ABSTRACT

Displacement-based seismic design could be an alternative to the traditional Force-based method of designing structures for seismic action, one of the key features and basic input being the displacement response spectrum. A ground motion prediction equation for displacement response spectrum ordinates for intermediate-depth earthquakes produced by Vrancea seismic source is presented. The seismic hazard in a large part of Romania is dominated by large magnitude earthquakes (\(M_w > 7.0\)), which can occur twice a century, originating from Vrancea intermediate-depth seismic source. The main features of the strong ground motions generated by Vrancea earthquakes in Romanian Plain are large predominant periods (1.5-1.6s) and large displacement demand. The ground motion prediction equation covers the part of the country located in front of Carpathian Mountains and has coefficients determined for soil classes B and C. The equation was developed using two-stage regression analysis. The database used for regression analysis contains both analog recordings from past large earthquakes (\(M_w \geq 6.4\)) and digital recordings from smaller earthquakes (\(M_w \leq 6.0\)) from Vrancea source. Significant effort was made to extend the equation up to periods of 10s, so the database was enriched with high-quality digital recordings of earthquakes observed in Japan in a similar seismo-tectonic environment. A good agreement was found between recorded data and data predicted by the equation for past events, especially for soil class C. The goodness of fit was evaluated using methods available in literature.

Keywords: Displacement-based design; ground motion prediction equation; Vrancea; intermediate-depth; seismic design.

1. INTRODUCTION

Traditionally, the design of earthquake resistant structures is force-based, using as primary input the design acceleration response spectrum. In the last decades, a new method for designing and assessing structures in earthquake prone regions has become available. Displacement-based design is a concept that it is focused on displacement and deformation limit states, instead of inertial forces. Excessive deformation of structural and nonstructural components is the source of structural damage which occurs during earthquakes. In the displacement-based design framework, relative displacement spectrum has an important role, being the key input for the entire computation procedure.

Romania is a country exposed to moderate-high seismic hazard, throughout the entire territory. There are written records more than 1000 years old that describe the effect of earthquakes on buildings and environment on Romanian soil. Probabilistic seismic hazard analysis points out that Vrancea intermediate-depth source generates most of the seismic hazard for a large part of the country. Although there are 14 known seismic sources that affect parts of the country, by far the most aggressive is Vrancea sub-crustal source, the other being crustal seismic sources which affect relatively small regions.

Intermediate-depth source Vrancea generates two to three major earthquakes per century which are felt at large distances. They occur at depths of 70-110km and 130-160km and the epicenters are usually confined in a relative small region (80x40km). Sub-crustal earthquakes, in general, are associated with the subduction process. However, there is evidence supporting that the active subduction process in

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Vrancea ceased 10 million years ago (Frohlich, 2006). The seismologists hypothesized that intermediate-depth seismicity in this region could be linked to the descending of a fragment of tectonic plate into the asthenosphere, as a last stage of subduction process. The interaction between gravitational, buoyancy, viscous and friction forces cause large enough shear stresses to generate earthquakes in the descending body (Ismail-Zadeh, Mueller & Schubert, 2005).

The epicenters of Vrancea sub-crustal source have a pronounced mobility along NE – SW direction, which localizes the earthquake effects towards Bucharest or Moldova region. Using empiric relationships between earthquake magnitude, surface rupture length and rupture area (Wells & Coppersmith, 1994) one can assess the maximum magnitude that the source can generate. Lungu et al. (2003) present the maximum values rupture parameters accepted for surface rupture length (150 – 200km) and rupture area (8000km²), which led them to an estimated maximum credible magnitude of Mw ≈ 8.1.

This paper aims at better describing the input for displacement-based design procedure, the relative displacement spectrum (RDS), for strong ground motions generated in the Romanian Plain (fore-arc of Carpathian Mountains).

2. GROUND MOTION PREDICTION EQUATION FOR RELATIVE DISPLACEMENT SPECTRUM ORDINATES

Empirical prediction equations for ground motion parameters are used for more than 50 years to evaluate the way in which the amplitude of the ground motion changes with distance, earthquake magnitude, soil conditions and other parameters. Although in 2016 more than 400 ground motion prediction equations (GMPEs) were available, most of them were centered on estimating peak ground acceleration or spectral accelerations. Orphal & Lahoud (1974) published a GMPE for peak ground displacement for California (Douglas, 2016). Faccioli, Paolucci & Rey (2004) developed an attenuation model for RDS as part of a national research project in Italy, following the interest and progress in displacement based-design in the last decades.

