DEVELOPMENT OF *GROUND MOTION RECORD SURFACE* AND *RESPONSE SPECTRA SURFACE*

Mladen Ćosić*, Stanko Brčić**, Nenad Šušić*, Radomir Folić***, Kristina Božić-Tomić*

* *Institute for Testing of Materials IMS, Belgrade,* mladen.cosic@institutims.rs, nenad.susic@institutims.rs, kristina.tomic@institutims.rs
** *University of Belgrade, Faculty of Civil Engineering, Belgrade,* stanko@grf.bg.ac.rs
*** *University of Novi Sad, Faculty of Technical Sciences, Novi Sad,* folic@uns.ac.rs

ABSTRACT
The paper is presenting a mathematical formulation of an originally developed *ground motion record surface* (GMRS) and *response spectra surface* (RSS) for the presentation of 2D seismic ground motion records (GMR) and the corresponding response spectra (RS), respectively. These surfaces are constructed by transformation from 2D polar coordinate system to a 3D cylindrical coordinate system and then to the 3D orthogonal coordinate system. The principle of application of three orthogonal coordinates for each discrete value is used in order to achieve easy manipulation and interpolation of spatial surface. Scaling of accelerograms was carried out using two procedures: the *Least Square Method* (LSM) and *Spectral Matching* (SM).
KEY WORDS: earthquake, *ground motion record surface* (GMRS), *response spectra surface* (RSS), scaling

RAZVOJ *POVRŠI AKCELEROGRAMA* I *POVRŠI SPEKTRA ODGOVORA*

REZIME
U radu je prezentovana matematička formulacija originalno razvijene *površi akcelerograma* (GMRS - *ground motion record surface*) i *površi spektra odgovora* (RSS - *response spectra surface*) za konstrukciju 2D seizmičkog zapisa kretanja tla i odgovarajućeg spektra odgovora, respektivno. Ove površi su konstruisane transformacijom iz 2D polarnog koordinatnog sistema preko 3D cilindričnog koordinatnog sistema, pa sve do 3D ortogonalnog koordinatnog sistema. Princip primene tri ortogonalne koordinate za svaku diskretnu vrednost je iskorišćen radi lakše manipulacije i interpolacije prostorne površi. Skaliranje akcelerograma je sprovedeno primenom dve procedure: metodom najmanjih kvadrata (LSM - *Least Square Method*) i kompatibilizacijom (SM - *Spectral Matching*).
KLJUČNE REČI: zemljotres, *površ akcelerograma* (GMRS), *površ spektra odgovora* (RSS), skaliranje

INTRODUCTION

The development of modern methodology for structural performance analyses in terms of seismic action (PBEE - *Performance-Based Earthquake Engineering*) has been initiated in the last twenty years and is based on continuous and discrete nonlinear mathematical models of structural behaviour. Methods based on which we estimate the nonlinear system behaviour are the following: *Nonlinear Static Pushover Analysis* (NSPA) and *Nonlinear Dynamic Analysis* (NDA). However, since the concept of PBEE methodology, among other things, is based on the analysis of the system response in a capacity domain, where a number of parameters is participating in the assessment of behavior, such as stiffness, strength, ductility, collapse status assessment etc, then *Incremental Dynamic Analysis* (IDA) is being applied. Input signal component that should be taken into system consideration is being presented through the accelerograms and response spectra, while the system response is presented using the pushover curve. Performance analysis of a 3D model building is carried out by using decomposition of planar models (in most cases and when conditions are favourable). Performance calculations of decomposed models are conducted on the basis of the NSPA, NDA and/or IDA analysis results. An alternative to the previous type of analysis is to determine the performances on a complete 3D model of the building. Performance calculations of a 3D model building is carried out using the results of NSPA and/or NDA analysis, and rarely using the IDA analysis, where due to the complexity of the numerical model and the time required in order to finish the processing, the techniques of parallel processing are being applied. Representative models of earthquake records for 3D building models are accelerograms (two-component accelerograms) or generated response spectra for two orthogonal directions. The procedure of performance evaluation of 3D building models is still in the development stage, where the particular problems associated with the torsionally sensitive constructions, irregular at the base and height and with a greater degree of stiffness discontinuity, appear, in which the complex forms are particularly favoured according to the requirements of modern architecture. When it comes to complex building forms, the question about the main directions is debatable, so the analyses for a number of directions are conducted, in order to verify all the relevant system parameters. In the paper [9] a governing equation of motion is postulated to compute the response of a SDOF (single degree of freedom) oscillator under a multi-component excitation. The proposed multi-component response spectra reflects kinematic characteristics of the ground motion that are not identifiable by the conventional spectra itself, at least for the near-fault region where high intensity vertical shaking and rotational excitation are likely to occur. On the other hand, in papers [15, 16, 17, 18] significance of rotating ground motions on nonlinear behaviour of symmetric and asymmetric buildings in near fault sites are examined. The influence that the rotation angle of the ground motion has on several engineering demand parameters (EDP) is examined in linear elastic and nonlinear inelastic domains to form a benchmark for evaluating the use of the fault normal/fault-parallel (FN/FP) directions as well as the maximum-direction ground motion. Evaluation of FN/FP directions rotated ground motions for response history analysis of an instrumented six-story building is presented in paper [10], while in [11] pros and cons of rotating ground motion records (GMR) to FN/FP directions for response history analysis of buildings is presented. Representation of bidirectional ground motions for design spectra in building codes is analyzed in [20]. The use of maximum-direction ground motions effectively assumes that the azimuth of maximum ground motion coincides with the directions of principal structural response.

