



THE APPLICATION OF SEISMIC CODE METHODOLOGY IN THE STRUCTURAL DESIGN AGAINST MINE TREMORS

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ABSTRACT

Deep mining may induce ground quakes with magnitude m_L up to 5.5 and *Modified Mercalli* intensities up to VIII. This may cause serious damages in civil infrastructure in the vicinity of mines. Any adaptation of the seismic code to design structures subjected to mine tremors faces however an impending problem of differences in spectral content and duration between the surface records of the rockbursts and natural earthquakes which shaped the methodology of the code, as well as in their different risk definitions. This paper presents a system to define design seismic load based on forecasted surface horizontal particle velocity from the rockbursts expected during the planned mining activities. Such forecasts are routinely prepared by the geophysical mine services. Respective seismic load may then be applied in the design of buildings and other structures to mitigate the rockburst induced seismic effects on them. For this purpose the European seismic code, Eurocode 8 is adapted.

INTRODUCTION

Deep mining affects the earth surface in two main ways:

- by causing extended subsidence (e.g. Kratzsch 1983, Sheorey et al 2000, Gonzalez et al 2005) and
- by induced seismic hazard (Gibowicz and Kijko 1994, Kijko, Lasocki, Graham 2001, Orlecka-Sikora et al. 2012).

The first problems are subject of already rather long research (Knothe 1953) whereas the mine tremors caused by the induced seismic hazard are getting more and more attention only recently, when it appeared that the mine quakes may reach magnitude m_L of 4.5 or even exceed 5 (Mc Garr et al. 1989), leading to surface ground motion with *Modified Mercalli* intensities up to VIII. Such the ground motion is capable to cause serious damages in civil infrastructure, particularly when the deep mining takes place near or below habited areas. The strong rockbursts usually are causing only minor damages, but for those few extremely strong the resulting damages may be serious (see Fig.1). In the situations of potentially strong seismic effects, one may expect the buildings and other structures, including the surface technical infrastructure of the mines, to be protected against seismic effects at the stage of their design, the same way as it is done for structures designed for the zones of natural

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seismicity. However the direct application of typical seismic structural codes for these purposes is not straightforward for various reasons with following three of them being the most important:

- a) surface mine tremor records differ from the acceleration records of natural earthquakes with respect to their spectral content and duration,
- b) there are problems how to define so called *design acceleration* for the 3-4 years return period of the strongest rockbursts as compare to typical 475-500 years return period of the classic seismic codes,
- c) the extend to which inelastic seismic response can be accepted in the design (behaviour 'q' factors of Eurocode 8) should carefully be re-evaluated



Figure 1. Damage to a residential building caused by M_L 5.3 rockburst from March 9, 2005 in Stilfontein, South Africa (courtesy of dr Artur Cichowicz, Council for Geoscience, South Africa)

In this paper, an approach to rationally adapt the European seismic code, Eurocode 8, for the structural design procedures in the areas of deep mining is presented in detail, on an example of LGOM Copper Mine Basin in Western Poland. To obtain such defined goal, the rockburst induced ground motion was first studied (Zembaty 2004) and later a concept of a technical methodology was developed (Zembaty 2011), where special rockburst design response spectrum was presented.

ROCKBURSTS AND THEIR SURFACE INTENSITY

Jonstone (1992) divided all rockbursts onto two general types:

- Type I, with lower to mid magnitude, close to mining face, with high stress drops and directly correlated with the mining activities.
- Type II, with high magnitude, often located on preexisting fault surface, even a few kilometers from the mine, with stress drop similar to natural earthquakes, not directly correlated with the mine activities.

When it comes to identify the extreme seismic loads from rockbursts, these are type II rockbursts which can generate more intensive tremors. It should however be noted that the peak ground accelerations of both types of rockbursts are very similar and even, in many cases, the type I rockbursts can generate higher accelerations on the ground surface than the type II rockbursts. These problems were investigated by Zembaty (2004), when ground motions produced by rockbursts from the LGOM basin were analyzed in detail. It was observed then, that the classification introduced by

Jonstone (1992) also fits well when surface rockburst records are studied. Thus, two characteristic types of rockburst surface records were identified:

- Records of type I with very short duration (1–2 s) and Fourier spectra shifted to higher frequencies (about 20–40 Hz) similar to those from blasts (Fig. 2). These records were collected from the events with rather low intensity and return period of 2–3 months.
- Records of type II with longer duration (about 5s or more) and with dominating part of Fourier spectra below 5 Hz, similar to weak, shallow earthquakes (Fig. 3). These records are collected from rather strong, rare events of return period 1–3 years.

