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MODELING INDUCED GROUND MOTION AS A SEISMIC DESIGN STRUCTURAL LOAD

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Abstract

Seismicity induced by deep mining is typically characterized by quakes with local magnitude ranging from 4.5 to 5.5 and surface ground motion with Modified Mercalli intensities up to VIII. Such strong ground motions may result with serious damages in civil infrastructures. However, any attempt to adapt the classic seismic design codes in order to account for mine tremors faces the differences in terms of spectral content and duration of the surface records of related to rockbursts with respect to the recordings typical of natural earthquakes and in their different risk definitions. The aim of this paper is to illustrate a methodology set-up to define design seismic load based on forecasted surface horizontal ground 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 has been adapted.

Keywords: mine tremors; rockbursts; response spectra; seismic code, Eurocode 8

1. Introduction

Seismic events induced by mining reach local magnitudes M_L greater then 5 (see e.g. paper by McGarr et al., 1989, [1]) and may generate significant surface ground excitations. Specific properties of the induced seismic events compare to natural earthquakes, like shallow location of seismic source and small epicentral distances to civil infrastructure, result in surface tremors which, in spite of moderate magnitude, can even be more intensive than respective earthquakes of similar magnitude (e.g. Zembaty, [2]). The induced seismic ground motion may then lead not only to minor damages but even to serious structural damages (see e.g. Fig. 1).

Fig. 1 – Dramatic photograph of a collapsed residential building in Welkom (South Africa) after a strong rockburst with local magnitude M_L=5.2, from December 8th 1976 (courtesy of Dr A. Cichowicz, South African Council for Geoscience).

For these reasons one may want to investigate

- how to retrofit existing buildings or
- how to mitigate these effects for newly designed buildings in close to mines.

Consider now the second of these issues i.e. adaptation of classic civil engineering codes modeling natural seismic effects on structures, [3], in structural design against induced tremors. In this case two important issues need to be addressed:

1) How to model specific spectral content and duration of the surface records of mine tremors, which are different with respect to natural earthquake records?

2) How to account in the design for different definitions of seismic risk associated with induced seismicity expected within not more than a few years return period, compare to extreme natural earthquakes expected with return period of about 500 years?.

In what follows a description of how these issues were addressed in the adaptation of Eurocode 8 (CEN, 2003 [3]; hereinafter referred to as EC8), to be used in design of buildings in the LGOM Copper Basin in Poland, is presented.

2. Intensity of mine tremors

Seismic waves induced by rockbursts propagate basically the same way as the natural earthquakes, i.e. originating in hypocenter and appearing at the surface as body and surface waves. Though most of rockbursts originate directly in the mining area and are directly correlated with the mine activities, the strongest ones usually appear as induced, shallow earthquakes in the existing faults (see e.g. Johnstone [4], Zembaty [2]). Key parameters of such the mining seismicity can be forecasted using various geophysical hazard prediction methods (e.g. Kijko, Lasocki, Graham [5], Gibowicz, Kijko [6]). As a result maps of peak ground accelerations and velocities are prepared by geophysical services of the mines and are used to ensure safe exploitation and protection of buildings and other infrastructure.

In 1992 Johnstone, [4], 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 far 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 in 2001-2004, [2], when ground motions produced by rockbursts from the LGOM Copper Basin were analyzed in detail. It was observed then, that the classification introduced by Jonstone, [4], also fits well when surface rockburst records are studied. Thus, two characteristic types of rockburst surface records were identified [2]:

- 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. 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. These records are collected from rather strong, rare events of return period 1-3 years.

3. Design response spectra

The collection of strong, intensive, type II ground recordings from the LGOM Copper Basin reached 18 and this allowed to build averaged, design response spectrum representing rockburst seismic loading. A methodology was proposed (see [7] for further details) to obtain special rockburst design response spectra for civil engineering purposes. This approach did not take into account local site effects, herein addressed.

