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GMM-s Based on Radius Vectors with Directly Included Azimuth

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ABSTRACT: Based on radius vectors, a verified new GMM with directly included azimuth has developed. It has been fitted into a generated databank computed by use of an originally developed method-generator of data for regression analysis. Records of strong earthquakes that occurred in 1977, 1986 and both earthquakes that took place in 1990 in the Vrancea zone in Romania have been used.

KEYWORDS: recorded seismic field, normalized seismic field, corrected epicentral distance, recorded PGA, generated PGA, expected PGA.

1 INTRODUCTION

The prognosis of seismic effects is of a particular importance since it provides an estimation of the intensity of the seismic hazard. The quantitative parameters of ground motion, namely, the amplitude and the frequency content of the seismic waves and vibrations, the time duration of an earthquake and the permanent ground deformations depend on the energy and the dimensions of the foci, the mechanism of motions at the foci, the distance between the focus and a structure, the geological composition of the environment through which the seismic waves propagate and the soil conditions under a structure. Mathematically, all these factors can hardly be taken into account, which results in a huge number of empirical mathematical models of GMM-s and methods of their development ([5], [6]).

1.1 STATE-OF-THE ART REFERRING TO GMM-S WORLDWIDE

The need and primary purpose of human existence on the Earth is to provide seismic safety of structures. With the use of the first records obtained by instruments in the USA in 1933, there started the empirical prediction of ground motion under earthquake effect not only in the USA but in a number of regions worldwide (Japan, Italy, Romania, Turkey, former Yugoslavia, etc.).

The first developed empirical equations - GMM-s ([5]), have so far undergone a number of modifications from the aspect of both mathematical form and methods of their development. According to the author, a considerable progress has been made by use of the method of double regression analysis that enabled better inclusion of the characteristics of each occurred earthquake in the equation ([2]).

The importance of the number of records for development of a GMM equation on one hand and having an insufficient number of records from a focus on the other hand, conditioned the use of created databanks on different foci in a country (for example, USA - west and east), Italy, Japan, Romania, former Yugoslavia, etc.) that further progressed in creation of European (European Strong Motion data –ESMD), American (West 2 data set, USGS database, IEEE database) and World databanks.

Up till now, as a result of the use of as many as possible data from different regions and foci, there have been obtained long and complex mathematical equations - GMM-s for empirical prediction of ground motion. An example is the generation of GMM-s for the USA, the so called NGA-Next Generation Attenuation ([6]). These include different definitions and sizes of magnitude and distance, types of fault structures, effect of local soil conditions, “statistic focal depth” - obtained by regression analysis, standard deviations - functions of magnitude or peak ground acceleration PGA, limited use of standard deviations per magnitude, limited use per distance and alike ([6], [36]).

The need for zoning, development of regulations and providing long-term strategies for seismic protection of a region or a country, in conditions of insufficient support by own data on occurred earthquakes, has led to use of GMM-s equations developed for a region or a country for another region or a country. Therefore, in addition to methods where GMM is developed from data - **forward to backward methods,** there have also been developed methods from GMM to data - **backward to forward methods** ([37]). The latter use GMM developed for a region/or a country to explore statistic parameters (median, mean value, standard deviation, distribution of residuals) by use of data from occurred earthquakes in another country and region, as statistic estimates of the applicability of that model ([28], [29], [3]; [18]).

The period of mathematical modeling of ground motion under earthquake effect based on the philosophy that records from an occurred earthquake, although dependent, are used as independent of a country, region and continent, represents the **early period of empirical prediction.** It is characterized by analysis and exploration of a created set of independent data and then, through long and complex mathematical-physical models, definition of the effect of the factors on which ground motion depends (magnitude, distance, local soil conditions, types of fault structures, direction of radiation, focal depth, etc.). For their use in practice, it is necessary to elaborate additional bases for certain parameters as are, for example, the shortest distance to the projection of the fault upon the surface, or the so called distance according to Joyner and Boore –R_{JB} ([10], [6]). Having no such bases, the user inserts a subjective estimation in the obtained results. Also, a larger number of them use the so called “statistic” focal depth–h_0, which has its own effect while used in analyses of the probabilistic-PSHA and the deterministic - DSHA hazard.

The new philosophy in mathematical modeling of ground motion analyzes and explores each earthquake as a natural phenomenon that is strictly geographically and regionally dependent, treating the set of records obtained from that earthquake as dependent on each other and in relation with each other ([31], [35], [36], [38], [39]). This is a philosophy of not mixing records of occurred earthquakes from different foci in one region as well as from different geographical regions, or **a model of a single focus.**

Depending on how the record of an occurred earthquake is included and used in a databank, the GMM-s developed for the earthquakes originating from the Vrancea focus in Romania are classified into two groups. Included in the first group are GMM-s developed with a created databank on records of occurred earthquakes in which each record is included as datum that is not dependent and is not connected to all the remaining records obtained from that specific earthquake ([27], [15], [16], [41], [30]). Contrary to this case is when, in the investigation, the earthquake is included as a strictly geographically/regionally dependent event, while the records of an occurred earthquake are included as dependent on each other and in connection with each other ([31], [35], [36], [38], [39]).

The presented investigations refer to the GMM-s from the second group.

2 NEW GMM DIRECTLY DEPENDENT ON AZIMUTH

Seismic imagination ([39]) is the basis upon which a methodological approach to development of new, directly dependent on azimuth GMM, has been developed. With it, the earthquake is analyzed and included in GMM as an integral event, whereas all records of that earthquake are included as dependent on each other and in relation to each other.

2.1 MATHEMATICAL EQUATION

A general empirical GMM ([10]) has been used for soil type - rock (equation 1)

$$\ln Y = b + b_M M + b_R \ln R_h + P\sigma_{\ln Y} \tag{1}$$

Where,

Y - maximum peak horizontal acceleration-PGA, in cm/s^2
M– Richter’s magnitude
R_h - hypocentral distance in km
b, b_M, b_R - regression coefficients
P - variable with the value of zero and unity for median and median plus one standard deviation, respectively

The term dependent on distance - Rhas been studied separately. A recorded seismic field represented by radius vectors has been used (Figure 1). From it, by scaling for a selected azimuth, the normalized seismic field has been defined, Figure 2 ([38]).

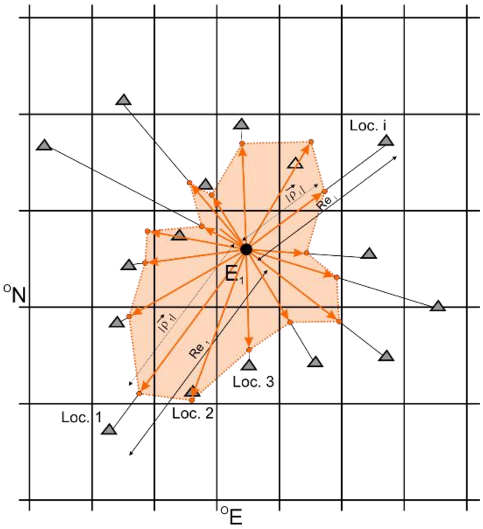

Fig. 1. Recorded seismic field of PGA

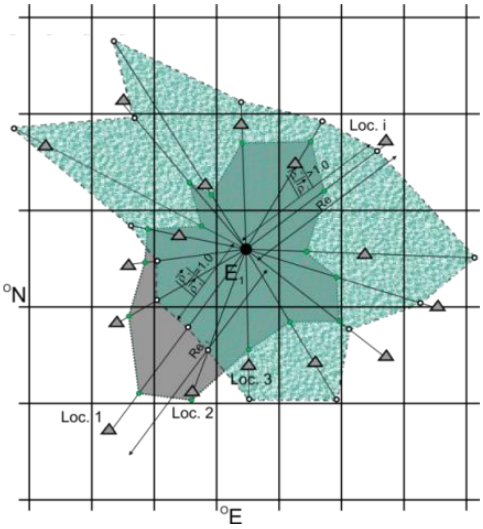

Fig. 2. Normalized seismic field according to location 1

The normalized seismic field represents the relative ratios of modules $\frac{\rho_i}{\rho_L}$ or $\frac{\rho_L}{\rho_i}$, whereρ_i = $|PGA_i|$. These are dimensionless and the corresponding epicentral distances are multiplied by them and **corrected epicentral distances**- R_e^c (equation 2) are computed. This is done separately for each occurred earthquake from a single seismic focus. The hypocentral distance computed with the corrected epicentral distance-R_e^c and hypocentral depth-h is the **corrected hypocentral distance**-R_h^c (equation 2).

$$(R_h^c)^2 = (R_e^c)^2 + h^2, R_e{}^c = R_e \frac{\rho_L}{\rho_i}, \frac{\rho_L}{\rho_i} = \frac{|\overrightarrow{\rho_L}|}{|\overrightarrow{\rho_i}|} \qquad (2)$$

where:

ρ_i - the module of the radius vector in respect to any location of instrument - i
ρ_L - the module of the radius vector in respect to location- L$(x_L; y_L)$ by which the seismic field is normalized
Re - epicentral distance in km

R_e^c - corrected epicentral distance in km
h - focal depth in km
R_h^c - corrected hypocentral distance in km

If the position of the instrument location is also defined with the coordinates of the end point of the radius vector- Loc= L$(x_L; y_L)$, then the value of the epicentral distance is defined from the following equation:

$$R_e = \sqrt{(x_L)^2 + (y_L)^2} \tag{3}$$

where,

$$tg\beta_L = \frac{x_L}{y_L} \rightarrow x_L = y_L tg\beta_L, y_L = R_e \cos\beta_L \tag{4}$$

and,

$$\ln\, Y = b + b\_M\, M + b\_R \ln\,(\sqrt{{y_L}^2(1 + tg^2\beta_L) + h^2} + P\sigma_{\ln Y} \tag{5}$$

or,

$$\ln\, Y = b + b\_M\, M + b\_R \ln\,(\sqrt{(R_e \cos\beta_L)^2(1 + tg^2\beta_L) + h^2} + P\sigma_{\ln Y} \tag{6}$$

In equations 3 through 6,

- x_L and $y_L$are the geographic longitude and latitude of the location for which we compute the GMM/or instrument location, in radians or degrees,
- β_L is the azimuth of the location for which we define the GMM/or instrument location, in radians or degrees.