DEVELOPMENT OF *GROUND MOTION RECORD SURFACE* (GMRS)

During the process of development of the ground motion record surface we accessed to identifying the optimum quality of motion record base, where using the extensive analysis of international data bases identified *Pacific Earthquake Engineering Research Center* ground motion database (PEER-NGA). This earthquake database has got more than 3500 processed components based on 173 earthquakes [14, 2]. Compared to other earthquake databases where the earthquake components are processed from North to South (NS) and from East to West (EW), where in PEER-NGA database the earthquake components are being processed for the component perpendicular to the direction of fault (FN) and the component parallel to the direction of fault (FP) [13]. Terminologically observed, these accelerograms, which have been taken from the PEER-NGA database, belong to the original unscaled ground motion records. Generally considering the ground motion record presents linearly interpolated discrete values of ground acceleration a_i in equal increments of time Δt from initiation to termination of the earthquake. Angle of fault position α_f, based on which the ground motion record has been recorded, is defined as the angle in the plane coordinate system, where the vertical axis corresponds to the direction NS, and horizontal axis to EW. Following the direction of a fault, we define the component that is parallel to the fault FP, and perpendicular to this direction, we define a component FN. The angle between the fault and vertical NS axis is the angle of the fault position α_f (strike angle) [12]. Reference coordinate system for which the effect of the earthquake relative to the position of the object is being considered is different from the previous coordinate system. In this coordinate system, the direction of rotation is opposite to the clockwise direction, starting in the horizontal axis. Determination of the earthquake components for the rotation angle increment $\Delta\theta$=30° is carried out so that the review is conducted in relation to the initial components θ_{EW}=0° i θ_{NS}=90°. Rotation procedure is done through the rotation of the components FP and FN within the reference coordinate system [1]:

$$\begin{bmatrix} a_{FP}(t) \\ a_{FN}(t) \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} a_\theta(t) \\ a_{\theta-90}(t) \end{bmatrix}, \tag{1}$$

where the $a_{FP}(t)$ ground motion record for direction FP, $a_{FN}(t)$ ground motion record for direction FN, $a_\theta(t)$ ground motion record for the rotation angle θ:

$$\left[a_{orig}(t)\right] = \begin{bmatrix} a_{FP}(t) \\ a_{FN}(t) \end{bmatrix}, \quad \left[a_{rot}(t)\right] = \begin{bmatrix} a_\theta(t) \\ a_{\theta-90}(t) \end{bmatrix}, \tag{2}$$

where is matrix of rotation:

$$\left[R_\theta\right] = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix}, \tag{3}$$

and where is angle θ:

$$\theta_i = \alpha_f + i\Delta\theta \quad \text{za} \quad i = 0,\ldots 11. \tag{4}$$

Components $a_\theta(t)$ and $a_{\theta-90}(t)$ are determined according to:

$$\left[a_{rot}(t)\right]=\left[R_{\varphi}\right]^{-1}\left[a_{orig}(t)\right], \tag{5}$$

so that the final form is:

$$\begin{bmatrix} a_{\theta}(t) \\ a_{\theta-90}(t) \end{bmatrix}=\begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix}\begin{bmatrix} a_{FP}(t) \\ a_{FN}(t) \end{bmatrix}. \tag{6}$$

After the ground motion record calculation for θ_i angles, we construct the *ground motion record surface* (GMRS) first by generating $a_{\theta}(t)$ ground motion records in the plane polar coordinate system. Then for each $a_{\theta}(t)$ ground motion record is given a vertical coordinate (acceleration) in the spatial cylindrical coordinate system, and then is converted into the spatial rectangular coordinate system (Figure 1):

$$t_x=t_r\cos\theta\,,\qquad t_y=t_r\sin\theta\,,\qquad t_r=\sqrt{t_x^2+t_y^2}\,, \tag{7}$$

where t_x, t_y are the times in the orthogonal coordinate system, t_r is the time in the polar coordinate system. *Ground motion record surface* (GMRS) is presented using the iso-surface or as multi-component ground motion record. The process of generating ground motion record surface is not related to the place of a fault and to the place where an earthquake is initiated, but to the place of a station where the earthquake is recorded, and as such it is used for the analysis of 3D models of building structures.