CONSTRUCTION OF THE DESIGN RESPONSE SPECTRUM.

The collection of intensive, type II ground recordings from the LGOM Copper Basin reached the number of 18 signals and this allowed to define a response spectrum representing rockburst seismic loading. A methodology was proposed by Zembaty (2011) to obtain special rockburst design response spectra for civil engineering purposes, but first the method how to treat the local site effects had to be decided.

It is well known that ground motion at the surface is very strongly influenced by the geotechnical characteristics of the soil formations below the ground surface. Some seismic codes, including Eurocode 8 (EN 1998-1, 2005), International Building Code (IBC, 2009) and Italian Building Code (NTC, 2008), allow to account for site effects using a simplified method based on the introduction of a number of different soil categories to which specific, frequency-independent, soil factors are associated. These factors are used to modify the shape of the elastic acceleration response spectrum computed at a rocky site (reference spectrum).

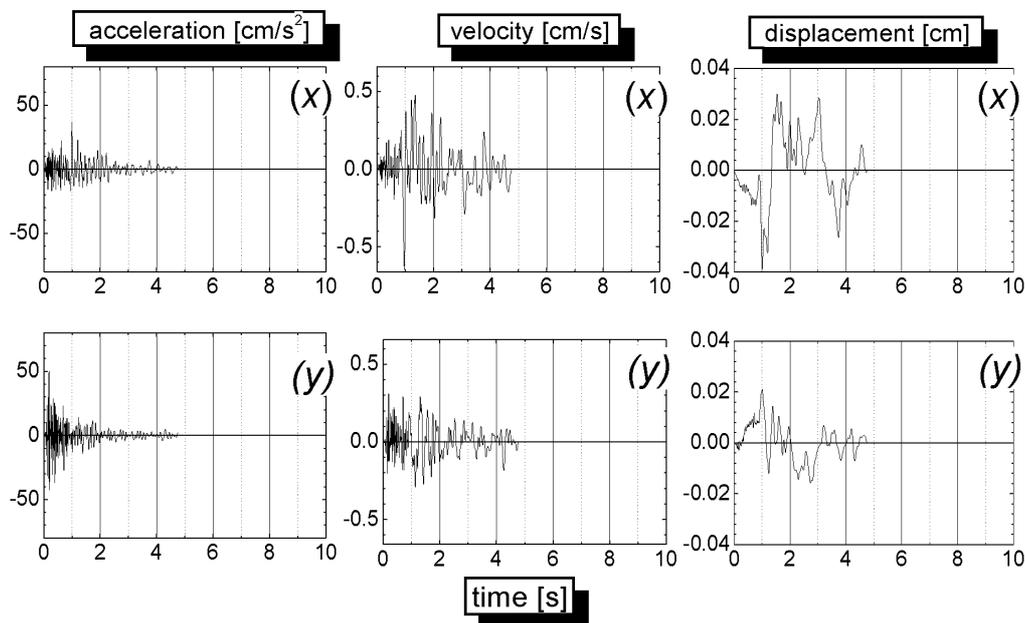


Figure 2. Example of strong rockburst record of a type I event from February 2nd, 2001 (station “3Maja”) in Polkowice, Poland, ($PGA_x=37\text{cm/s}^2$, $PGA_y=93\text{cm/s}^2$, $PGV_x=0.48\text{cm/s}$, $PGV_y=0.31\text{cm/s}$)

The parameter used to identify the soil category is $V_{s,30}$, defined as a weighted average of the shear wave velocity in the uppermost 30 m of soil profile.

For the purpose of this research a procedure has been set-up to take into account the significant role played by local site conditions in the definition of the rockburst seismic action, including the litho-stratigraphic amplification effects in the rockburst design response spectra. The procedure was based on the stochastic approach to perform one-dimensional (1D) ground response analyses, proposed by Lai et al. (2009), Rota et al. (2011) and Bozzoni et al. (2013).