Equations 5 and 6 are the equations for the new GMM with directly included azimuth. They are equally applicable for both shallow and subduction earthquakes as well as for all parameters of ground motion and its amplitude-frequency content.

2.2 METHOD

A multi-linear regression analysis has been used for assumed normal distribution for lnY, which is a dependent parameter, while independent parameters are magnitude M and the corrected hypocentral distance-R_h^c (equation 2). The data for the regression analysis have been computed by use of an originally developed general method - generator of data for regression analysis (Enclosure A). The method uses real recorded seismic field from an occurred earthquake and all its normalized seismic fields. The mathematical algorithm for the computation of the data for the regression analysis is as follows:

$$\ln Y_{i,ji} = b + b_M M_i + b_R \ln\left(\sqrt{{y_{i,j_i}}^2 \left(1 + tg^2\beta_{i,j_i}\right)\left(\frac{\rho_{L=i,j_i}}{\rho_{i,j_i}}\right)^2 + {h_i}^2} \right) + P\sigma_{\ln Y}$$

for

$$i = 1, .., n, j_i = 1, \dots, m_i \tag{7}$$

where,

$-$ i refers to occurred earthquakes originating from a single focus or $i = 1, n$.
$-$ n is the total number of occurred earthquakes originating from a single seismic focus
$-$ $j$refers to records obtained from each occurred earthquake, or $j_i = 1, m_i$
$-$ $m_i$is the total number of records obtained from a single earthquake
$-$ L is the instrument location according to which we normalize the recorded seismic field

If, for example, the number of records related to an occurred earthquake is 21, then 21 normalized seismic fields are obtained from it, each with 21 data, or a total of 441 data in the databank for regression analysis, related to that earthquake only. The total number of data is the sum of the computed data from all earthquakes from a single focus

The computed R_e^c and $R_h^c$are used only for computation of data for regression analysis, whereas $R_e$and $R_h$are used in practical application of GMM since the following holds: when $\rho_i = \rho_L$, then $R_e^c = R_e$ and $R_h^c = R_h$.

3 Verification Of The Method

Verification of the method has been done by use of records of occurred intermediate earthquakes from the Vrancea focus, obtained from the strong earthquakes that occurred in 1977, 1986 and both earthquakes that occurred in 1990 ([31]; [38], [39]).

3.1 Vrancea Zone

The impact of the seismic energy generated at the intermediate foci in the Vrancea zone (Romania) upon the wider region is big. It has been confirmed with the historic and instrumental data on the occurred catastrophic earthquakes ([7], [17]; [25], [26], [23], [24]), the lost human lives and the inflicted material losses. Its impact in the past and the impact that it could have on the area of central and southeast Europe in future ([19], [20], [21], [22], [11], [12], [13], [14], [31], [32], [33]) was and remained a strong challenge and motivation for the author ([34], [35], [36], [38], [39]). All this required and requires a constant consideration and familiarization with the characteristics of the intermediate earthquakes from this seismic zone ([7], [17], [25], [26], [23], [24]).

3.2 Data For Regression Analysis

Available from the occurred four earthquakes (1977, 1986, 1990/1 and 1990/2) were 190 horizontal components for type of soil -rock ([31], [38]) and the same number for type of soil -soil, all in the form of corrected time histories of acceleration. The number of horizontal components amounted to 4, 48, 81, and 57, successively following the occurred earthquakes (Figure 3, right). Obtained from these were 2, 24, 42 and 29 (a total of 97) data when the larger of the two horizontal components was used (Figure 3, left).

These data are distributed as follows: magnitude M_L=6.1-7.2, focal depths $89km \le h \le 131km$, epicentral distances R_e= (12.315 - 472.380) km./ or R_h= (89.947 - 472.793) km. and azimuths of $\beta\left(ONS^{\frac{90}{1}}\right)$ = 1.057^0 to $\beta\left(ONS^{\frac{90}{2}}\right)$ = 347.380^0. The minimal and maximal values of epicentral and hypocentral distances were obtained at instrument locations VRI $^{90/2}$ and NIS ^{77,} respectively.

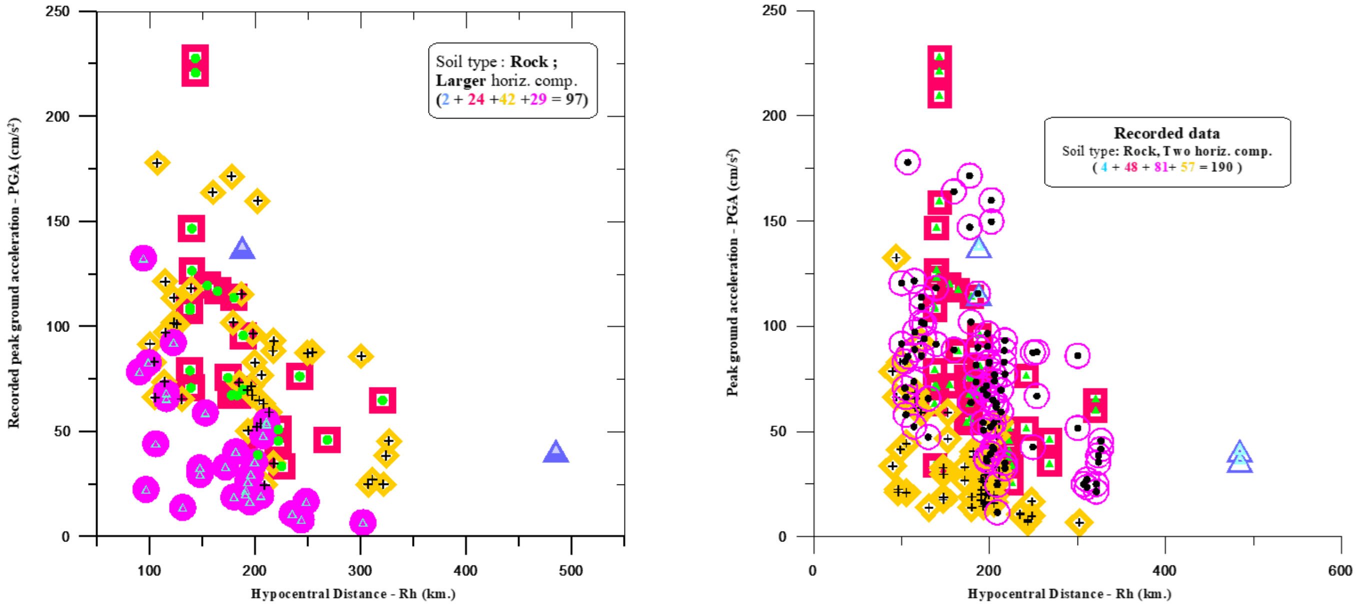

Fig. 3. Distribution of PGA recorded, for type of soil – rock
(the greater of the two horizontal components - left and two horizontal components - right)

3.3 GMM-S FOR ENTIRE REGION

Four GMM-s have been developed for the entire region, or for azimuths -β between 0^0 and 360^0. Out of these, two refer to soil type - rock (SS20-RL and SS20-RA), both for soil type - soils (SS20-SL and SS20-SA). For one type of soil, one of the models has been defined by application of the greater of the two horizontal components (labeled L), while the second has been defined by application of both horizontal components (labeled A).

The total number of data generated for regression analysis, computed by use of equation 7, was 3185 and 12130, when the greater of the two horizontal components and both horizontal components were used, respectively. The graphically computed peak horizontal accelerations - PGA $^{\text{computed/generated,}}$ for soil type - rock are shown in Figure 4, respectively, left and right.

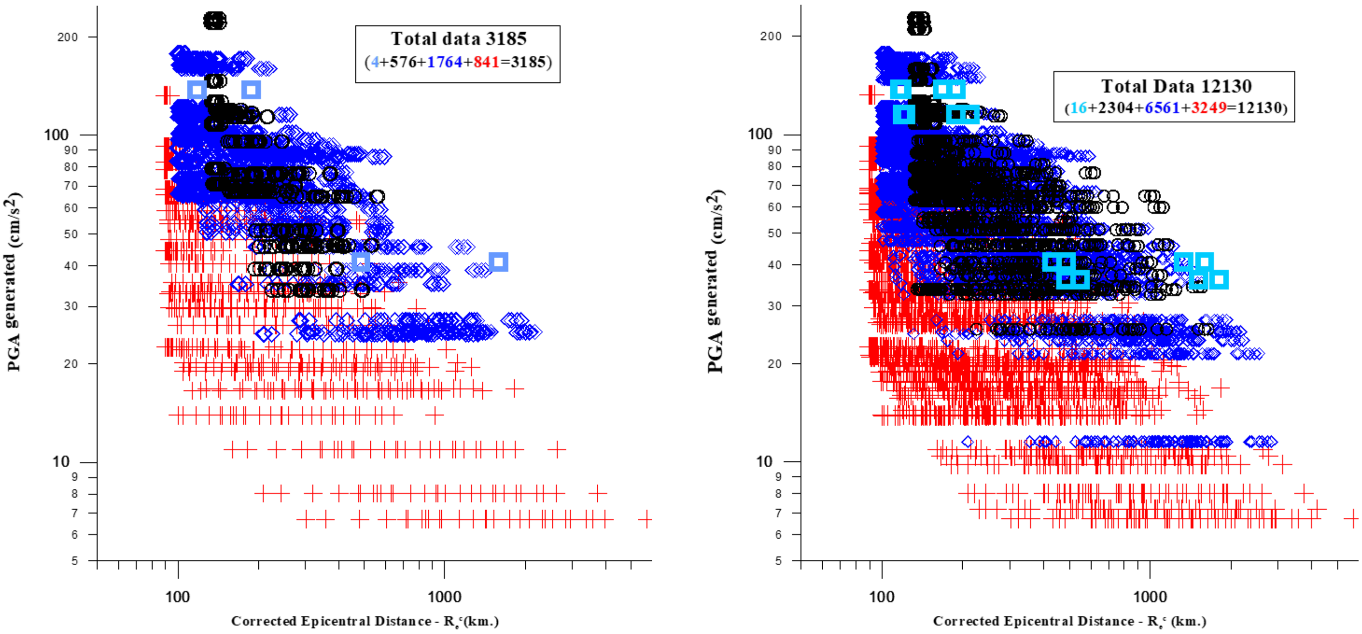

Fig. 4. Distribution of PGA $^{\text{computed /generated,}}$ for soil type – rock
(greater of the two horizontal components - left and two horizontal components - right)

It is important to note that PGA$^{\text{computed}}$ contain the originally recorded PGA$^{\text{recorded}}$. These are with invariable values of both PGA$^{\text{recorded}}$ and epicentral/or hypocentral distance ($R_e^c = R_e$ and $R_h^c = R_h$), since $\rho_i = \rho_L$ holds for them. This is graphically presented in Figure 5. It shows PGA$^{\text{computed}}$ and PGA$^{\text{recorded,}}$ with different colors and symbols, respectively for the four occurred earthquakes of 1977, 1986, 1990/1 and 1990/2.

