared error) actually observed values E_u. Given any prior information [e.g. „*e*(x,y) decreases as the distance from the longwall face increases"] we can suggest, hopefully better fitting reality, a parametric equation of *e*(x, y) with the number of parameters no greater than the number of sensors, estimate the parameters values and then estimate the E^P_{AE}, AE energy estimated „given the model".

There are some obvious benefits of using so defined notion of energy emission field:

- the subiect of AE observation and analysis is well defined despite the lack of sources' locations
- physical energy of emission can be (conditionally

on the model, but optimally) estimated, again despite the lack of locations

- in case of multisensor observations, their subiect $\{e(x, y)\}$ is univocally defined and the seismic hazard can be so assessed (much decreasing – comparing with the present method of seismic hazard evaluation – the rate of false alarms)
- almost any prior information concerning singularities of stress or emission field (resulting from ridges or faults) can be taken into account
- mean value of absorption coefficient (α) in front of the longwall can be estimated and sequentially (every Δt) updated.

These are sufficient reasons to develope a theory of the emission field. Previous paper on this subiect is: Kornowski (2003b).

Note that

E_u is called, in miners jargon, a "conventional energy". It is a modified, mainly due to a measurement system, wavefield energy density near the sensor. Without any upper index, it is "the observed E_u"

E_{AE} is the physical energy (of emission field P)

$e(x, y)$ – or generally $e(x,y,z,t)$ – is the spatial density of E_{AE} called the intensity of P. Integrating e over S, its spatial support, we obtain E_{AE} (in a given time interval or moment).

Upper index "p" (eg. E_u^p or E_{AE}^p) denotes energy (conventional or physical) conditional on a given model (i.e. energy that "would be" observed or generated given the intensity model e).

Relation between the observed (E_u) and generated (E_{AE}) emission field energy is needed (in mining seismoacoustics, where AE sources are not localized), as an "observation equation" in a set of AE state-space equations (where E_{AE} can be estimated with a "state evolution equation") and this is the intended application of this relation.

2. ENERGY OF EMISSION FIELD ESTIMATION

Let $\dot{u}(t)$ denotes particle velocity of the medium nearby the sensor located at (x_s = 0, y_s) and let e_g denotes integral of $\dot{u}^2$ during a seismogram duration (since t_1 till t_2). Then

$$e_g = \int_{t_1}^{t_2} [\dot{u}(t)]^2 dt \tag{1}$$

defines the spatial density of the wave field energy in the normalized (v = 1 m/s, ρ = 1 t/m^3) medium

A. CASE OF A SINGLE SOURCE OF KNOWN (x, y) LOCATION.

Observed conventional energy E_u registered/displayed with the AE-observing system can be estimated as

$$E_u^p = k_d^2 \, k_c^2 \, k_a \, e_g \tag{2}$$

where k_d=cosφ is the „directional (amplitude) amplification" of the sensor and

$$\cos\varphi = x/r \tag{3a}$$

$$r = \sqrt{(x - x_s)^2 + (y - y_s)^2} \tag{3b}$$

k_c – measurement channel (amplitude) amplification

k_a – effective A/D converter and software (amplitude) amplification

Assuming that waves propagate in the half-plane of a coal seam (in front of the longwall face) we can express the physical energy E_{AE} of the wavefield (reduced to the source) as

$$E_{AE} = \pi \, r \, h \, V \, \rho \, e^{2\alpha r} \, e_g \tag{4}$$

where V, h, ρ and α are, respectively, the velocity of the wave, seam thickness and density, and attenuation coefficient (α) resulting from the wave energy absorption in the medium. Applying (1) – (3) we can write

$$E_u^p = K(x, y, \alpha) \, C_1 E_{AE} \tag{5a}$$

$$C_1 = k_c^2 \, k_a^2 \, (\pi \, h \, V)^{-1} \tag{5b}$$

$$K(x, y, \alpha) = r^{-1}(x/r)^2 \, e^{-2\alpha r} \tag{5c}$$

(note that C_1 does not, while K does depend on the source location). Equations (5a, b, c) constitute the relation between the (estimate E_u^p of) observed E_u and the emitted E_{AE} wavefield energies in case of the single source located at (x, y) if our assumptions apply and allow to estimate E_{AE} given observed E_u.