The reason for developing a GMPE for displacement spectra and not deriving it from the acceleration response spectra is that the former are strongly influenced by earthquake magnitude than the latter. The size and shape of displacement spectra are heavily influenced by filtering of the ground motion records when compared with acceleration spectra.

2.1 Database. Record processing

In order to develop the attenuation model, a ground motion database was assembled. The compiled database includes 272 pairs of perpendicular horizontal components recorded from 16 intermediate-depth earthquakes. Vrancea intermediate-depth source generated ten of the earthquakes, the rest being recorded in Japan. The national records account for 86% of the ground motions contained in the database. Moment magnitude range is 5.2 ≤ Mw ≤ 7.4 while recorded depth is between 66 and 154km. The records are sorted by ground types according to CEN (2004) typologies, through Vr,30. Ground type C records represent 62% of the total, the rest coming from ground type B. Both digital and analogue ground motion records are present in the database, 52% are digital and generated by 5.2 ≤ Mw ≤ 7.1 earthquakes, so the majority of earthquakes of magnitude 7 and greater are recorded in analogue format and generated by Vrancea intermediate-depth seismic source.

Having available a small number of national records on firm soil (rock or rocky ground with less than 5m of weaker material and Vr,30 > 800m/s – ground type A) and from beyond the Carpathian arch (Transylvania), these records were not selected for regression analysis, so the attenuation model is valid for ground types B and C located in front of the Carpathian Mountains (Moldova, Muntenia and Dobrogea).

Ground motions not generated by Vrancea sub-crustal source were included in the database to cover the lack of high quality national records for moderate to strong earthquakes and to explore the shape and magnitude of the RDS at larger periods (> 4s). Japanese high quality digital records of earthquakes with depths of 66 – 122km and magnitude range of 6.0 ≤ Mw ≤ 7.1 from K-net and Kik-net networks were included in the database.

Distribution of magnitude, epicentral distance and ground type is shown in Figure 2.
The relative displacement spectrum is especially sensible to the quality of the record (digital or analogue) and ground motion processing. It is known that analogue records are affected by a number of errors which have an impact on high frequency and low frequency content. Whilst high frequency errors alter the peak ground acceleration value, the low frequency errors disturb the velocity and displacement traces. There are filtering techniques that can limit to some extent the errors but in doing so, useful information is also removed. For this study, the analogue records were already processed, so no further processing was applied. The methodology was described in Borcia (2008), and consists in applying Ormsby filters with cutoffs at 0.15-0.25Hz and 25-85Hz. Digital records were processed by applying 4th order Butterworth filters with cutoffs at 0.05Hz and 50Hz.

In this study, the EN 1998-1 (Eurocode 8) methodology for ground type classification was used, based on shear wave velocity as weighted average on first 30m, $V_{s,30}$. There are a small number of sites for which stratification, compression and shear wave velocities are known. However, Allen & Wald (2007) proposed an approach in which the shear wave velocity are derived from topographical slope data. Shear wave velocity data collected in this manner was confronted with measured shear velocities on sites in United States, Taiwan, Italy, New Zealand and Japan. A good correlation was observed, the authors recommending to use $V_{s,30}$ data based on topographical slope for regional description of soil conditions. In Romania studies by Neagu and Aldea, cited in Neagu et. al (2017), compared measured velocities for 19 boreholes located in Bucharest area with velocities from Allen & Wald methodology and found good agreement between them.

Figure 3 shows a map of Romania and neighboring countries in which $V_{s,30}$ is codified using a color
scale, dark-yellow to light green representing type C soil, green denotes type B soil and dark green illustrates type A soil.  

For some of the sites located in Japan, the boreholes had depths smaller than 30m, so the procedure described in Boore (2004) was followed in order to extrapolate borehole data to get \( V_{s,30} \).