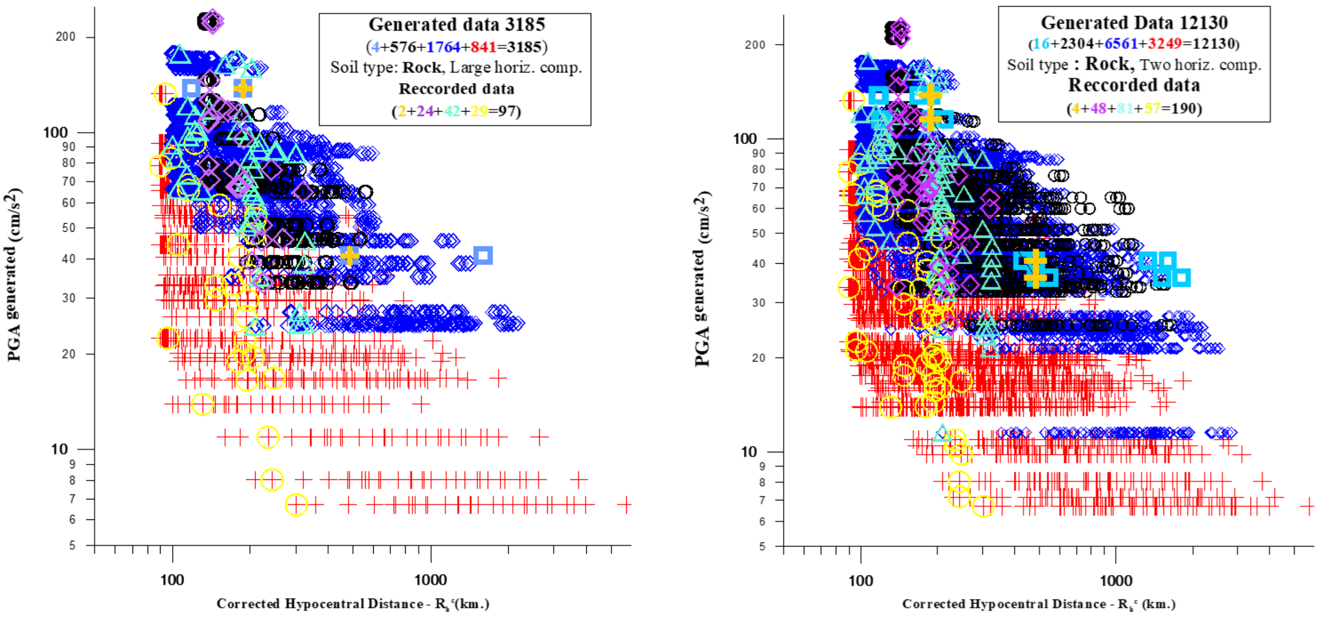

Fig. 5. Graphic presentation of PGA^{recorded} (97and 190 data), for soil type - rock, and PGA^{computed} (3185 and 12130 data, left and right, respectively).

PROOF:

For a selected instrument location, from an occurred earthquake, we graphically present the values of PGA^{recorded} and PGA^{computed,} for the case when normalization is done according to that instrument location. Taken for an example are the recorded (red symbol) and the computed accelerations (blue symbols) of the earthquake of 1986, for the instrument location FOC (Figure 6). The figure shows that there is no change of value of the recorded acceleration and the epicentral distance of the instrument location at which it is recorded.

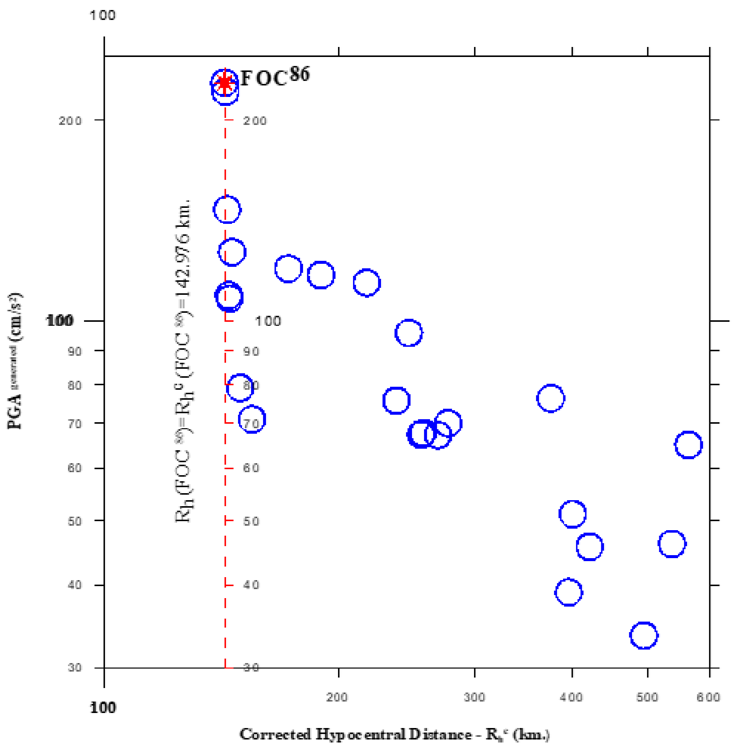

Fig. 6. Location FOC - Recorded acceleration and computed accelerations of the earthquake of 30 August 1986.

3.4 REGRESSION ANALYSIS AND RESULTS OBTAINED

A multi-linear regression analysis has been carried out for an assumed normal distribution of the natural logarithm of the ground motion parameter – lnY, (Equation 6). In it, the peak horizontal ground acceleration- lnPGA is a dependent parameter, whereas independent parameters are: earthquake magnitude-M and corrected hypocentral distance - R_h^c (Equation 2). Four regression analyses have been carried out. The results of the regression analyses are: constants/regression coefficients (b,$b_M$and b_R) with their standard deviations - SD, confidence intervals defined with a probability of 95% as well as conditional standard deviation ($\sigma_{\ln PGA}$), all given in Table 1.

Table 1. Results from regression analyses

Mathematical model: $\ln PGA = b + b_M M + b_R \ln\sqrt{(R_e\cos\beta)^2(1+tg^2\beta)+h^2} + P\sigma_{\ln PGA}$

GMM-s Type of soil	Constants		Standard deviation - SD	Confidence interval with probability of 95%		$\sigma_{ln\,PGA}$
SS20-RL Rock (Greater comp.)	b	-0.4097	0.14960	-0.7029	-0.1165	0.3814
	b_M	1.1790	0.02127	1.1370	1.2210	
	b_R	-0.6123	0.00963	-0.6312	-0.5935	
SS20-RA Rock (Two comp.)	b	-0.8859	0.07977	-1.0420	-0.7296	0.3997
	b_M	1.2260	0.01130	1.2040	1.2490	
	b_R	-0.6055	0.00529	-0.6159	-0.5951	
SS20-SL Soils (Greater comp.)	b	-0.2641	0.15070	-0.5594	0.0312	0.3836
	b_M	1.1900	0.02140	1.1490	1.2320	
	b_R	-0.6082	0.00981	-0.6274	-0.5889	
SS20-SA Soils (Two comp.)	b	-0.7161	0.08113	-0.8751	-0.5571	0.4060
	b_M	1.2370	0.01148	1.2140	1.2590	
	b_R	-0.6043	0.00542	-0.6149	-0.5937	

Applying the results from Table 1, PGA^{expected} for the earthquake that occurred on 30th August 1986 (M=7.0, h=131км. and $\beta_{BUC}^{86} = 196.251^0$) and 30th August 1990 (M=6.7, h= 99км. and $\beta_{BUC}^{86} = 201.165^0$) has been computed. The comparison between the recorded (PGA^{recorded} -pink symbols), the computed for regression analysis (PGA^{computed} - black symbols) and the expected as median + 1 standard deviation (PGA^{expected} - green symbols) and median (PGA ^{expected} - red symbols) for the earthquakes of 1986 and 1990/1 is given in Figure 7, left and right, respectively.