It is well known that ground motion at the surface is influenced by the geotechnical characteristics of the soil formations below the ground surface. Most of the seismic codes, e.g. [8, 9] and E8, in particular, [3], allow, at stable sites, to account for site effects using a simplified method based on the introduction of a number of different ground 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).

The parameter used to identify the ground 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, based on SHAKE program ([10]), proposed by Lai et al. (2009, [11]), Rota et al. (2011, [12]) and Bozzoni et al. (2013, [13]).

These fully stochastic, site response analyses permitted to account for the uncertainty of soil properties, as well as the variability of the input motion. Details of the procedure are given in paper [14]. Three most important ground categories of EC8, i.e. A, B, C, were considered. As a result of this procedure elastic design response spectra for the ground categories 'A' and 'B':

$$R(T) = a_g \beta(T) = a_g S \cdot \begin{cases} [1+\dfrac{T}{T_B}(2.5\eta - 1)] & 0 < T < T_B \\ 2.5\eta & T_B \le T \le T_C \\ 2.5\eta \dfrac{T_C}{T} & T_C < T \le T_D \\ 2.5\eta \dfrac{T_C T_D^2}{T^3} & T > T_D \end{cases} \tag{1a}$$

as well as 'C'

$$R(T) = a_g \beta(T) = a_g S \cdot \begin{cases} [1+\dfrac{T}{T_B}(2.5\eta - 1)] & 0 < T < T_B \\ 2.5\eta & T_B \le T \le T_C \\ 2.5\eta \dfrac{T_C^{1.5}}{T^{1.5}} & T_C < T \le T_D \\ 2.5\eta \dfrac{T_C^{1.5} T_D^{1.5}}{T^3} & T > T_D \end{cases} \tag{1b}$$

were developed. In equations (1a, b), T is natural period of an oscillator, η=√([10/(5+100ξ)], is the EC-8 correction factor for damping ratio ξ other than 0.05, a_g stands for design peak acceleration, while the remaining parameters, shaping the response spectra, depend on ground category and are given in Tab. 1.

Table 1 – Parameters to compute design response spectra of eqs. 1a,b for different EC8ground categories.

Ground Categories	S	T_B	T_C	T_D
A (V_{S30}>800m/s)	0.8	0.1	0.85	1.3
B (360m/s<V_{S30}<800m/s)	1.0	0.1	0.95	1.3

C (180m/s<V v_{S30}<360m/s)	1.5	0.3	0.80	1.3

The response spectra given in eqs. 1a and 1b are plotted in Fig. 2.

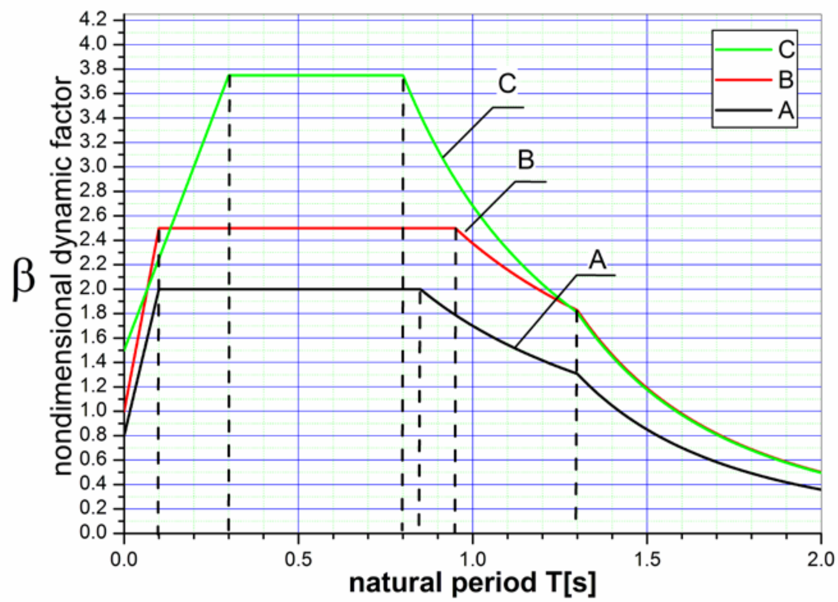

Fig. 2 – Elastic design response spectra of EC8 ground categories A, B and C given by eqs. 1a & 1b for ξ=0.05