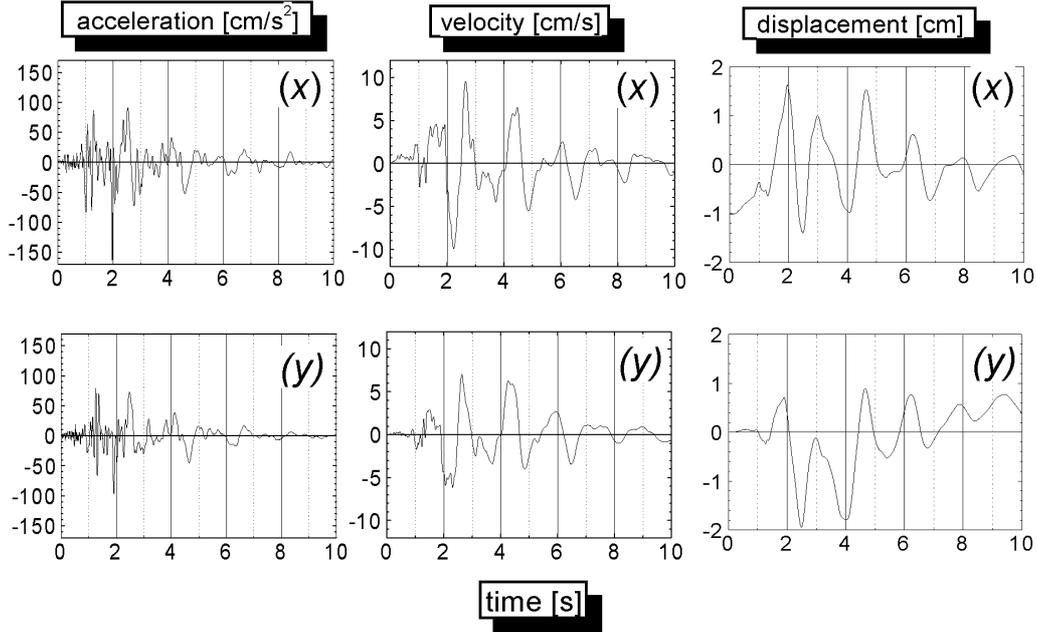


Figure 3. Example of strong rockburst record of a type II event from February 20th, 2002 (station “Miedziana”) in Polkowice, Poland, ($PGA_x=163.4 \text{ cm/s}^2$, $PGA_y=96.5 \text{ cm/s}^2$, $PGV_x=9.95 \text{ cm/s}$, $PGV_y=7.04 \text{ cm/s}$)

These fully stochastic site response analyses permitted to account for the uncertainty of soil properties, as well as the variability of the input motion. Three most important soil profiles of Eurocode 8 were considered. As a result of this procedure design response spectrum for the soil profiles A and B were developed as follows:

$$S_a = a_g \beta(T) = a_g S \left\{ \begin{array}{ll} \left[1 + \frac{T}{T_B} (2.5\eta - 1) \right] & 0 < T < T_B \\ 2.5\eta & T_B \leq T \leq T_C \\ 2.5\eta \frac{T_C}{T} & T_C < T \leq T_D \\ 2.5\eta \frac{T_C T_D^2}{T^3} & T > T_D \end{array} \right. \quad (1)$$

with a different formula for soil profile C:

$$S_a = a_g \beta(T) = a_g S \left\{ \begin{array}{ll} \left[1 + \frac{T}{T_B} (2.5\eta - 1) \right] & 0 < T < T_B \\ 2.5\eta & T_B \leq T \leq T_C \\ 2.5\eta \frac{T_C^{1.5}}{T^{1.5}} & T_C < T \leq T_D \\ 2.5\eta \frac{T_C^{1.5} T_D^{1.5}}{T^3} & T > T_D \end{array} \right. , \quad (2)$$

where η is a correction factor for damping ratio other than $\xi = 5\%$ (Eurocode 8),

$$\eta = \sqrt{\frac{10}{5 + 100\xi}} \geq 0.55 , \quad (3)$$

while the rest of the above parameters depend on the soil profile and equal:

- $S=0.8$, $T_B=0.1$, $T_C=0.85$, $T_D=1.3$ for Eurocode 8 soil category A,
- $S=1.0$, $T_B=0.1$, $T_C=0.95$, $T_D=1.3$ for Eurocode 8 soil category B,
- $S=1.5$, $T_B=0.3$, $T_C=0.80$, $T_D=1.3$ for Eurocode 8 soil category C.

In Fig. 4 the plots of response spectra given by formulas (1) and (2) are presented.