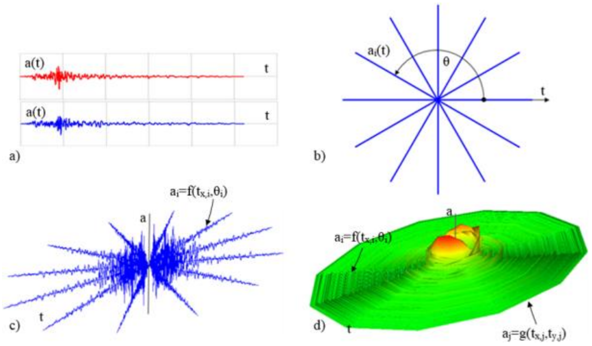


Figure 1. Procedure of the generation of GMRS: a) 2D orthogonal coordinate system, b) 2D polar coordinate system, c) 3D cylindric coordinate system, d) 3D orthogonal coordinate system

Definition 1: *Ground motion record surface (GMRS) $a=f(t_x,t_y)$ is linearly interpolated asymmetric rotation surface generated by connecting discrete values $I_i(t_{r,i},a_{z,i},\theta_i)$ of individual ground motion records $a_i=f(t_{r,i},\theta_i)$ using the linear functions $a_j=g(t_{x,j},t_{y,j})$ in the tangential direction*:

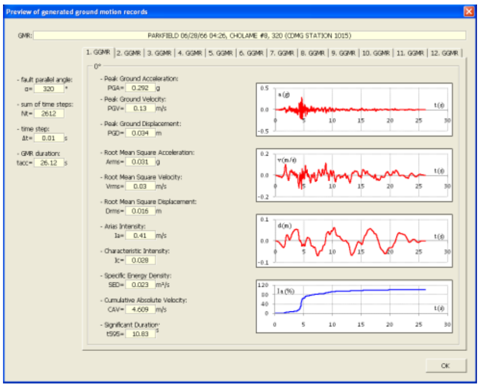
$$a=f\left(t_x,t_y\right)=\left[\bigcup_{\theta_i=0}^{360^{\circ}} f\left(t_{r,i},\theta_i\right)\right]\bigcup\left[\bigcup_{j=0}^{t_{max}} g\left(t_{x,j},t_{y,j}\right)\right], \tag{8}$$

where:

$$I_i\left(t_{r,i},a_{z,i},\theta_i\right)\subset a=f\left(t_x,t_y\right),\quad t_{x,j},t_{y,j}\in\left[0,t_{max}\right]\ \text{ i }\ \theta_i\in\left[0,360^{\circ}\right]. \tag{9}$$

The procedure for generating the components of the *ground motion record surface* (GMRS) was implemented in the original software solution *Nonlin Quake* GMP (*Ground Motion*

Processing), which is part of a complex software platform *Nonlin Quake* for nonlinear seismic analysis of the building performances [3]. *Nonlin Quake* GMP is written in VB/VBA (*Visual Basic*/*Visual Basic for Applications*) programming language, where the user-software interaction takes place via graphic user interfaces (GUI). Figure 2 shows the GUI for viewing the generated ground motion records for all angles θ_i and all relevant calculation parameters.



GMR: PARKFIELD 06/28/66 04:26, CHOLAME #8, 320 (CDMG STATION 1015)

- fault parallel angle: α= 320 °
- sum of time steps: Nt= 2612
- time step: Δt= 0.01 s
- GMR duration: tacc= 26.12 s

- Peak Ground Acceleration: PGA= 0.292 g
- Peak Ground Velocity: PGV= 0.13 m/s
- Peak Ground Displacement: PGD= 0.034 m
- Root Mean Square Acceleration: Arms= 0.031 g
- Root Mean Square Velocity: Vrms= 0.03 m/s
- Root Mean Square Displacement: Drms= 0.016 m
- Arias Intensity: Ia= 0.41 m/s
- Characteristic Intensity: Ic= 0.028
- Specific Energy Density: SED= 0.023 m²/s
- Cumulative Absolute Velocity: CAV= 4.609 m/s
- Significant Duration: t595= 10.83 s

Figure 2. The GUI for viewing the generated ground motion records for all angles θ_i and all relevant calculation parameters in *Nonlin Quake* GMP

Before processing and generating the ground motion records from PEER-NGA earthquake database, the selection and classification into two groups have been made: far field ground motions (FF GMR) and near fault ground motions (NF GMR). The basic parameters of the selected FF GMR and NF GMR earthquakes are shown in Table 1.