4. Design acceleration

The seismic hazard at a regional scale is typically expressed in probabilistic terms as the probability of exceedance of a specified level of a ground motion parameter (e.g. peak ground acceleration, peak ground velocity, spectral acceleration referred to a specific structural period, etc.) in a specified interval of time for standard ground conditions (i.e. outcropping bedrock and horizontal topographic surface). Probabilistic seismic hazard studies have been carried out in many countries worldwide. The results of such studies available for different return periods are often used to define the reference seismic hazard in the building codes (e.g., in Italy). Such definition for mine tremors is not that straightforward. Typically, in building codes like EC8, for ordinary structures, the requirement of withstand the design seismic action without local or global collapse should be met for a reference seismic action with 10 % probability of exceedance in 50 years (recommended value) i.e. with 475 years return period. It is so because seismic design is used in design to protect life of the building inhabitants, accepting even partial (safe) structural damage. When it comes to mine tremors such approach cannot be accepted because the strongest mine tremors may happen every 2-3 years in the same area. On the other hand, in the ref. [2], it was demonstrated that the best measure of surface rockburst intensity is its horizontal peak ground velocity i.e. PGV. For these reasons respective zones of mine tremor intensities should be defined using the surface ground velocities forecasted by seismological services of mines planning their ore excavations. What remains is to link the forecasted peak ground velocity with the design acceleration. For this purpose a simple implementation of displacement method can be adopted. Assuming that the same level of strains and stresses in the structure occurs for the same structural displacement response levels, one can calculate the displacement responses from spectra of eqs. 1a, 1b using familiar relation between acceleration response spectra S_a and respective displacement response spectra $S_d=(T/2\pi)^2S_a$,.

This is illustrated in Fig. 3, where *Eurocode 8* displacement response spectrum is calculated, the way described above, from acceleration spectrum and plotted together with plots of displacement response spectra of two horizontal records of a mine tremor with PGV_X=4.55cm/s and PGV_Y=5.21 cm/s. The displacement response spectrum which best fits these two plots corresponds to a_g=55cm/s^2. For the two, above mentioned records, this corresponds with their spatial horizontal maximum, PGV_{hor}=max $\sqrt{[V_x(t)^2 + V_y(t)^2]}$=6.37 cm/s.

As a result of such the approximate fit, a coefficient r between the design acceleration a_g and the surface horizontal velocity of the mine tremor PGV_{hor} is established:

$$r = \frac{a_g}{PGV_{hor}} = \frac{55}{6.37} \cong 8.63 \tag{2}$$

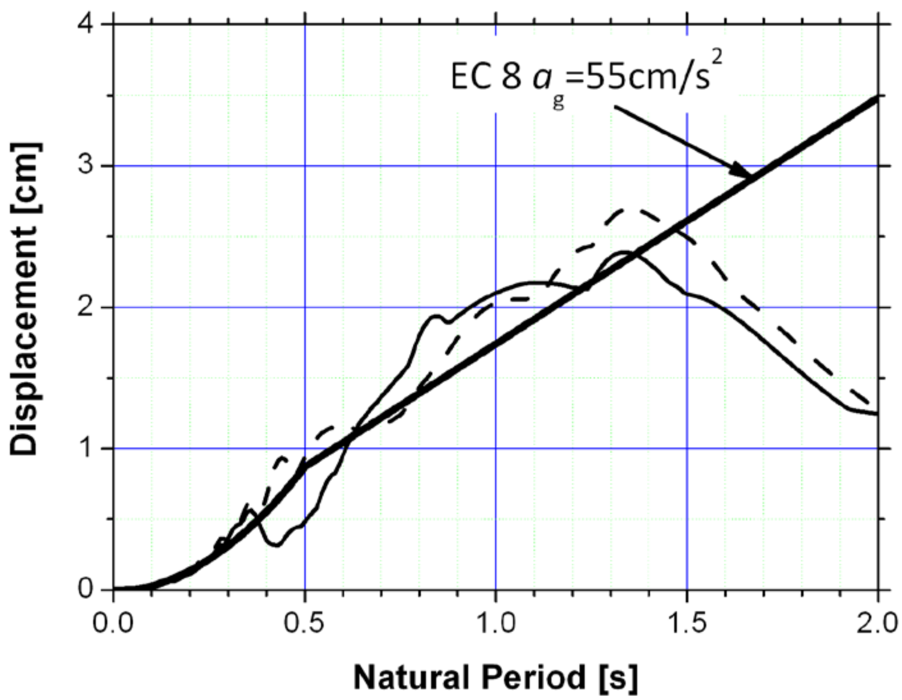

Fig. 3 – Fitting EC8 displacement response spectrum to rockburst displacement response spectra

It represents the relation between horizontal peak ground velocity and design response spectrum leading to similar (best matched) oscillator displacement responses. Such the match holds for natural periods up to about 1.3s, which covers most of typical buildings. One can also calculate respective acceleration response spectra which are given in Fig. 4.

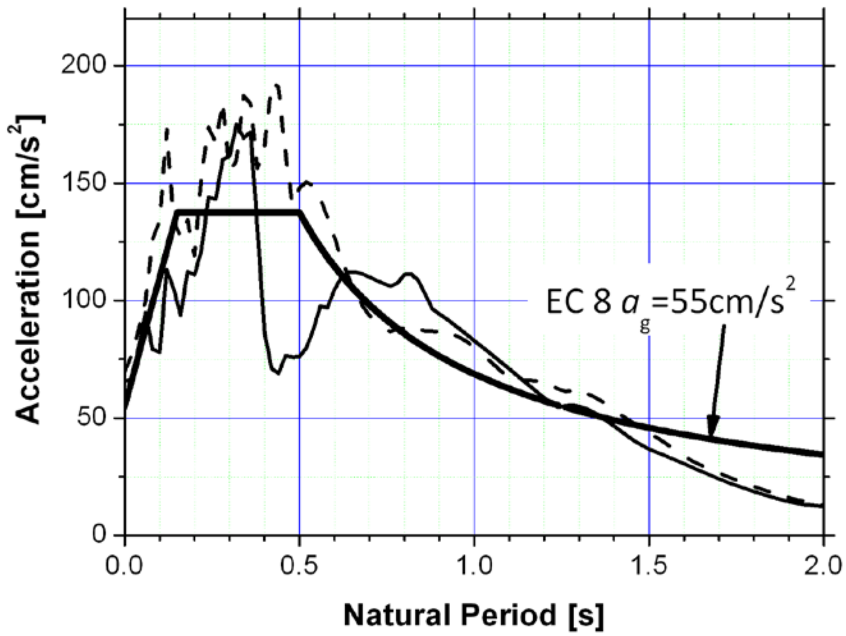

Fig. 4 – Acceleration response spectra of the displacement response spectra of Fig. 3

The procedure described above was repeated for all the available 18 strong mine tremor records, leading to average *r* factor (eq. 2) equal to 5.77, with standard deviation equal to 1.97 ([14]). After a discussion with the *KGHM* mine consortium management and the regulator (Polish *State Mining Authority*) a conclusion was drawn that a credible and reasonable (from engineering point of view) value of *r*, to be applied in structural design, should be equal to 10.00 ([15]).