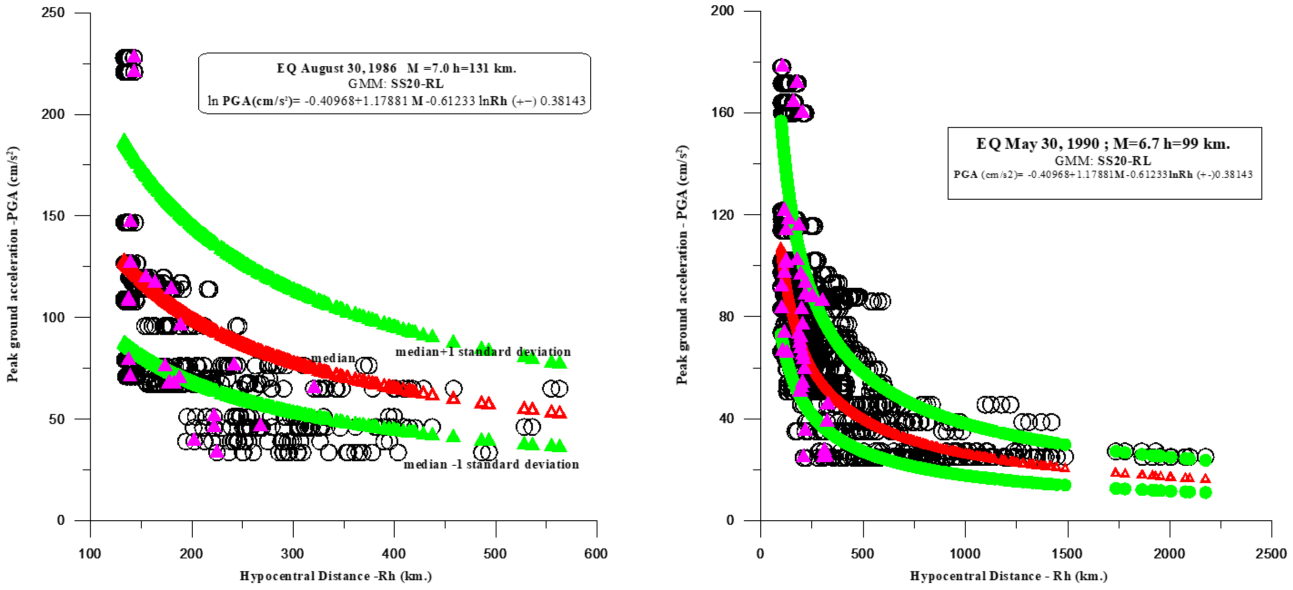

Fig. 7. Earthquakes: 1986 and 1990/1- recorded, computed and expected PGA (cm/s²), (24, 576, 576) and (42, 1764,1764), left and right, respectively

3.5 DISCUSSION ABOUT RESULTS OBTAINED

The results obtained from the regression analyses (Table 1) show that the values of the conditional standard deviation- $\sigma_{\ln PGA}$are between 0.38143 and 0.40603, those of the regression coefficients per distance -b_R are between -0.60432 and -0.61233, and those of the regression coefficients per magnitude -b_M are between 1.17881 and 1.23679.

The values on the left and the right boundary of the confidence intervals for b_M and b_R are very close between themselves, which points to good fitting of the mathematical equation in the computed data for regression analysis. For example, the value of the magnitude dependent regression coefficient for GMM SS20-RL, is b_M= 1.179, whereas the left and the right boundary of its confidence interval are [1.137, 1.221]. The same holds also for the distance dependent coefficient, b_R= -0.6123, with confidence interval [-0.6312; -0.5935]. The conditional standard deviation for this model is the least and amounts to 0.38143. This points out that the scattering of data around the computed mean value is very small or that there is very good fitting of the model per both distance and magnitude. This is also proved through the distribution of the computed residuals per distance (Fig. 8). It shows that only the earthquake of 1990/2 has a very small number of residuals that are between -1 and -1.50, whereas for all other earthquakes, the distribution is between +1 and -1. This discussion also holds for all the remaining models of ground motion in Table 1.

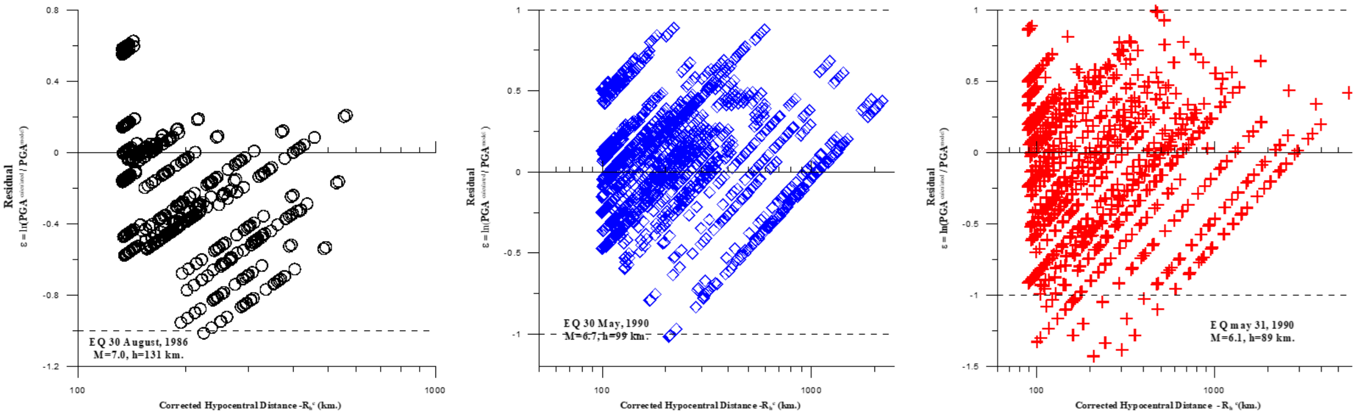

Fig. 8. Distribution of residuals per distance for the earthquakes of 1986, 1990/1 and 1990/2, for GMM SS20-RL.

The distributions of $PGA^{computed}$ (symbol- a black circle in Figure 7, left and right) and the residuals per distance (Figure 8) show that the developed mathematical equations in these investigations are not limited per epicentral/or hypocentral distance, but are supported by the data computed for regression analysis for much larger epicentral/or hypocentral distances. This is in accordance with the character of the intermediate earthquakes from the Vrancea zone, felt at very large distances in central and southeastern Europe ([7]; [17]), i.e., with the size of the earth's volume through which the seismic waves propagate.

This proves that, through the developed method of generation of data for regression analysis, there have been defined and included the information contained in the obtained records of occurred earthquakes referring to the effect of the focal mechanism, the size of released energy, the volume of earth affected by seismic waves and its transmission characteristics. Therefore, the developed mathematical model (equation 5 or 6) and the method for computation of data for regression analysis (Enclosure A, equation 7) in which the equation has been fitted, are advantageous over all other mathematical equations and methods for their development in which there is limitation of distance, which in turn, is connected with the distances at which the used records of occurred earthquakes were obtained ([30]; [41], [4]).

All this has been achieved through analysis and investigation of each occurred earthquake as an integral natural phenomenon that is strictly regionally dependent, whereas the obtained records have been treated as dependent on each other and in relation with each other ([31], [38], [39]).

3.6 COMPARISON WITH GMM-S OF OTHER AUTHORS

For the purpose of comparison, the ground motion models developed for intermediate focus earthquakes from the Vrancea focus in Romania have been divided into two groups. The first group includes those developed with data on occurred strong deep focus earthquakes from the Vrancea focus of 1977, 1986, 1990/1 and 1990/2 ([26], [16], [17]), without their classification per type of soil. In this group, there also belongs the model developed by Sokolov et al. ([30]), who, in addition to data on intermediate focus earthquakes, also uses data on shallow earthquakes from the Vrancea zone, the model being developed for soil type - rock. In addition to records of earthquakes from the Vrancea focus, the second group also includes records from other countries worldwide ([41], [4]).

The mathematical equations for GMM-s with which comparison has been made are the following:

- **Lungu et al., 1997** ([16])

$$\ln P\,GA\left(\frac{cm}{s^2}\right) = 5.128 + 1.063M_{MG} - 1.297\ln R_h - 0.009h + 0.449P \tag{8}$$

- **Sokolov et al., 2008,** ([30])

$$PGA(sm/s\hat{}2) = \exp\left(-8.49907 + 7.73683\ln\ 〖M\_W〗\right) - \exp\left(-1.49548 - 072045h\right)R\_e - 0.01825h \tag{9}$$

(M_w=5-8, h =70-160km., R_e up to 500km., for soil type - rock)

- **Vacareanu et. al., 2014-VEA14,** ([41])

$$\ln P\,GA\left(\frac{cm}{s^2}\right) = 8.5851 + 1.4863(M_W - 6) - 0.4758(M_W - 6)^2 - \ln R_e - 0.00138R_e + 0.00484h,$$

$$\sigma_T = 0.738, \tag{10}$$

(Distribution of data: $69 \leq h \leq 173$, $100km. \leq R_e \leq 200km.$; For use $R_e = (60 - 200)km.$)

Where,

- M_w is moment magnitude,
- Mи M_{GR}- Gutenberg-Richter's magnitude,
- R_h - hypocentral distance in km,
- R_e- epicentral distance in km,
- h - focal depth in km, and
- P - variable with zero value and unity for median and median plus one standard deviation, respectively.

All compared GMM-s refer to an entire region, or to azimuths of 0^0 to 360^0. The following moment - Gutenberg-Richter magnitude relationship has been used: $M_W = 1.09M_{MG} - 0.36$ ([30]).

The comparison between the GMM-s developed through these investigations with the GMM-s - Lungu et al., 1997 [16], is given in Figure 9. It shows the $PGA^{expected,}$ median (solid line) and median +-1 standard deviation (broken line) for the INCERC location and an earthquake with an epicenter equal to the epicenter of the catastrophic earthquake of 4 March 1977, with magnitude M=7.2 and hypocenter h=109 km. Figure 9 presents that $PGA^{expected,}$ computed with GMM SS20-SL, for azimuth INCERC, median + 1 standard deviation, shows considerably lower values than those computed according to [16], for distances of up to about 150 km.