Table 1. The basic parameters of the selected FF GMR and NF GMR earthquakes

FF GMR earthquakes								
No.	ID	NGA	earthquake	year	M_w	D5-95 (s)	R_{rup} (km)	$v_{s,30}$ (m/s)
1.	IV79	172	*Imperial Valley*	1979	6.5	19.5-15.1	21.7	237.3
2.	LP89	737	*Loma Prieta*	1989	6.9	18.4-21.1	24.6	239.7
3.	NR94	953	*Northridge*	1994	6.7	8.5-8.5	17.1	355.8
NF GMR earthquakes								
No.	ID	NGA	earthquake	year	M_w	D5-95 (s)	R_{rup} (km)	$v_{s,30}$ (m/s)
1.	KO95	1119	*Kobe*	1995	6.9	5.1-3.4	0.3	312
2.	MH84	458	*Morgan Hill*	1984	6.2	12.8-16.4	11.5	221.8
3.	PS86	529	*Palm Springs*	1986	6.1	4.5-5.6	4	345.4

After the selection of the earthquakes, from the PEER-NGA database of earthquakes, they are imported into the program *Nonlin Quake* DB (*Data Base*) within the expert system *Nonlin Quake*. In *Nonlin Quake* DB original, unscaled ground motion records are being formatted based on AT2 (auto template) in XLSB format (*Excel* binary), and then the time increments are generated for each individual ground motion record:

$$t_0 = 0, \quad t_{i+1} = t_i + \Delta t, \quad t_n = \sum_{i=1}^{n} \Delta t_i \; . \tag{10}$$

where t is time. After completion of ground motion record formatting in *Nonlin Quake* DB, they are imported in *Nonlin Quake* GMP, where the ground motion record processing takes place for different angles θ_i, and then a ground motion record surface is being generated. Generated FF GMRS $a=f(t_x,t_y)$ of *Imperial Valley*, *Loma Prieta* and *Northridge* are shown in Figure 3, while Figure 4 shows the generated NF GMRS $a=f(t_x,t_y)$ of *Kobe*, *Morgan Hill* and *Palm Springs*.

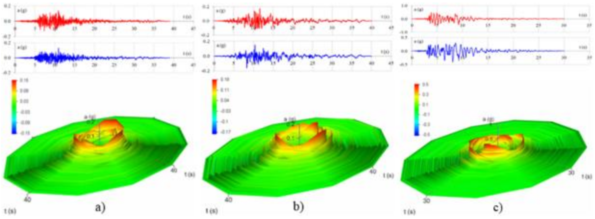


Figure 3. Generated FF GMRS $a=f(t_x,t_y)$ of: a) *Imperial Valley*, b) *Loma Prieta*, c) *Northridge*

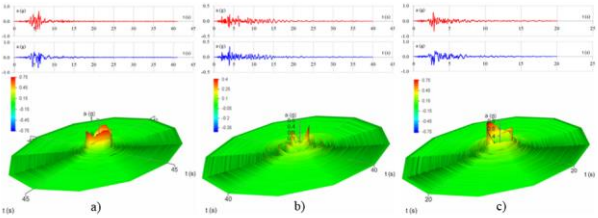


Figure 4. Generated NF GMRS $a=f(t_x,t_y)$ of: a) *Kobe*, b) *Morgan Hill*, c) *Palm Springs*

DEVELOPMENT OF *RESPONSE SPECTRA SURFACE* (RSS)

Generally considering the response spectra presents linearly interpolated discrete values of maximum accelerations a_i (velocity v_i or displacement d_i) that are determined using *Linear Dynamic Analysis* (LDA) of SDOF system for the corresponding increments of periods ΔT. Depending on the parameter considered to be a maximum value in successive analyzes of SDOF system, we can generate acceleration response spectra (ARS), velocity response spectra (VRS) or displacement response spectra (DRS). This study introduced the term *response spectra surface* (RSS), which is related to the general case of the response spectra. In case the parameter of acceleration is considered to be authoritative, the term *acceleration response spectra surface* (ARSS) has been introduced, while in case the parameter of displacement is considered as authoritative, the term *displacement response spectra surface* (DRSS) is being introduced. The construction of the *response spectra surface* (RSS) is carried out by generating response $S_\theta(T)$ in the plane polar coordinate system for the angles θ_i. Then, each response spectra $S_\theta(T)$ is given a vertical coordinate (S_a or S_d) in the spatial cylindrical coordinate system, and then is converted into a spatial rectangular coordinate system:

$$T_x = T_r \cos\theta \, , \quad T_y = T_r \sin\theta \, , \quad T_r = \sqrt{T_x^2 + T_y^2} \; , \tag{11}$$

where T_x, T_y are the periods in the orthogonal coordinate system, T_r is the period in the polar coordinate system.