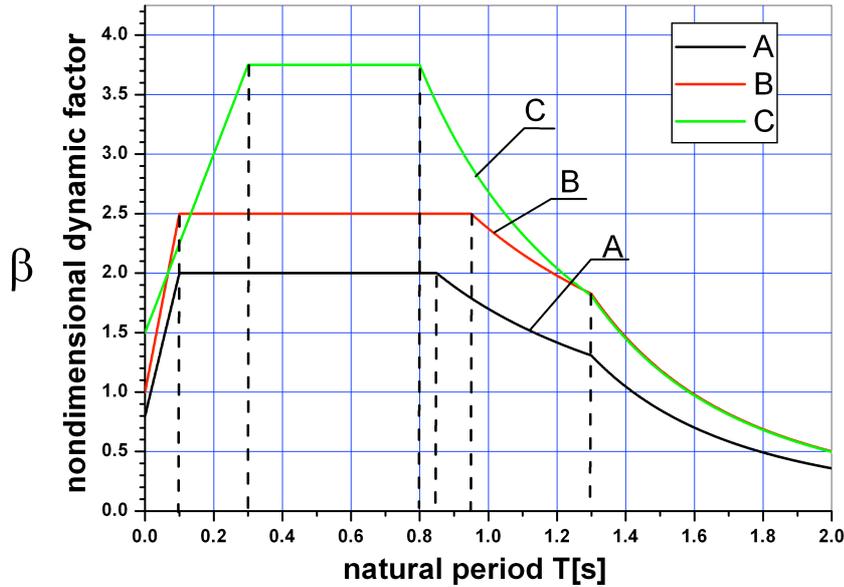


Fig. 4 Plots of design response spectra (formula 1) for damping ratio $\zeta = 0.05$ and three Eurocode 8 soil categories A, B, C (design acceleration $a_g = 1 \text{ m/s}^2$)

It should be noted that in traditional design against rare seismic events (return period 475 years) the linear response spectra, as in the formulas (1) and (2), are rarely applied because their application leads often to excessive internal forces. Instead the response spectra accounting for inelastic response are used with behavior factor ‘ q ’ changing from 1.5 to 5 and effectively reducing the design load. In case of extreme rockbursts, which may appear with return period of 2-3 years such the approach is not possible. However some kind of “overstrength” (Fardis et al. 2005) should be taken into account to avoid too still too great internal forces. After careful analyses it was decided to allow application of $q=1.5$ and construct respective inelastic response spectra as follows:

$$S_a = a_g \beta(T) = a_g S \left\{ \begin{array}{ll} \left[\frac{2}{3} + \frac{T}{T_B} \left(\frac{2.5}{q} - \frac{2}{3} \right) \right] & 0 < T < T_B \\ \frac{2.5}{q} & T_B \leq T \leq T_C \\ \frac{2.5 T_C}{q T} & T_C < T \leq T_D \\ \frac{2.5 T_C T_D^2}{q T^3} & T > T_D \end{array} \right. \quad (3)$$

and for soil profile C

$$S_a = a_g \beta(T) = a_g S \left\{ \begin{array}{ll} \left[\frac{2}{3} + \frac{T}{T_B} \left(\frac{2.5}{q} - \frac{2}{3} \right) \right] & 0 < T < T_B \\ \frac{2.5}{q} & T_B \leq T \leq T_C \\ \frac{2.5 T_C^{1.5}}{q T^{1.5}} & T_C < T \leq T_D \\ \frac{2.5 T_C^{1.5} T_D^{1.5}}{q T^3} & T > T_D \end{array} \right. \quad (4)$$

SETTING THE DESIGN ACCELERATION VALUE

Particularly difficult problem appears when a decision about the design acceleration a_g is to be considered for the mine tremors actions. The solution applied in this case is based on the application of the displacement approach.