The comparison of the expected PGA, for soil type - rock, computed with the GMM-s developed in these investigations and the GMM developed by Sokolov et al. [30], is given in Figure 10. The GMM-s of Sokolov et al. [30], refer to 8 separate regions, while here, they have been applied for two regions, namely, "east" and "south-west" ([30]) for soil type - rock. For these GMM-s, no standard deviations have been defined, while a logarithmic value of 1.1 to 0.7 has been used as a measure for the data scatter, for the regions "east" ("East" - a circle symbol connected with a thick solid line) and "south-west" ("South-West", a circle symbol connected with a broken line), respectively ([30]). Bucharest location is in region no. 6 or "south-west". The comparison between median + 1 standard deviation shows that SS-20-RL (triangle symbol connected with a solid line) and SS20-RA (rhombus symbol connected with a solid line) give higher values of PGA for the entire region "south-west", while for the region "east", for Re>90 km.

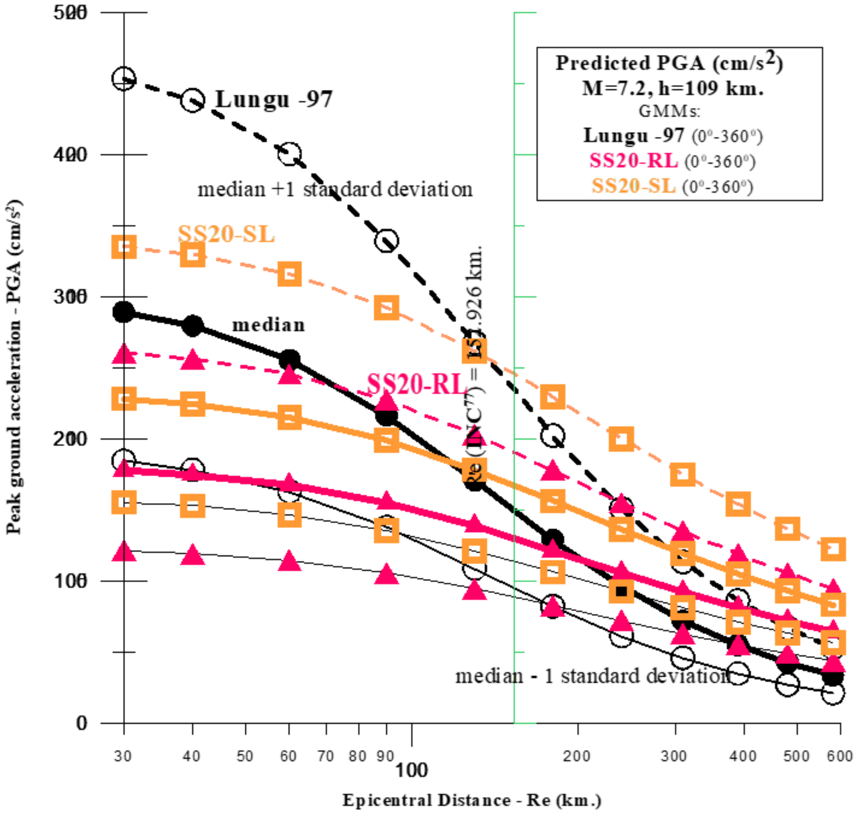

Fig. 9. PGA^{expected} according to Lungu-97 and SS20

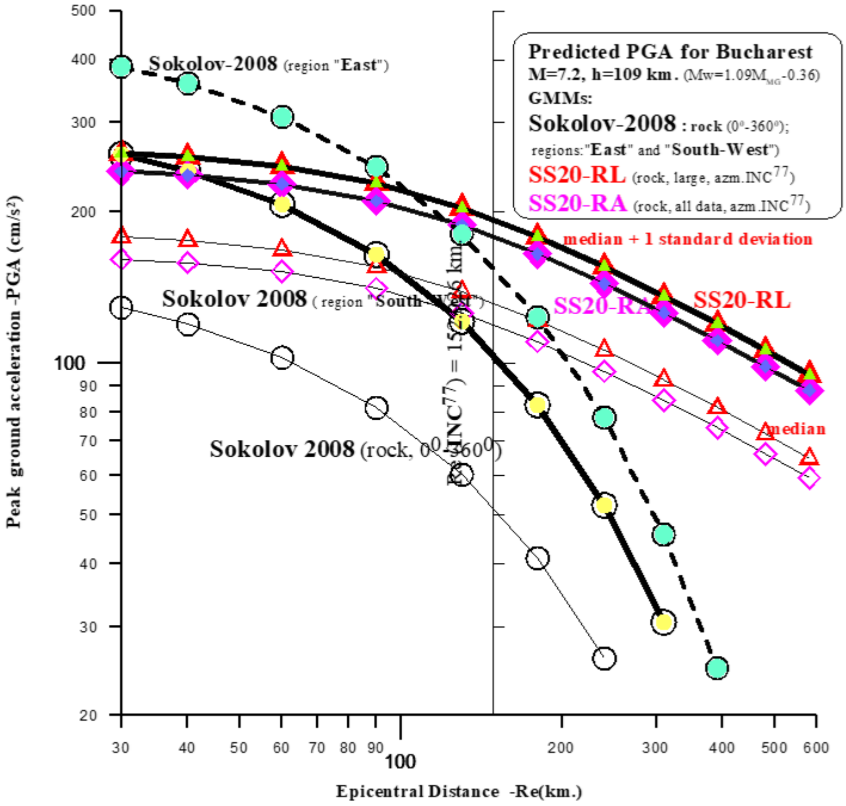

Fig. 10. PGA^{expected} according to Sokolov and SS20

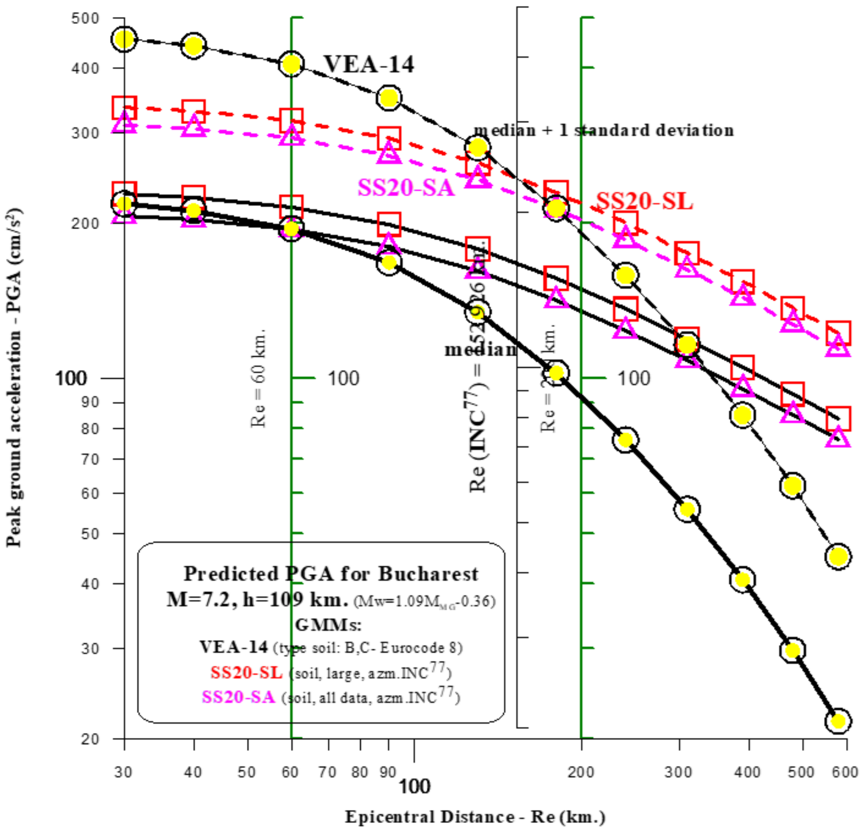

Fig. 11. Expected PGA according to GMM-VEA14 and SS20 (SL and SA)

The comparison with the GMM from the second group, Vacareanu et al., 2014 –VEA14 [41], and the developed ones in these investigations is given in Figure 11. For epicentral distances of up to about 180 km GMM SS20-SL (soils, the greater of the two horizontal components) as median + 1 standard deviation (broken line), it gives lower values of PGA, whereas for all remaining distances, it gives greater values of PGA. The expected PGA as median per VEA 14 are lower for all epicentral distances. This model refers to soil type B, C and D (without A) according to Eurocode 8, EN 1998-1, 2004 [9] and ([40], [41],). With special investigations ([18]) it has been evaluated and proposed for one of the four alternative GMM-s, defined in ([3]), and applicable for computation of the probabilistic hazard in Romania – PSHA: **YEA97** ([42]), for soil type A- rock and for soil type B; **AB03** ([1]); **ZAT06** ([43]) and **VEA14** ([41]).

This comparison shows that, when we use data on only one focus and the new philosophy of development of GMM-s ([38], [39]), we obtain higher values of median and very small standard deviations. This is considerably different from the philosophy of using mixed data and their analysis as independent of region, country, and use of data on a single occurred earthquake as independent among themselves. The result of application of such philosophy are lower values of median and very high values of standard deviation ([41]), which are the result of the large dispersion of the analyzed data around the expected mean values. They have a very strong effect upon the computed, practically applicable results, with the probabilistic and the deterministic hazard.

3.7 COMPARISON WITH GMM-S FROM OWN PREVIOUS INVESTIGATIONS

In addition to comparisons with other researchers, a comparison has been made (Figure 12) between the expected PGA computed with GMM SS20-RL and the models published in 2012 ([38], indicated by SS12-RL - instrument location) for the effect of an earthquake with magnitude 7.0 and focal depth of 131 km, as median + 1 standard deviation. The GMM-s from 2012 ([38]) have been computed with the greater of the two horizontal components, whereas the azimuth has been included indirectly.

The comparison (Figure 12) shows that the effect of the azimuth, magnitude and epicentral distance is better included in GMM defined according to instrument location. It also shows that, when a model for an entire region is used, underestimated and overestimated values of $PGA^{expected}$ are used.