Definition 2: *Acceleration response spectra surface (ARSS) $S_a=f(T_x,T_y)$ is linearly interpolated asymmetric rotational surface generated by connecting discrete values $I_{a,i}(T_{r,i},S_{a,z,i},\theta_i)$ of individual response spectra $S_{a,i}=f(T_{r,i},\theta_i)$ using linear functions, $S_{a,j}=g(T_{x,j},T_{y,j})$ in the tangential direction (Figure 5)*:

$$S_a = f(T_x,T_y)=\left[\bigcup_{\theta_i=0}^{360^\circ} f(T_{r,i},\theta_i)\right]\bigcup\left[\bigcup_{j=0}^{T_{max}} g(T_{x,j},T_{y,j})\right], \tag{12}$$

where:

$$I_{a,i}(T_{r,i},S_{a,z,i},\theta_i)\subset S_a = f(T_x,T_y),\quad T_{x,j},T_{y,j}\in[0,T_{max}],\quad \theta_i\in[0,360^\circ]. \tag{13}$$

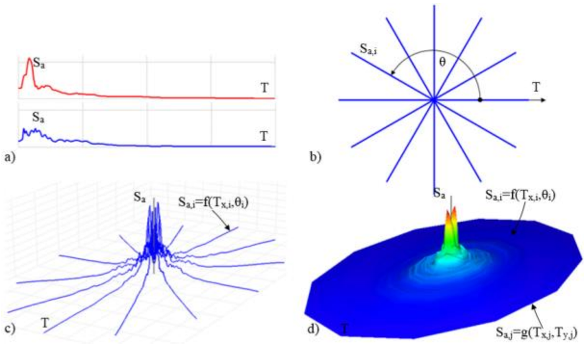


Figure 5. Procedure of the generation of ARSS: a) 2D orthogonal coordinate system, b) 2D polar coordinate system, c) 3D cylindrical coordinate system, d) 3D orthogonal coordinate system

Definition 3: *Displacement response spectra surface (DRSS) $S_d=f(T_x,T_y)$ is linearly interpolated asymmetric rotational surface generated by connecting discrete values $I_{d,i}(T_{r,i},S_{d,z,i},\theta_i)$ of individual response spectra $S_{d,i}=f(T_{r,i},\theta_i)$ using linear functions of $S_{d,j}=g(T_{x,j},T_{y,j})$ in the tangential direction (Figure 6)*:

$$S_d = f(T_x,T_y)=\left[\bigcup_{\theta_i=0}^{360^\circ} f(T_{r,i},\theta_i)\right]\bigcup\left[\bigcup_{j=0}^{T_{max}} g(T_{x,j},T_{y,j})\right], \tag{14}$$

where:

$$I_{d,i}(T_{r,i},S_{d,z,i},\theta_i)\subset S_d = f(T_x,T_y),\quad T_{x,j},T_{y,j}\in[0,T_{max}],\quad \theta_i\in[0,360^\circ]. \tag{15}$$

Response spectra surface (RSS) are shown using iso-surfaces or as multi-component response spectra. Analogous to the generated number of ground motion records for the angle increment $\Delta\theta$=30°, the same number is obtained for the response spectra. After generating ground motion records in *Nonlin Quake* GMP, the same are imported in *Nonlin Quake* RSP (*Response Spectra Processing*) where the generation of response spectra for the angles θ_i is being done, and then a *response spectra surface* (RSS) is being constructed.

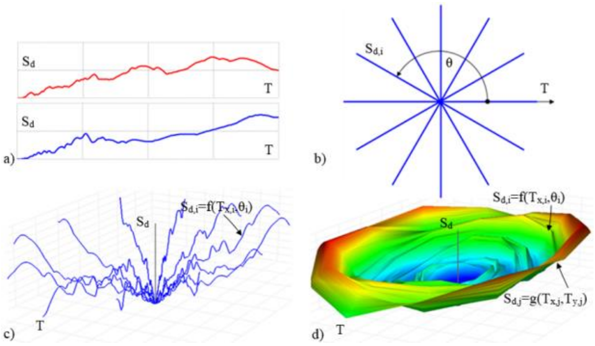
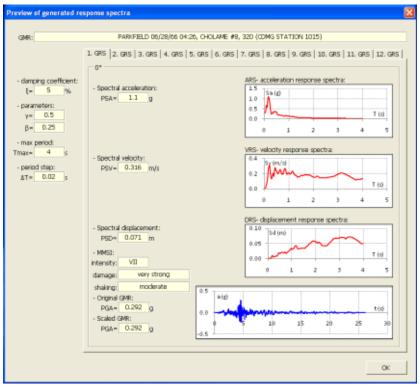


Figure 6. Procedure of the generation of DRSS: a) 2D orthogonal coordinate system, b) 2D polar coordinate system, c) 3D cylindric coordinate system, d) 3D orthogonal coordinate system

Figure 7 shows the GUI for viewing the generated response spectra for all angles θ_i and all relevant calculation parameters. Generated *response spectra surfaces* ARSS $S_a=f(T_x,T_y)$ and DRSS $S_d=f(T_x,T_y)$ of *Imperial Valley*, *Loma Prieta* and *Northridge* FF GMR are shown in Figure 8 (left), while Figure 8 (right) shows the generated response spectra surfaces ARSS $S_a=f(T_x,T_y)$ and DRSS $S_d=f(T_x,T_y)$ of *Kobe*, *Morgan Hill* and *Palm Springs* NF GMR.