Consider Fig. 5, where displacement response spectra are shown for two horizontal rockburst records along x and y axes. Respective horizontal peak particle velocity equaled in this case $PGV_{hor}=6.37\text{cm/s}$, where $PGV_{hor} = \max \sqrt{V_x(t)^2 + V_y(t)^2}$. The plots from Fig. 5 include also Eurocode 8 displacement response spectrum calculated as $S_d = (2\pi/T)^2 / S_a$. By changing design acceleration a_g , the EC-8 displacement response spectrum is set to best fit the response spectra of the two records, in the range of typical natural frequencies of buildings, here from zero to about 1.5s. The best fit is reached for $a_g=55\text{cm/s}^2$. This means that the design acceleration equal to 55cm/s^2 will lead to the relative displacements (deflections) in the structures the same as rockbursts with horizontal peak particle velocity of 6.37cm/s. This way one obtains an r factor between the rockburst intensity measured by PGV_{hor} and the design acceleration:

$$r = \frac{a_g}{PGV_{hor}} = \frac{55}{6.37} \cong 8.63 \quad (5)$$

The same fitting process was carried out more systematically, using minimization algorithms, between all the 18 records of strong rockbursts used to formulate response spectra (1-2). As a result an average value for r equal to 5.77 was obtained with standard deviation 1.97. It was decided then that in the future designs in the LGOM region $r=10$ will be applied with an appropriate safety margin, i.e. $a_g=10v_g$, where v_g is the forecasted surface peak horizontal velocity for the respective mining region. This means, that accepting the peak horizontal velocity as the most appropriate measure of mine tremor intensity (Zembaty 2004), a relation between the rockburst intensity at a site and the design acceleration was established.

For the purposes of civil infrastructure design, the LGOM basin region was divided onto four mine regions:

- with expected maximum ground velocity $v_g < 1\text{cm/s}$, where no measures against mine tremors are planned for the design,
- with expected maximum ground velocity $2\text{cm/s} > v_g > 1\text{cm/s}$, where only some limited measures are planned,
- with maximum ground velocity $4\text{cm/s} > v_g > 2\text{cm/s}$, where the response spectra (1-2) or (3-4), with $a_g=40\text{cm/s}^2$, should be applied,

- with maximum ground velocity $6 \text{ cm/s} > v_g > 2 \text{ cm/s}$, where the response spectra (1-2) or (3-4), with $a_g = 60 \text{ cm/s}^2$, should be applied.

For all the four mining regions one can now rationally define a design procedure to mitigate rockburst effects in the designed structures.

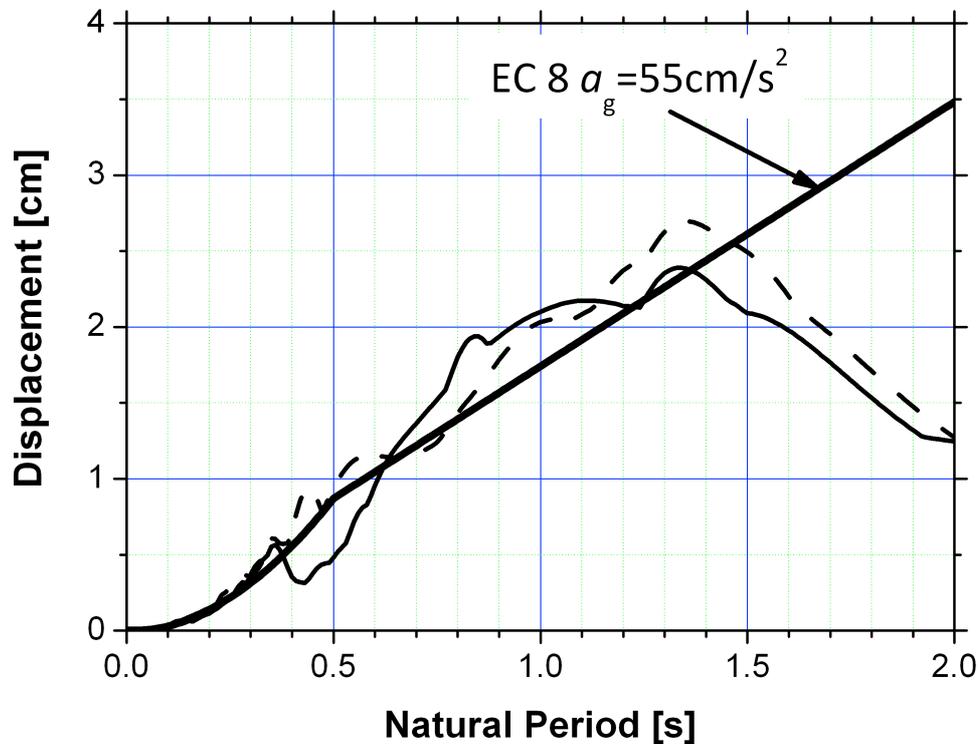


Fig. 5 Illustration of fitting of the EC-8 displacement response spectrum into corresponding rockburst displacement response spectra of particular peak particle velocity, in a search to find corresponding design acceleration value

CONCLUDING REMARKS

A methodology how to apply Eurocode 8 response spectrum to design civil engineering structures under rockburst surface excitations is presented. Respective response spectra were obtained based on a collection of strong rockburst records, including the local site effects for three Eurocode 8 site profiles *A*, *B* and *C*.