### 2.5 Ground motion prediction equation for relative displacement spectrum ordinates

The attenuation model was developed through two stage regression, following the procedure described in Joyner & Boore (1993). Two stage regression analysis is used to decouple magnitude scaling from distance scaling. In the first stage amplitude factors describing distance dependence are determined along with a vector of deviations, than the amplitude factors are regressed against magnitude in order to capture magnitude dependence. In the same paper, the authors also introduced a single stage regression method, in which the coefficients controlling magnitude and distance dependence are calculated in the same time. Both procedures are based on maximizing the likelihood of the set of data. 

The functional form, adapted from Joyner & Boore (1993) is:

\[
\lg (SD) = a + b(M_W - 6) - \lg \sqrt{D_{epi}^2 + h^2} + c \sqrt{D_{epi}^2 + h^2} + \varepsilon_r + \varepsilon_e
\]  

where SD (cm) is relative displacement spectrum ordinate (expressed as the geometric mean of two horizontal components) for 5% damping, \( M_W \) is the moment magnitude of the earthquake, \( D_{epi} \) (km) is the epicentral distance, \( a, b, c, h \) are coefficients to be determined through regression analysis, \( \varepsilon_r \) is an independent normal random variable with values for each record (harnessing intra-event variability), \( \varepsilon_e \) is an independent normal variable with values for each earthquake (describing inter-event variability) and \( \lg \) implies base 10 logarithms. Both random variables \( \varepsilon_r \) and \( \varepsilon_e \) have zero mean, the variance is \( \sigma_r^2 \) for \( \varepsilon_r \) and \( \sigma_e^2 \) for \( \varepsilon_e \). Total standard deviation is:

\[
\sigma = \sqrt{\sigma_r^2 + \sigma_e^2}
\]

Original functional form (Joyner & Boore, 1993) used Joyner-Boore distance as predictor variable. Since there is no available data on Joyner-Boore distances for the sites and earthquakes considered in the analysis, epicentral distance was used instead. 

The first and second terms account for quasi-linear variation of the logarithm of amplitude with magnitude, the third considers geometric attenuation of seismic waves, and the fourth corresponds to anelastic attenuation. 

Intra-event variability (between stations), expressed through variance \( \sigma_r^2 \), can be calculated (Boore, Joyner, Fumal 1997):

\[
\sigma_r^2 = \frac{1}{\text{no.rec.}} \sum_{j=1}^{\text{no.rec.}} \frac{(\lg Y_{1j} - \lg Y_{2j})^2}{4}
\]  

no.rec. being the number of records, indexes 1 and 2 are the horizontal component numbers of record j. The original expression was written in natural logarithms (as the ground motion prediction equation with which it was employed). 

GMPE’s coefficients were calculated separately for ground type B and C because of the large differences between spectral shapes and values corresponding to the two ground types. Convergence problems were encountered, especially for ground type B; so, for a few spectral periods, the coefficients were computed by single step regression analysis. 

To improve the model’s predictions for large magnitude earthquakes (\( M_W > 7.1 \)) it was explored the opportunity of adding a quadratic term to the functional form, Equation 1 becoming:

\[
\lg (SD) = a + b(M_W - 6) + d(M_W - 6)^2 - \lg \sqrt{D_{epi}^2 + h^2} + c \sqrt{D_{epi}^2 + h^2} + \varepsilon_r + \varepsilon_e
\]  

which produced better estimations for 1977 seismic event and reduced residuals to some extent. 

As mentioned above, the database is composed of analogical records of moderate-strong national
earthquakes, for which valid displacement spectra can be calculated up to 4s. High quality digital Romanian ground motions were available for earthquakes past 2004, but the largest recorded magnitude is $M_W = 6.0$. In order to extend the validity of the spectrum to higher periods, Japanese digital records of stronger earthquakes were added. Accurate displacement spectra produced using the aforementioned digital records can be generated for periods beyond 10s. Database dependence of the model was investigated running regression analysis on three sets of data: one which contains the national records of seismic events of 1977, 1986 and 1990, the second which comprises only digital records ($5.2 \leq M_W \leq 7.1$) with regression coefficients determined up to 8s, and a third set which uses the entire database.