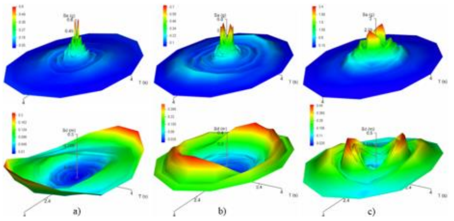
GMR: PARKFIELD 06/28/66 04:26, CHOLAME #8, 320 (CDMG STATION 1015)

0°

- damping coefficient:
ξ= 5 %
- parameters:
γ= 0.5
β= 0.25
- max period:
Tmax= 4 s
- period step:
ΔT= 0.02 s

- Spectral acceleration:
PSA= 1.1 g
- Spectral velocity:
PSV= 0.316 m/s
- Spectral displacement:
PSD= 0.071 m
- MMSI:
intensity: VII
damage: very strong
shaking: moderate
- Original GMR:
PGA= 0.292 g
- Scaled GMR:
PGA= 0.292 g

Figure 7. The GUI for viewing the generated response spectras for all angles θ_i and all relevant calculation parameters in *Nonlin Quake* RSP



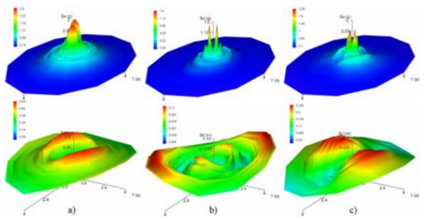


Figure 8. (left) Generated ARSS $S_a=f(T_x,T_y)$ and DRSS $S_d=f(T_x,T_y)$ of FF GMR: a) *Imperial Valley*, b) *Loma Prieta*, c) *Northridge*

Figure 8. (right) Generated ARSS $S_a=f(T_x,T_y)$ and DRSS $S_d=f(T_x,T_y)$ of NF GMR: a) *Kobe*, b) *Morgan Hill*, c) *Palm Springs*

SCALING OF GROUND MOTION RECORDS

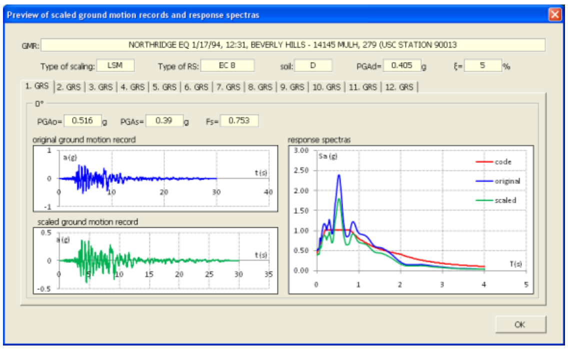
Scaling of ground motion record was carried out using two procedures: based on response spectra and *Spectral Matching* (SM). Scaling procedure through response spectra has been implemented in the software *Nonlin Quake* SP (*Scaling Procedure*) using the *Least Square Method* (LSM), which is based on minimizing the difference between the scaled response spectra and the target response spectra [5]:

$$|\Delta| = \int_{T_A}^{T_B} \left[F_s S_{a,us}(T) - S_{a,d}(T)\right]^2 dT \,, \tag{16}$$

where $S_{a,us}$ is a spectral acceleration of observed (unscaled) ground motion record, and $S_{a,d}$ spectral acceleration of the target response spectra, T_A the lower the value of the period, T_B upper value of the period. Determination of the scaling factor F_s was conducted by minimizing the differences which have been defined in the previous equation:

$$min|\Delta| \Rightarrow \frac{d|\Delta|}{dF_s} = 0 \Rightarrow F_s = \frac{\sum_{T_A}^{T_B}\left(S_{a,us}(T) S_{a,d}(T)\right)}{\sum_{T_A}^{T_B}\left(S_{a,us}(T)\right)^2} \,. \tag{17}$$

In *Nonlin Quake* SP horizontal elastic response spectra can be constructed according to EC 8 [4], FEMA 356 [6] and FEMA 750P [7]. Figure 9 shows the GUI for viewing the scaled response spectra at all θ_i angles and calculation parameters. Another procedure that is used to scale the ground motion record in this study is *Spectral Matching* (SM) which is implemented in software *SeismoMatch* [19]. SM is the procedure of creating a compatible ground motion record based on real ground motion record according to the target response spectra. This is known as the compatibilization, where based on the response spectra of a real earthquakes and the target response spectra a compatible earthquake is being generated so that a certain interval of period the best fit can be obtained [8]. The process is iterative and it is based on the application of the *Wavelet Theory* (WT).