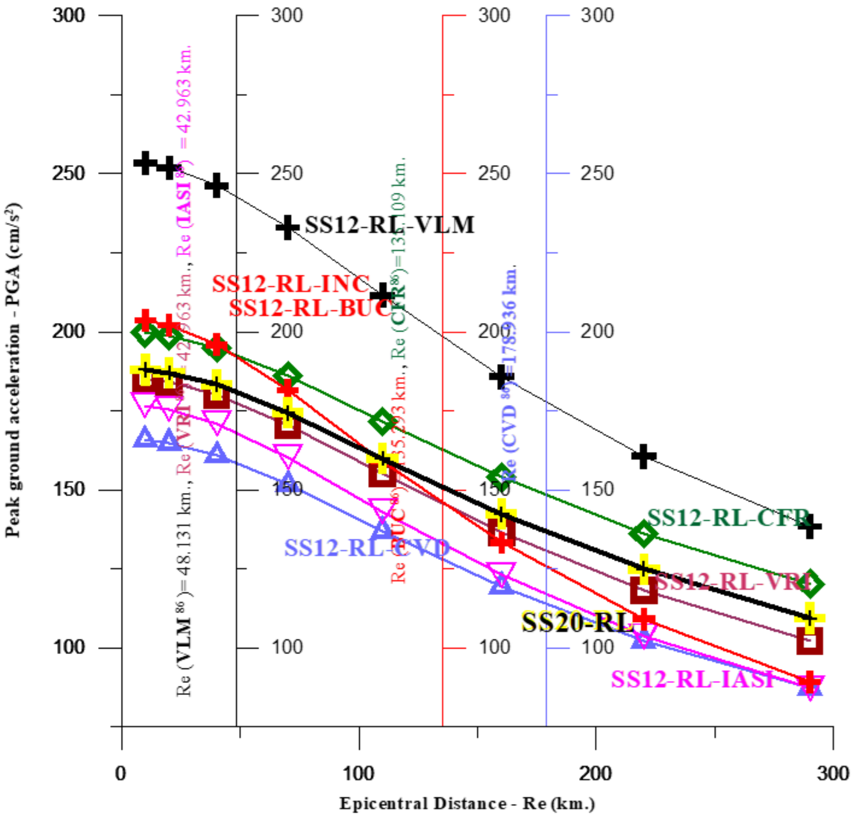

Fig. 12. *Comparison of PGA^{expected} (median + 1 standard deviation) computed with GMM SS20-RL and GMM-s for instrument locations (Stamatovska, 2012)*

PROOF:

If we compute PGA with GMM for the entire region, it means that, for any azimuth between 0^0 and $360^{0,}$ a PGA curve is obtained for median, median + 1 standard deviation and median -1 standard deviation, for an earthquake with magnitude - M and focal depth - h. A proof is given in Figure 13. It shows expected values of PGA for four different locations (symbols: FOC-yellow, BUC - black, CVD - red and VRI - blue). Despite that each of the expected PGA has been computed with the corresponding azimuth for each instrument location (equation 6), they depend only on the epicentral distance at which the location was in respect to the earthquake epicenter. This does not mean that the azimuth is not included, but that its effect is included in the regression coefficients and the standard deviation and is distributed over the entire region, or that the regression coefficients have identical value for any azimuth between 0^0 and 360^0. This also confirms the accuracy of all mathematical operations applied in these investigations.

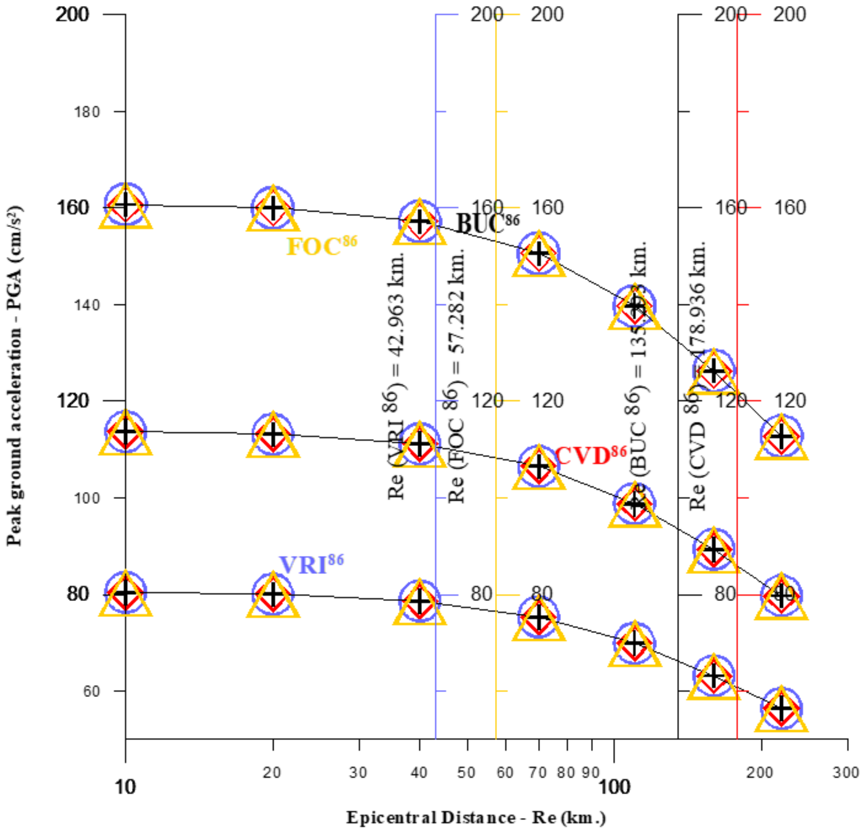

Fig. 13. Distribution of PGA^{expected} (cm/s^2) for an earthquake with M=7. and h=131km (GMM for the entire region, SS20-RL)

3.8 GMM-S FOR AZIMUTH ACCORDING TO INSTRUMENT LOCATION

GMM for instrument location can be computed only if the instrument location is permanent and if the instrument has recorded all occurred earthquakes. In the investigations that have been published by the author so far, GMM-s have been computed according to instrument locations ([31], [38]). Both include the azimuth in an indirect way.

Prior to development of GMM according to instrument location with directly included azimuth, it is necessary to respond to the following question:

- If we perform investigations with the same databank of records of occurred earthquakes and if we had previously developed GMM according to one instrument location with indirectly included azimuth, is it necessary that we develop GMM according to instrument location with directly included azimuth?

The answer is **no.**

PROOF:

We compute GMM with directly included azimuth for instrument locations: INCERC, VLM and CFR. The greater of the two horizontal components is used, or 95 data for VLM and CFR each and 97 for INCERC, all for soil type - rock. The computed regression coefficients and standard deviation are given in Table 2.

Table 2. Regression coefficients and standard deviations

Mathematical model: $\ln PGA = b + b_M M + b_R \ln\sqrt{(R_e \cos\beta)^2(1+tg^2\beta)+h^2} + P\sigma_{\ln PGA}$

Type of soil (number of data)	GMM-s	Regression coefficients			Standard deviation
		b	b_M	b_R	σPGA_{ln}
Rock (97)	SS20-RL-INC	-1.41100	1.49015	-0.84124	0.35861
Rock (95)	SS20-RL-VLM	-3.90509	1.76247	-0.67717	0.39395
Rock (95)	SS20-RL-CFR	0.94251	0.96256	-0.56948	0.38344

Also, comparison has been made between the expected PGA, median + 1 standard deviation, for three instrument locations (VLM, CFR and INCERC) by use of GMM-s developed with indirectly included azimuth ([38], models SS12-RL-INC, SS12-RL-CFR and SS12-RL-VLM) and the herein developed ones with directly included azimuth (Table 2, SS20-RL-INC, SS20-RL-CFR and SS20-RL-VLM). The comparison is graphically presented in Figure 14 and shows that the mathematical equations for GMM with indirectly and directly included azimuth give identical results. The minor differences are the result of different mathematical operations for indirectly and directly included azimuth ([38]). With this proof, it is confirmed and proved that, also in the case when the azimuth is indirectly included and is not visible in the mathematical equation, the regression coefficients and the standard deviation include its effect and one cannot think that, the azimuth is not included if it is not visible in the equation and that the model is not dependent on the azimuth.

The comparisons shown in Figure 14 are also a proof that, when the same databank is used, then both the indirect and direct way of including the azimuth give the same result. At the same time, the figure is a proof of the accuracy of the results obtained from these investigations and the investigations done in 2012 ([38]).

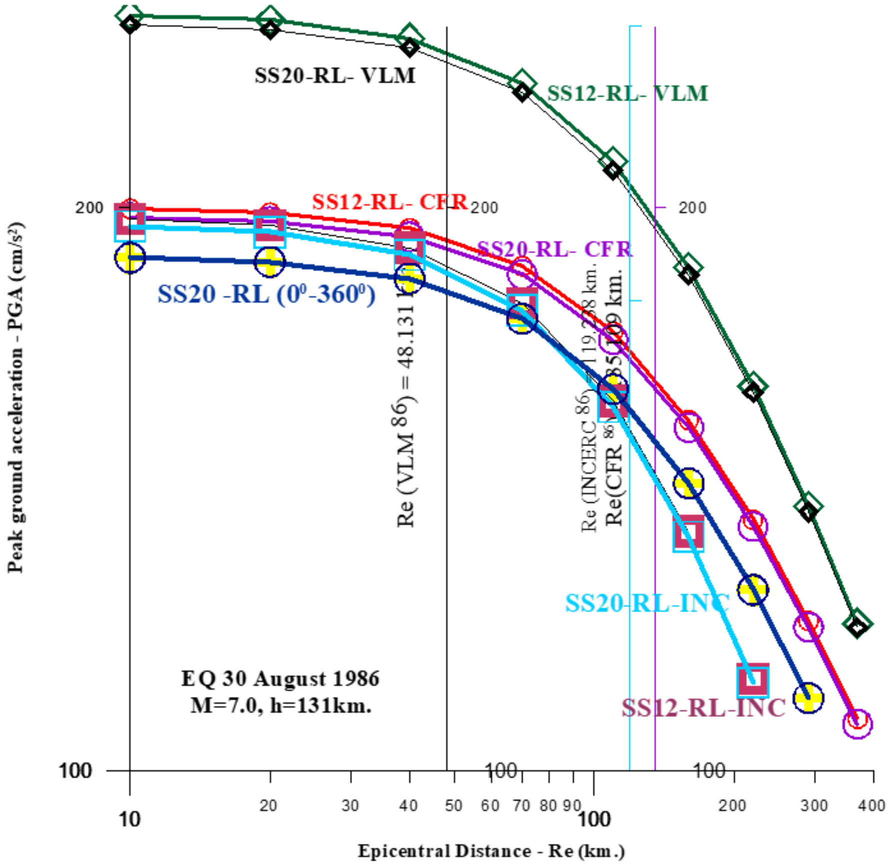

Fig. 14. Comparison of PGA^{expected} computed with the GMM-s from the presented investigations (SS20) and GMM-s from the investigations done in 2012 (SS12) for instrument locations VLM, CFR and INC

Given herein is also a note about what computation of PGA with GMM according to instrument location means.