5. Inelastic design response spectra

Substituting moderate mine tremor excitation level of PGV_{hor}=10cm/s and assuming typical building structure with fundamental natural period 0.5s founded on soil category B may lead to base shear equal to 25% of the weight of the structure *G*, which is rather high value. For soil C base shear can reach almost 40% G. The reason for this it is unrealistic assumption that one can design a structure which would respond to mine tremors without any damages and with its response kept totally in linear range.

In the design for natural earthquakes it is assumed that an extreme earthquake occurs with return period of 475 years and the designed structure is allowed to suffer even substantial damages, yet its collapse is prevented. With such the assumption substantial ductility of structural response can be assumed. This is controlled by reduction factor ‘q’ which can reach up to 5 for properly designed reinforced concrete or steel structures. Since most of the structures represent certain, so called “overstrength” in their seismic behavior (e.g. buildings with their ‘box-shaped’ structures) the *q* factor equals at least 1.5 and easily can be assumed as equal to 2 for any buildings, even masonry ones with some reinforcement bars. The only exceptions of the inelastic design are unreinforced single walls, chimneys and towers or so called ‘inverted pendulum’ structures, [3], which have no strength reserves and should be calculated assuming their linear response against any seismic effects (earthquakes or rockbursts). For all the other structures one can apply the response spectra with q=1.5 and in some cases q=2. The in-elastic response spectra proposed for the design are given by following equations 3a (A and B ground categories) and 3b (C soil category) – see Fig. 4:

$$R(T) = a_g \beta(T) = a_g S \cdot \begin{cases} [1 + \frac{T}{T_B}(2.5\eta - 1)] & 0 < T < T_B \\ 2.5\eta & T_B \le T \le T_C \\ 2.5\eta \frac{T_C}{T} & T_C < T \le T_D \\ 2.5\eta \frac{T_C T_D^2}{T^3} & T > T_D \end{cases} \tag{3a}$$

$$R(T) = a_g \beta(T) = a_g S \cdot \begin{cases} [1 + \frac{T}{T_B}(2.5\eta - 1)] & 0 < T < T_B \\ 2.5\eta & T_B \le T \le T_C \\ 2.5\eta \frac{T_C^{1.5}}{T^{1.5}} & T_C < T \le T_D \\ 2.5\eta \frac{T_C^{1.5} T_D^{1.5}}{T^3} & T > T_D \end{cases} \tag{3b}$$

6. Summary and conclusions

Seismicity induced by deep mining may cause from minor to moderate/extensive damages on neighboring structures and infrastructures. Thus, the urban development in the vicinity of mines should require that the planned building, structures, etc. not only have to be resistant against the mine tremors, but also have to be constructed to minimize costs of compensating the future cosmetic damages. This requires formulating specific design recommendations. For this purpose, a methodology to define seismic load for the design of structures under strong mine tremors has been proposed. Peak horizontal velocity as a measure of ground motion intensity and a displacement approach was applied to adapt Eurocode 8 for this purpose.