Preview of scaled ground motion records and response spectras

GMR: NORTHRIDGE EQ 1/17/94, 12:31, BEVERLY HILLS - 14145 MULH, 279 (USC STATION 90013

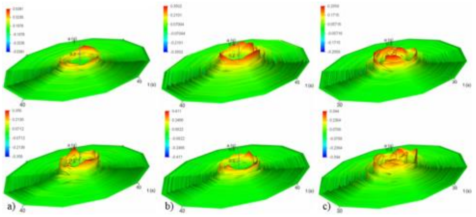
Type of scaling: LSM   Type of RS: EC 8   soil: D   PGAd= 0.405 g   ξ= 5 %

PGAo= 0.516 g   PGAs= 0.39 g   Fs= 0.753

Figure 9. The GUI for viewing the scaled response spectra at all θ_i angles and calculation parameters in *Nonlin Quake* SP

Scaling and SM of ground motion records and response spectra were carried out according to FEMA 750P [7] elastic response spectra for S_S=1.25, S_1=0.5, T_L=8s and C soil type.

Generated FF GMRS $a=f(t_x,t_y)$ using the LSM and SM for *Imperial Valley*, *Loma Prieta* and *Northridge* shown in Figure 10 (left), while Figure 10 (right) shows the generated NF GMRS $a=f(t_x,t_y)$ using the LSM and SM for *Kobe*, *Morgan Hill* and *Palm Springs*.



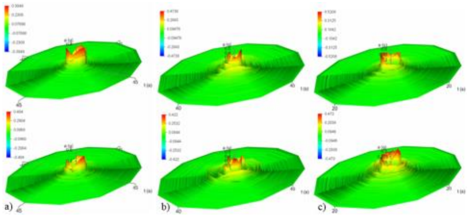
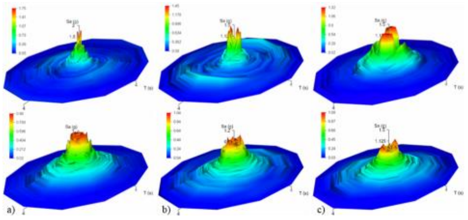


Figure 10. (left) Generated FF GMRS $a=f(t_x,t_y)$ using the LSM and SM: a) *Imperial Valley*, b) *Loma Prieta*, c) *Northridge*

Figure 10. (right) Generated NF GMRS $a=f(t_x,t_y)$ using the LSM and SM: a) *Kobe*, b) *Morgan Hill*, c) *Palm Springs*

According to FEMA 750P [7] interval of periods which has to be taken into account is from $0.2T$ to $1.5T$, so an interval of periods from 0.05s to 2s has been considered. Number of iterations has been incrementally increased from 1 to 50 iterations. In certain calculation situations, the convergence of solution problem has appeared, while for final constructed compatible ground motion records, the convergence with the fitting error to 4.1% has been achieved. Generated FF ARSS $S_a=f(T_x,T_y)$ using LSM and SM for *Imperial Valley*, *Loma Prieta* and *Northridge* are shown in Figure 11 (left), while Figure 11 (right) shows the generated NF ARSS $S_a=f(T_x,T_y)$ using the LSM scale and SM for *Kobe*, *Morgan Hill* and *Palm Springs*.



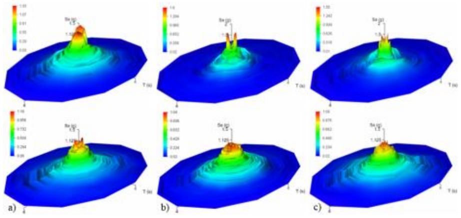


Figure 11. (left) Generated FF ARSS $S_a=f(T_x,T_y)$ using LSM and SM of: a) *Imperial Valley*, b) *Loma Prieta*, c) *Northridge*

Figure 11. (right) Generated NF ARSS $S_a=f(T_x,T_y)$ using the LSM and SM of: a) *Kobe*, b) *Morgan Hill*, c) *Palm Springs*

The difference in the structure and form of generated response spectra is a direct consequence of the applied procedure of scaling and SM. *Response spectra surfaces* (RSS) generated by the process of SM have a domain of constant acceleration greater than the *response spectra surfaces* (RSS) generated by scaling using the LSM method. On the other hand, since SM has been made in relation to the elastic response spectra under the regulations, the *generated response spectra surfaces* (RSS) have a certain degree of rotational symmetry around the vertical axis S_a.

FINAL REMARKS AND CONCLUSION

The main concept of the mathematical formulation presented in this study is to provide a better access and higher level in the presentation of 2D seismic ground motion record, and thus a better estimate of respective performance in terms of seismic action. For this purpose, *ground motion record surface* (GMRS) and *response spectra surface* (RSS) were originally developed. Scaling of ground motion records was carried out using two procedures: the *Least Square Method* (LSM) and *Spectral Matching* (SM). *Response spectra surfaces* (RSS) that are generated using the process of SM possess a domain of constant acceleration greater than the *response spectra surfaces* (RSS) generated using the LSM method. Developed and generated *ground motion record surface* (GMRS) is used for NDA analysis for determination of the target displacement and IDA analysis, while *response spectra surface* (RSS) is used for NSPA performance analysis and determination of the target displacement of 3D models of buildings.

ACKNOWLEDGEMENTS

The work reported in this paper is a part of the investigation within the research project TR 36014 supported by the *Ministry of Education, Science and Technological Development* of Serbia.