The region of mine induced seismic hazard is divided into zones with particular maximum surface horizontal peak particle velocity, as expected during the mine activity. For each of the velocity zone an appropriate design procedure is settled. The ground velocity forecasted by geophysical mine services is used to define respective design acceleration based on a factor $r=10$ i.e. $a_g=10v_g$, where v_g stands for expected, rockburst induced horizontal ground velocity.

REFERENCES

- Bozzoni F., Lai C.G., Mangriotis M.D., Margiotta S. (2013). Definition of Seismic Input at the archeological site of Marte Ultore Temple in Rome (Italy). Proceedings of International Conference on Rehabilitation and Restoration of Structures, Chennai, India, February 13-16, p. 2013.
- EN 1998-1 (2005), Eurocode 8: Design of structures for earthquake resistance.

- Fardis M.N., Carvalho E., Elnashai A., Faccioli E., Pinto P. And Plumier A., (2005) *Designers' Guide to EN 1998-1 and EN 1998-5, Eurocode 8: Design of structures for earthquake resistance. General rules, seismic actions, design rules for buildings, foundations and retaining structures*, Thomas Telford.
- Gibowicz S.J., Kijko A. (1994), *An introduction to mining seismology*. San Diego: Academic Press
- Gonzalez Nicieza C, Alvarez Fernandez MI, Menendez, Diaz A, Alvarez Vigil AE. The new three-dimensional subsidence influence function denoted by n–k–g. *International Journal of Rock Mechanics and Mining Sciences* 2005;42(3):372–87.
- IBC (2009). International Building Code, International Code Council 2009, Inc., www.iccsafe.org/Pages/default.aspx.
- Johnston J.C. (1992), Rockbursts from a global perspective. In: Knoll P, editor, *Induced seismicity*. Rotterdam, Brookfield: Balkema, pp. 63–78.
- Kijko, A., Lasocki, S., Graham, G. (2001), Non-parametric seismic hazard in mines, *Pure and Applied Geophysics*, 158: 1655-1675
- Lai C.G., Corigliano M., Sánchez H.L. (2009). Some examples of 1D, fully stochastic site response analyses of soil deposits. Proceedings of the ACES Workshop: Advances in Performance-based Earthquake Engineering. Corfu, Greece
- Knothe S. Rownanie profilu ostatecznie wykształconej niecki osiadania, *Archiwum Gornictwa i Hutnictwa*, tom 1, zeszyt 1, 1953, str 22–38
- Kratzsch H. *Mining subsidence engineering*. Berlin: Springer; 1983
- McGarr, A., Bicknell J., Sembera E., Green R. W. E., (1989) Analysis of exceptionally large tremors in two gold mining districts of South Africa, *Pure and Applied Geophysics*, 129: 295-307
- NTC (2008). *Norme Tecniche per le Costruzioni*, D.M. 14.1. 2008 (Italian building code).
- Orlecka-Sikora B., Lasocki S., Lizurek G., Rudzinski L., (2012) Response of seismic activity in mines to the stress changes due to mining induced strong seismic events, *International Journal of Rock Mechanics and Mining Sciences*, 53: 151–158
- Rota, M., Lai, C.G., Strobbia, C. (2011). “Stochastic 1D Site Response Analysis at a Site in Central Italy *Soil Dynamics and Earthquake Engineering*”. 31(4): 626-639.
- Sheorey PR, Loui JP, Singh KB, Singh SK. (2000) Ground subsidence observations and a modified influence function method for complete subsidence prediction. *International Journal of Rock Mechanics and Mining Sciences* 2000, 37(5):801–18
- Zembaty Z. (2004), Rockburst induced ground motion—a comparative study, *Soil Dynamics & Earthquake Engineering*, 24(1):11–23
- Zembaty Z., (2011), How to model rockburst seismic loads for civil engineering purposes?, *Bulletin of Earthquake Engineering*, 9(5):1403-1416