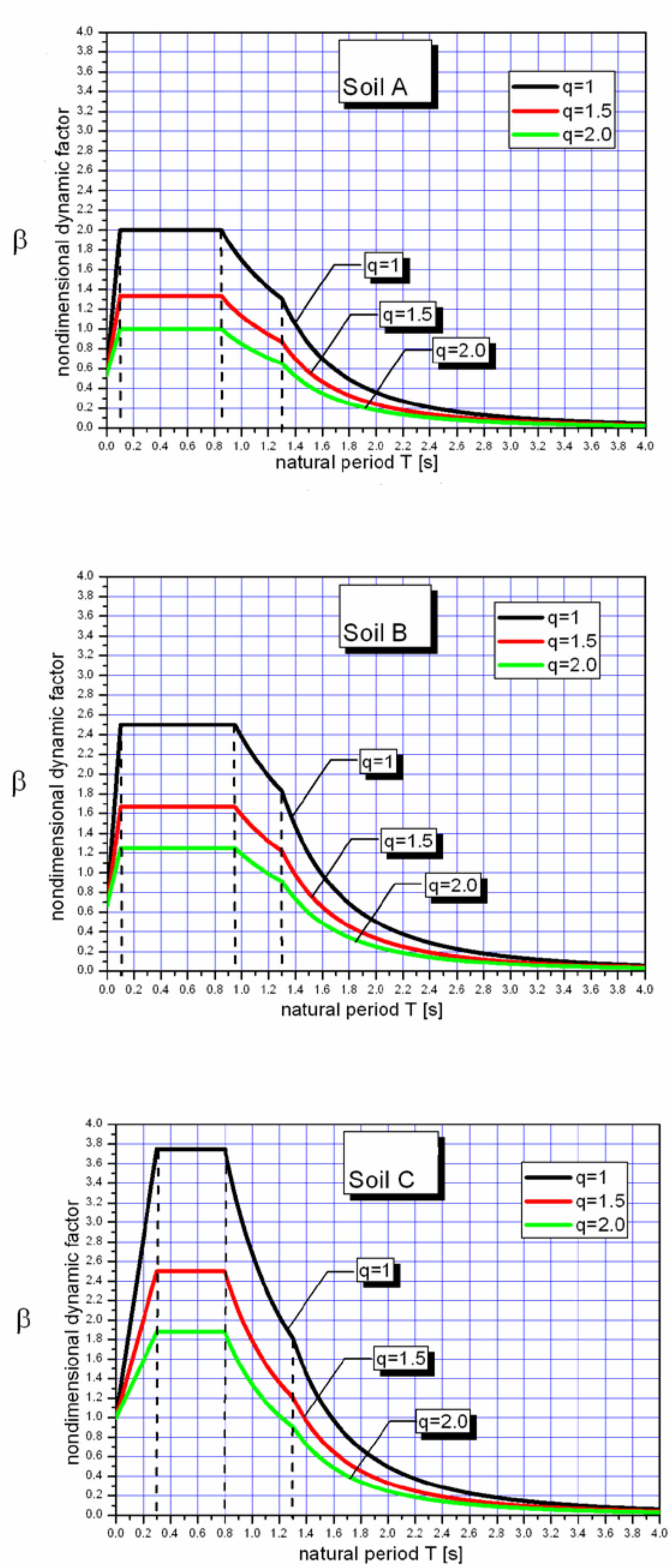

Fig. 5 – Plots of inelastic response spectra of for soil profiles *A*, *B* & *C* given by eqs. 3a & 3b for q=1.0, 1.5 & 2

The procedure to account for the rockburst effects in structural design consists of the following four steps:

a. A map of forecasted maximum surface horizontal ground velocities is prepared for the area affected by the deep mining which is done by the mine geophysical services, applying methods of predicting seismic hazard, using more or less sophisticated approaches, particularly the methods involving probabilistic methodology (e.g. [5], [6]) and taking into account information about the planned underground mine activities, local attenuation law etc.

b. Based on these maps the ground surface around the mine is divided onto the velocity zones (of maximum expected horizontal velocities: e.g. 8cm/s, 10cm/s, 15cm/s etc.)

c. By multiplying the "*velocity-acceleration*" coefficient 'r' by maximum "*zone velocity*" v_g expected at the site of the designed building, respective design acceleration a_g is obtained: $a_g=r*v_g$ (here r=10 was applied).

d. The seismic code (e.g. *Eurocode 8*, [3]) is applied with the design acceleration calculated in the previous point and response spectrum given by eqs. 1a,b or 3a,b).

The present research has shown that even for moderate and frequent, strong mine tremors the linear assumption in the design is unrealistic. The method requires meaningful collection of strong mine tremors as well as a careful calibration to actual local site conditions so further research necessary to improve the site effects as at present it only covers the basic EC8 ground categories, i.e. A, B and C. The above procedure is described in a detail in the paper [14] and report [15].

7. Acknowledgements

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