REFERENCES

1. Beyer K., Bommer J.: *Selection and Scaling of Real Accelerograms for Bi-Directional Loading: A Review of Current Practice and Code Provisions*, Journal of Earthquake Engineering, Taylor & Francis, Vol. 11, pp. 13-45, 2007.
2. Chiou B., Darragh R., Gregor N., Silva W.: *NGA Project Strong-Motion Database*, Earthquake Spectra, Vol. 24, No. 1, pp. 23-44, 2008.
3. Ćosić M., Brčić S., Folić R., Šušić N.: Nonlin Quake: *Expert System for Performance-Based Analysis of Structures*, The 5th International Conference of Earthquake Engineering and Engineering Seismology, Sremski Karlovci, Serbia, pp. 303-316, 2016.
4. *Eurocode* 8, *Design of Structures for Earthquake Resistance - Part* 1: *General Rules, Seismic Actions and Rules for Buildings*, European Committee for Standardization, Brusseles, Belguim, 2004.
5. Fahjan Y., Ozdemir Z., Keypour H.: *Procedures for Real Earthquake Time Histories Scaling and Application to Fit Iranian Design Spectra*, The 5th Iranian Conference on Seismology and Earthquake Engineering, Paper No. 164, Tehran, Iran, 2007.
6. FEMA 356, *Pre-Standard and Commentary for the Seismic Rehabilitation of Buildings*, American Society of Civil Engineers, Federal Emergency Management Agency, Washington D. C., USA, 2000.
7. FEMA 750P, NEHRP *Recommended Seismic Provisions for New Buildings and Other Structures*, Building Seismic Safety Council, Federal Emergency Management Agency, Washington D. C., USA, 2009.
8. Hancock J., Watson-Lamprey J., Abrahamson N., Bommer J., Markatis A., McCoy E., Mendis R.: *An Improved Method of Matching Response Spectra of Recorded Earthquake Ground Motion Using Wavelets*, Journal of Earthquake Engineering, Imperial College Press, Vol. 10, No. 1, pp. 67-89, 2006.

9. Kalkan E., Graizer V.: *Multi-Component Ground Motion Response Spectra for Coupled Horizontal, Vertical, Angular Accelerations and Tilt*, ISET Journal of Earthquake Technology, Vol. 44. No. 1, pp. 259-286, 2007.
10. Kalkan E., Kwong N.: *Evaluation of Fault-Normal/Fault-Parallel Directions Rotated Ground Motions for Response History Analysis of an Instrumented Six-Story Building*, U.S. Geological Survey Open-File Report, Reston, USA, 2012.
11. Kalkan E., Kwong N.: *Pros and Cons of Rotating Ground Motion Records to Fault-Normal/Parallel Directions for Response History Analysis of Buildings*, Journal of Structural Engineering, 2013.
12. Lee W., Kanamori H., Jennings P., Kisslinger C.: *International Handbook of Earthquake & Engineering Seismology*, Part A, Academic Press, Orlando, USA, 2002.
13. PEER-NGA URL: http://peer.berkeley.edu
14. Power M., Chiou B., Abrahamson N., Bozorgnia Y., Shantz T., Roblee C.: *An Overview of the NGA Project*, Earthquake Spectra, Vol. 24, No. 1, pp. 3-21, 2008.
15. Reyes J., Kalkan E.: *Should Ground Motion Records be Rotated to Fault-Normal/Parallel or Maximum Direction for Response History Analysis of Buildings?*, U.S. Geological Survey Open-File Report, Reston, USA, 2012.
16. Reyes J., Kalkan E.: *Significance of Rotating Ground Motions on Nonlinear Behavior of Symmetric and Asymmetric Buildings in Near Fault Sites*, 9th International Conference on Urban Earthquake Engineering / 4th Asia Conference on Earthquake Engineering, Tokyo, Japan, 2012.
17. Reyes J., Kalkan E.: *Significance of Rotating Ground Motions on Behavior of Symmetric- and Asymmetric-Plan Structures: Part I. Single-Story Structures*, Earthquake Spectra, Vol. 31, No. 3, pp. 1591-1612, 2015.
18. Reyes J., Kalkan E.: *Significance of Rotating Ground Motions on Behavior of Symmetric- and Asymmetric-Plan Structures: Part II. Multi-Story Structures*, Earthquake Spectra, Vol. 31, No. 3, pp. 1613-1628, 2015.
19. *SeismoSoft*: URL: http://www.seismosoft.com
20. Stewart J., Abrahamson N., Atkinson G., Baker J., Boore D., Bozorgnia Y., Campbell K., Comartin C., Idriss I., Lew M., Mehrain M., Moehle J., Naeim F., Sabol T.: *Representation of Bidirectional Ground Motions for Design Spectra in Building Codes*, Earthquake Spectra, Vol. 27, No. 3, pp. 927-937, 2011.