B. CASE OF MANY SOURCES WITH ENERGY DISTRIBUTED AS *e*(x, y).

Assume now that during the Δt interval, the AE-observing system has observed many events from sources distributed in space according to known (source) energy density $e(x,y)$ and reported the cumulated, actually observed, value E_u of conventional energy. Then

$$E_{AE}^p = \int_0^{\infty}\int_0^{L} e(x, y) dx \, dy \tag{6}$$

is the estimate of energy emitted given the model [equation of $e(x, y)$] of P-field intensity and equation (5a) can be immediately generalized to

$$E_u^p = C_1 \int_0^{\infty}\int_0^{L} K(x,y,\alpha) \, e(x,y) \, dxdy \tag{7}$$

(with upper index „p” meaning „estimated, given the model”). Knowing sensor coordinates (x_s, y_s), value of α and the *e*(x,y) equation, relation (7) allows to estimate E_u^p without individual sources location. But, as the E_u values are observed, we are rather interested in the inverse task: given observed $E_u(i)$, i=1,..., M values, observed during the same Δt interval with M sensors, estimate the unknown parameters of *e*(x,y). This is the subiect of the next chapter.

3. EMISSION INTENSITY EQUATION AND ESTIMATION OF ITS PARAMETERS

A. THE SIMPLEST MODEL OF INTENSITY

To begin with let us assume that all the AE energy (during a Δt interval) is emitted from the sources almost evenly distributed alongside the longwall face of length L, inside the narrow strip of unit width and constant height and that we know the value of α. Then

$$e(x,y) = \beta_o \text{ for } 0 \le y < 1,\ 0 \le x < L \tag{8a}$$

$$e(x, y) = 0 \text{ elsewhere} \tag{8b}$$

with energy E_{AE}^P emitted from the P-field

$$E_{AE}^P = \int_0^\infty \int_0^L e(x,y)\,dxdy = L\,\beta_o \tag{9}$$

we can also approximate

$$K(x, y, \alpha)\, e(x, y) \approx K(x, 0, \alpha)\beta_o \tag{10}$$

and estimate [applying (7) and (10)] energy observed given the model

$$E_u^P = C_1\beta_o I_o \tag{11a}$$

$$I_o = \int_0^L K(x, 0, \alpha)\,dx \tag{11b}$$

[quadrature of (11b) should be calculated numerically]. Then taking β_o from (11a) and inserting it into (9) we obtain

$$E_{AE}^P = LE_u^P/(C_1 I_o) \tag{12}$$

so that, with a single sensor observing conventional energy E_u, we can insert it into (12) in place of E_u^P thus estimating the physical energy E_{AE}. If M sensors are used, we may assume normally distributed intensity of emission energy

$$e(x, y) = N(\beta_o, \sigma_o^2) \tag{13}$$

with β_o defined by (8a,b), estimate $E_{AE}(i)$, i=1,..., M according to (12) and then calculate their mean value and variance, which informs us of the measurement and model errors. The function

$$T(y_s) = L/(C_1 I_o) \tag{14}$$

may be thought of as a generalized transmittance function [for the given – by (13) or (8a, b) – intensity *e*(x,y) and values of L and α] relating generated (E_{AE}) and observed (E_u) energies. For practical purposes (with $0.005 \le \alpha \le 0.05$ and $1 \le y_s \le 200$ m), it can be calculated for a few values of y_s and approximated with simple exponential function. For example, at the longwall 37/501 at „Wesoła” Coal Mine [with known C_1, $\alpha = 0.012\ m^{-1}$, L = 200 m and $40 \le y_s \le 120$ m] we used, for prolonged period of time, the approximation

$$E_{AE} \approx E_u \cdot 5.915 \exp [0.0229\,(y_s - 40)] \tag{15}$$

for a few geophones installed at distances $y_s(i)$, i=1,...,M from the nearest point of the longwall.