NOTE:

Computation of PGA with GMM for instrument location is quite different than computation with GMM for an entire region. An example is shown in Figure 15. Presented are the computed median (solid line) and median plus one standard deviation (broken line) for PGA with GMM-s for instrument locations VLM, VRI and CFR, as well as with the GMM for the entire region SS20-RL. Figure 15 shows that there are considerable differences between the computed values of PGA, whereat the effect of the azimuth is better included in the GMM for instrument location and provides more realistic values of PGA, compared with the computed ones with GMM for the entire region. More specifically, when GMM for an entire region is used, smaller values of PGA are obtained for locations VLM and CFR, while larger values are obtained for the location VRI, for an earthquake with M=7.2 and h=109 km (Figure 15).

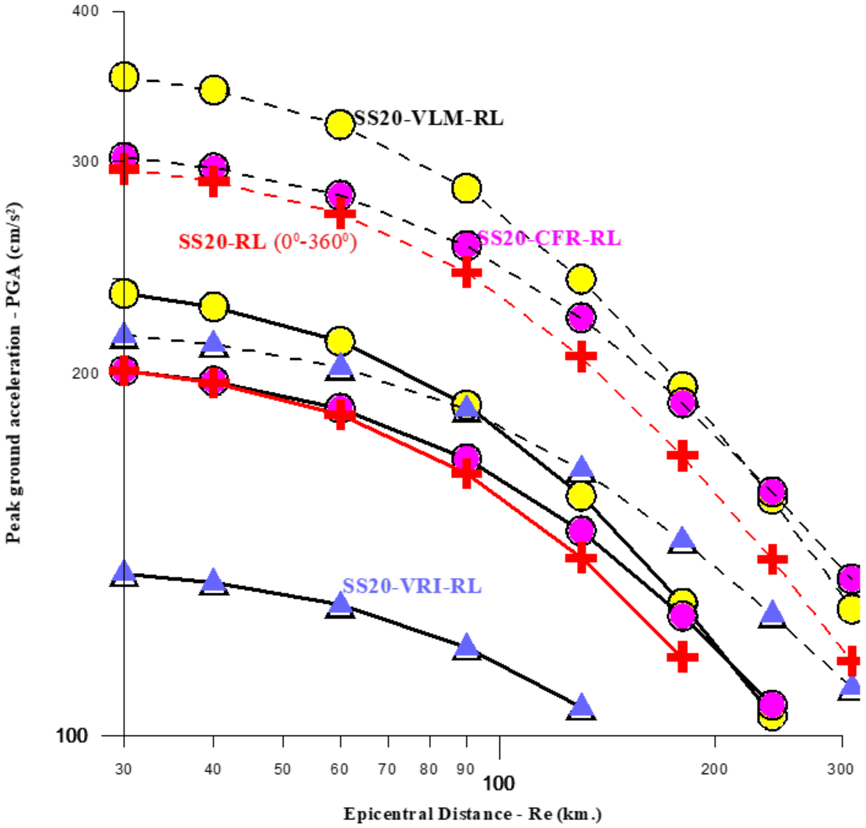

Fig. 15. Distrubution of PGA^{expected} (cm/s^2) for an earthquake with M=7.2 and h=109 km, median (solid line) and median + 1 standard deviation (broken line).

We herewith note that the GMM for an instrument location does not refer to a single azimuth only, but to an azimuth segment defined by the least and the greatest value of the azimuth at which the instrument location is in respect to the epicenters of all occurred earthquakes recorded on it. The size of this azimuth segment for one location may be confirmed or changed with each new occurred earthquake. It is referred to as **characteristic/natural width of the azimuth segment**. Depending on the position of the location in respect to the earthquake epicenter, the characteristic width can be small, medium or large. For example, for the instrument locations INCERC, Bucharest, the least azimuth value is $192^{0,}$ whereas the greatest is 200^0 (Figure 16), or the characteristic width of the azimuth segment is $\Delta\beta = 8^0$. For the instrument location VLM (Valeni) (Figure 16) $\Delta\beta = 3^{0,}$ for the instrument location CVD (Cherna Voda) $\Delta\beta = 15^0$ (Figure 16, [31]).

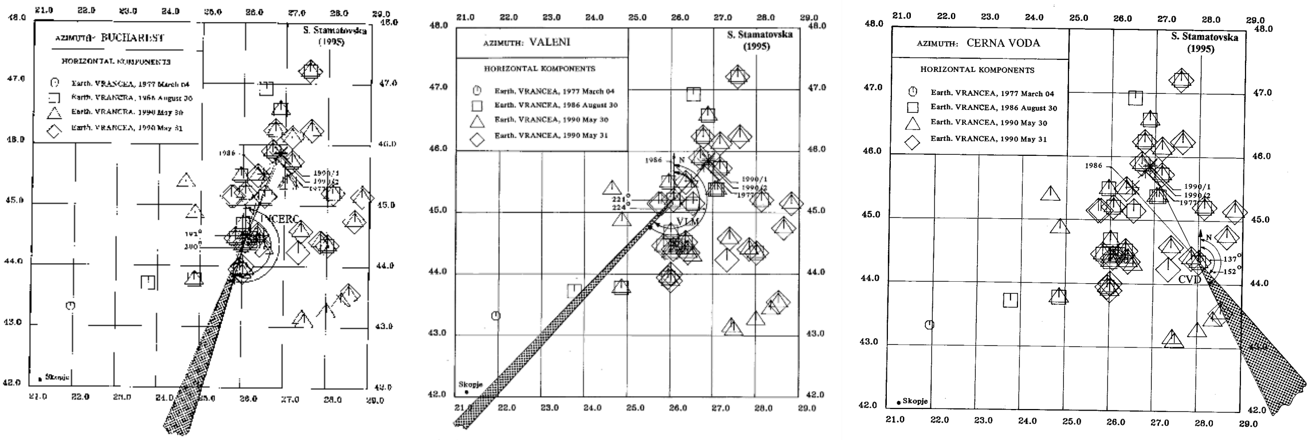

Fig. 16. Distribution of azimuths included in the GMM for instrument locations INCERC, VLM and CVD (Stamatovska, 1996)

Taken as a characteristic example herein is the instrument location VRI, which was between azimuth 279^0 and 22^{0,} or characteristic azimuth segment width $\Delta\beta$ =102^0 ([31], [38]) during the occurred earthquakes. Computed for this instrument location was PGA, median (solid line) and median +1 standard deviation (broken line) for the earthquakes that occurred in 1986 and both earthquakes that occurred in 1990 (Figure 17).

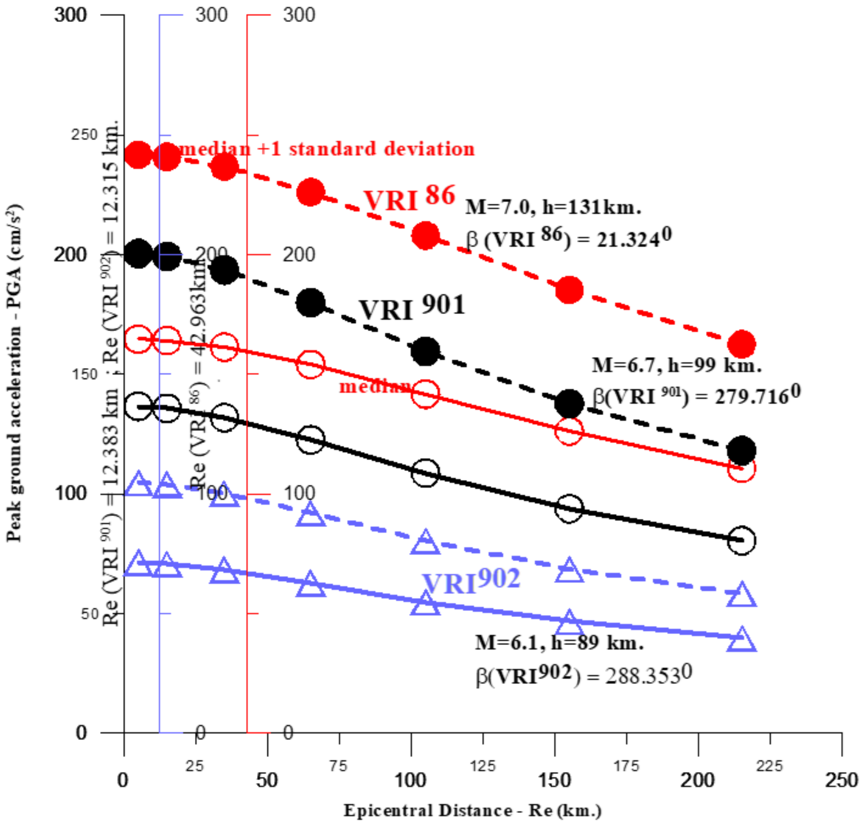

Fig. 17. Distribution of PGA^{expected} (cm/s^2) for VRI location

Figure 17 shows that location VRI, which is in the epicentral zone was at quite different azimuths and epicentral distances depending on the earthquake epicenter, wherefore we have different values of the expected PGA from each occurred earthquake.