B. MULTIPARAMETRIC EQUATIONS OF EMISSION INTENSITY

Usually AE from a longwall is observed using 1<M<5 sensors, depending on expected seismic hazard and then equations more realistic then (8a,b) can be suggested. A simple equation, usful at homogeneous geological and stress conditions, models intensity steadily decreasing with increasing distance (y) from the longwall face

$$e(x,y) = \beta_o\ e^{-\beta_1 y} \tag{16a}$$

(for observations with two sensors) or

$$e(x,y) = N(\gamma, \sigma^2) \tag{16b}$$

with γ distributed in space according to (16a), for M>2. It can be checked – inserting (16a) into (6) – that, in this case

$$E_{AE}^P = L\beta_o/\beta_1 \tag{16c}$$

but E_u^P of (7) remains a non – elementary integral which should be evaluated numerically.

Another energy intensity model has been used at the longwall 37/501 in Wesoła Coal Mine, where serious asymmetry of AE at both longwall ends has been observed

$$e(x,y) = \beta_o\ e^{-\beta_1 x} e^{-\beta_2 y} \tag{17a}$$

This is a 3-parameter model of intensity decreasing with growing distance (y) from the longwall face as well as with the distance (x) from the transport gallery. Given values of β_o, β_1, β_2, energy emitted from P (provided Δt = 1) is

$$E_{AE}^P = \beta_o(1 - e^{-\beta_1 L})/(\beta_1\beta_2) \tag{17b}$$

but parameters estimation requires much more calculations.

Depending on prior information and on the number M of sensors, models taking into account more complicated singularities (of emission field) can be considered, for example

$$e(x,y) = ß_o \; e^{-\beta_1 (x-x_1)} e^{-\beta_2 y} \tag{18a}$$

modelling a fault at x_1-th meter of the longwall face, or

$$e(x,y) = ß_o \; e^{-\beta_2 (y-y_1)} \; e^{-\beta_1 x} \tag{18b}$$

modelling a line of maximum stress (e.g. due to an edge of old exploitation) parallel to the longwall face, y_1-meters in front of it.

It should be mentioned here that exponential models are much better than polynomial or linear ones, automatically ensuring positivity of intensity – what is an important physical constraint.

Values of parameters (ß's) can be estimated – given the model e(x,y) and M observations $E_u(i)$, i=1,..., M taken in the same Δt interval – minimizing the sum of squared errors [between observed (E_u) and estimated (E_u^P) values]:

$$\beta = \arg\min \sum_{i=1}^{M} [E_u(i) - \int_0^{\infty}\int_0^{L} C_1 K_i(x,y,\alpha)\, e\,(x,y)dxdy]^2 \tag{19}$$

where β is the vector of unknown parameters.

Minimum of the squared error surface should be looked for using a method which need not function derivatives (e.g. known Nelder-Mead „simplex method”) and two-dimensional quadrature (7) should be carefully programmed taking benefit of a priori known form of the integrand.

Note that no problem arises if we include α, the mean value of attenuation coefficient in front of the longwall face, into the vector β of unknowns – what gives us an automatic, cheap method of α estimation, which may be updated every Δt.

4. REMARKS AND CONCLUSIONS

A. Models of emission field, independent in consecutive time intervals Δt and constant inside any given Δt have only been considered. Assuming small changes of β's in time, various adaptive estimation schemes can be applied, improving estimation results.

B. For simplicity, P-field has been presented as a deterministic and continuous one, but we can consider it as (a realization of) a two- or three-dimensional point process with its mean value (or intensity) equal to e(x,y). In cases when actual AE can be considered stationary, our P-field approximates the asymptotic field of actual AE, and e(x,y) approximates its intensity. This is the physical interpretation of P and e.

C. Without locating individual AE sources – what has been excluded in this paper – more detailed, nonparametric analysis of the emission field seems impossible.

D. Energy emitted from any (x,y) source-point is a result of inelastic, locally damaging strains, so that e(x,y) can also be interpreted as the local damage (increase) during the Δt and e(x,y,t) as the local damaging rate.

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