All the above stated shows the importance of computation of GMM for instrument location and through it, arriving at the need to develop GMM-s for an azimuth segment with **selected width** - $\Delta\beta$. What will be the width of the azimuth segment

$\Delta\beta$and how it will be defined depends on whether the instrument network of a country or an entire region is uniformly or non-uniformly distributed, the number of distributed records of occurred earthquakes per azimuth segments and the objectives of the investigation.

If GMM is developed for an azimuth according to location of an instrument, which has not recorded all the occurred earthquakes, one can use a selected width of an azimuth segment obtained by variation of its least or the greatest azimuth, or of both azimuths by which the characteristic width of the azimuth segment is defined according to that instrument location. Such defined azimuth segment may also include in itself azimuths from other locations at which strong earthquakes from that focus were recorded.

If GMM-s are developed for preparation of ground motion maps for a country or region, then the region is divided into azimuth segments with different width-$\Delta\beta$. The tendency should be toward as little as possible selected azimuth width, whereas the division of the region may start from any azimuth. For this, a computer program could be elaborated and computer processing could be used.

The results from the investigations of GMM-s for azimuth segments with different selected width and use of the same databank in the presented investigations will be published separately. These and the results presented herein are a constituent part of the monograph entitled “New Model of Ground Motion with Directly Included Azimuth” written in the mother tongue (Macedonian) of the author.

4 CONCLUSIONS

Based on the investigations presented herein, the author has drawn the following conclusions:

1. Developed and verified is a new mathematical equation for an empirical model of ground motion based on radius vectors, with directly included azimuth.
2. The mathematical equation has been developed based on data for regression analysis obtained by use of a developed general method/their generator.
3. The method uses the recorded seismic field from earthquakes that occurred at a single seismic focus and all its normalized seismic fields according to each instrument location at which it was recorded.
4. With it, each earthquake is analyzed as a single random natural phenomenon that is strictly regionally/geographically dependent, whereas the regional records obtained from it are analyzed as dependent on each other and in relation with each other.
5. The mathematical equation is applicable for investigation of all ground motion parameters (peak ground acceleration/or peak velocity/ or peak displacement and Fourier amplitude spectra), as well as all parameters of linear and nonlinear dynamic response of a model of a single-degree-of-freedom system.
6. It can be equally used for investigation of shallow, deep and subduction earthquake foci.
7. Its application is not limited to epicentral distance at which the records of occurred earthquakes are obtained. It is applicable for all distances computed by the method of generation of data for regression analysis.
8. Practically, it is applicable in all deterministic and probabilistic methods that have been developed so far for prediction of expected seismic effect, from location to region.

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Enclosure A:

A.1 General method – Generator of Data for Regression Analysis

An original general method - generator of data for performance of regression analysis has been developed. It uses recorded seismic field and its normalized seismic fields for each occurred earthquake, taken separately. With the normalized seismic fields, corrected epicentral distances are computed for all instrument locations at which that earthquake has been recorded.

The method enables definition of data for regression analysis for azimuth dependent GMM with **indirectly** ([31], [38]) and **directly** included azimuth, as a parameter affecting the amplitude and frequency content of ground motion. Here, one should also use the corresponding equation for computation of the term dependent on distance. For example, when the azimuth is directly included and is visible in the equation, equation 5 or 6 is used.

A.2 Description of the Method

Let us consider a general case of distribution of records in an azimuth segment (Figure A-1). In these investigations, the term azimuth segment means part of the region lying between two azimuths, initial and end azimuth.

Let instrument locations L_1 to L_4. be distributed over it. We assume that records of 4 occurred earthquakes are obtained as follows: at location L_1 - from earthquake EQ^1 and EQ^2; at location L_2 - from occurred earthquakes $EQ^{1,}$ EQ^2 and EQ^3; at location L_3 - only from EQ^2 and at location L_4 - from EQ^4. Let the total number of records obtained over the entire region, per the order of occurrence of earthquakes is, for example, 5, 20, 33 and 1. The recorded value of the ground motion parameter, for example, the absolute value of PGA, from the earthquake EQ^1 obtained at location $L_{1,}$ is indicated by ρ_1^1, while that at location 2, is indicated by ρ_1^2 (Note: In the ρ_1^2sub-script, 1 refers to location $L_{1,}$ whereas superscript 2 refers to earthquake EQ^2. The value of ρ_1^2=$|PGA|_1^2$.

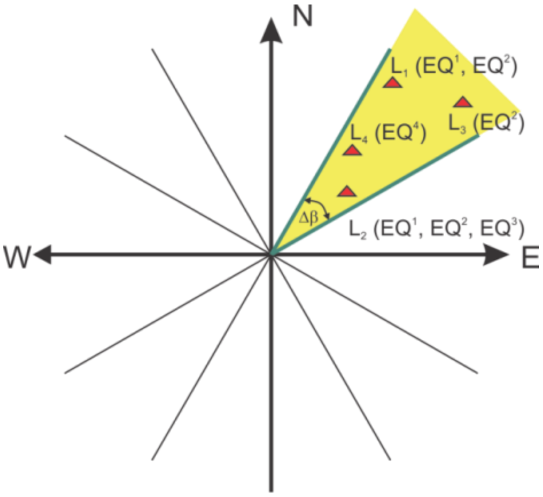

Figure A-1. Azimuth segment

We compute data for regression analysis, namely, we perform correction of epicentral distances by application of normalized seismic field as follows:

1) We define normalized seismic field for location L_1 due to earthquake EQ^1 $((\rho\_1\^1)/(\rho\_i\^1), i = 1,5)$. With it, we correct the epicentral distances for all records of earthquake EQ^1 $[((R\_e\^c)\_i\^1 = (\rho\_1\^1)/(\rho\_i\^1)(R\_e)\_i\^1, i = 1,5)]$, and we enter them in the data for regression analysis. Thus, we obtain 5 data with corrected epicentral distances.
2) With the normalized seismic field for location $L_{1,}$ for earthquake $EQ^{2,}$ we compute corrected epicentral distances for all 20 records of earthquake EQ^2 $[((R\_e\^c)\_i\^2 = (\rho\_1\^2)/(\rho\_i\^2)(R\_e)\_i\^2, i = 1,20)]$ and we enter them in the data for regression analysis.
3) We define the normalized seismic field for location $L_{2,}$ separately for each occurred earthquake $EQ^{1,}$ EQ^2 and EQ^3. We compute corrected epicentral distances, separately for each occurred earthquake, and in the data for regression analysis, we include 5 + 20 +33, or a total of 58 data.

4) We define normalized seismic field for location $L_{3,}$ for the effect of earthquake EQ^2. We compute corrected epicentral distances for all records of this earthquake or 20, and we include them in the data for regression analysis.
5) The record obtained at location L_4 due to earthquake $EQ^{4,}$ being only one, is included as normalized by itself, and as a single datum, it is added to the remaining data for regression analysis.

According to the above stated, although we have only 7 records of occurred earthquakes in the azimuth segment (2 at location 1, 3 at location 2, 1 at location 3 and 1 at location 4), by use and analysis of the earthquake as an inseparable entirety and with the presented method herein, we obtain 104 data for regression analysis (5+20+58+20+1=104).

Over the created set of 104 data, we carry out a multi-linear regression analysis and compute regression coefficients b, b_M and b_R and standard deviation-$\sigma_{\ln PGA}$. Thus, we compute GMM for the selected azimuth segment.

In practical application of this method, there are two boundary cases. The first is when the initial and the end azimuth define an azimuth according to instrument location or an azimuth segment with a natural width, while the latter is when the initial azimuth is 0^0 and the end one is 360^0 / or the entire region is defined. For any other case, it is necessary to define initial and end azimuth by which an azimuth segment of a selected width is defined. The selection of the initial and the end azimuth may be based on the needs and the objectives of the research as well as on the distribution of the azimuths from the occurred earthquakes according to an investigated location or region. Each of these cases is investigated separately.

A.3 IMPORTANCE OF THE METHOD

The application of this original method enables avoiding the including of each record of an occurred earthquake obtained by a single instrument in the investigations as a datum that is independent of the remaining records obtained from that earthquake. In fact, each record of an occurred earthquake is much needed and is very important, but not sufficient enough. If it is not connected with all the other records obtained from that earthquake, it cannot thoroughly describe by itself only the characteristics of the occurred earthquake as are: the focal mechanism, the direction of the fault structure, the effect of the hypocenter, the effect of the volume affected by seismic waves and the effects of the regional characteristics at different azimuths. It is only through analysis of the earthquake as an event that is strictly regionally/geographically dependent, and including all its records with their spatial distribution taken as dependent on each other and in relation with each other, that one can include, in the simplest way, all the stated characteristics of an occurred earthquake in the ground motion model.

A.4 ASSOCIATION CONNECTED WITH THIS METHOD

This method is associated with mutual communication of obtained records from an occurred earthquake and exchange of their information by which the following is included in the investigation: the focal mechanism, the direction of the fault structure, the effect of the hypocenter, the effect of the volume affected by seismic waves and the effect of the characteristics of the region from the greatest depths of the seismic focus up to the earth's surface in different azimuth directions. It therefore opens a new way and a new philosophy in development of empirical mathematical-physical models of ground motion and their practical application.

A.5 PRACTICAL APPLICATION

As a method, it does not have any limitations in practical application. It can be used to develop GMM-s for earthquakes from shallow, deep and subduction foci as well as for all parameters of ground motion, parameters of elastic and inelastic dynamic response of a model of a single-degree-of-freedom system and Fourier amplitude spectra.

With the computed data for regression analysis, a support is given to development and use of GMM-s for epicentral distances greater than the epicentral distances at which an earthquake is recorded, or for all distances by which is defined the earth's volume affected by the seismic waves from the occurred earthquakes at that specific focus.

In addition, the method can also be used in other scientific investigations. It is referenced in the investigations of Gyongyosi&Imre, 2019 ([8]).