2.5.1 Moderate-strong national set

The largest earthquakes instrumentally recorded in Romania were the seismic events which occurred in 1977, 1986 and 1990, with moment magnitudes descending from 7.4 (4th of March 1977) to 6.4 (31st of May 1990). These earthquakes are known for their effects on tall buildings located in Bucharest, on medium – soft soil. Historical data confirm this fact: 1940 earthquake inflicting damage on high-rise buildings, and the devastating 1802 earthquake ($M_W \approx 7.9$) which destroyed almost all bell towers of the churches in Bucharest. This set of records was already processed, and due to the fact that there used just analogical records, the computed displacement spectra are considered valid in the interval $0.025 – 4.0s$. The spectra were calculated with Seismosignal software (Seismosoft 2016) with $0.025s$ increment for 5% damping. In Figure 4 are shown two representative spectra for ground type B and C, the two stations being located at the same epicentral distance ($136 – 137km$). Note the different shape and values of the spectral ordinates and the prominent peak around $1.5 – 1.6s$ typical for type C ground sites located in the Romanian Plane.

![Figure 4](image)

Figure 4. Ground type B (left) vs. ground type C (right) spectra, $M_W = 7.1$ 1986 earthquake, $D_{eq} = 137km$

Geometric mean for the spectral displacement of the two horizontal components and intra-event variance were calculated for all the records in the set, then two stage regression was performed following the procedure given in Joyner & Boore (1993). The coefficients of the prediction equation were computed for a range of periods between 0.10s and 4.00s with a 0.1s increment, for both functional forms given by Equations 1 and 4. Two simulations for an event with $M_W = 6.9$, using equation 1, for terrain types B and C are compared with actual displacement spectra calculated for two stations, Bacau and Iasi, for 1990-1 earthquake.
With continuous line the GMPE data is presented (mean and mean ± 1σ) while the computed spectra from the records is displayed with dotted line. A good fit between prediction and real displacement spectra can be observed, the GMPE being able to capture both the shape and size of the spectra.

The strong dependence of displacement spectra with magnitude can be analyzed using the GMPE. Considering the mean values given by the attenuation model, the variation of the values and shape of the RDS can be examined. In Figure 6 one can observe the very strong dependence on magnitude, especially for type C ground, the ratio between maximum displacement for $M_W = 7.5$ and $M_W = 7.0$ exceeding 4.5. For stiffer ground, the ratio is close to 2, for the mean values predicted by the attenuation model.

Also, as the magnitude of the earthquake increases, the range of periods for which the maximum amplification occurs is shrinking. For moderate magnitudes, there are no notable peaks, a plateau being present for a large range of periods. No evident period shift of the peak amplification with increasing earthquake magnitude is present.

The dependence on ground type can also be investigated using the GMPE. The ratio between displacement spectra on ground type C and B is considered relevant. In Figure 7 it is displayed the
variation of this ratio with the period. It is strongly dependent on magnitude of the earthquake, as was shown before, soil B and C responding differently to increasing magnitude. For large earthquakes there is a very large amplification of displacement demand of sites located on medium-soft soils as compared to those located on firmer ground. However, for moderate earthquakes, the values of this ratio are similar to those reported in the literature (Cauzzi & Faccioli, 2008).

Figure 7. Soil conditions (left) and distance dependence (right) of the RDS

In Figure 7 there is shown the change of the RDS with increasing distance for a $M_W = 7$ earthquake and sites located at epicentral distances of 50, 100 and 150km. The distance has a large impact on ordinate values of the spectrum, for each 50km the peak value dropping about 33%. For the closest site, the curve has a small peak around 1.0s, which is not present at larger distances. Again, there is a tendency towards flattening of the curves with increasing distance.

The addition of a quadratic term to the basic functional form resulted in a better prediction of the spectral ordinates for large earthquakes ($M_W \geq 7.1$). However, the quadratic term introduces a superior limit to the range of applicability of the GMPE. For a range of periods between 0.20 and 0.60s, Equation 4 reaches a maximum (saturates) at a minimum value of $M_W = 7.62$. There are two other periods in the above mentioned range for which saturation is reached at $M_W = 7.83$ and $M_W = 7.98$ respectively. Below there is a comparison of predicted versus actual displacement spectra for $M_W = 7.4$ earthquake recorded at INCERC station, with and without the quadratic term.

Figure 8. Prediction vs. calculated displacement spectra for $M_W = 7.4$ earthquake
In Figure 8, with dotted lines are the actual spectra (two components and geometric mean) and with continuous line are the predicted spectral ordinates. One can observe a better match between the two for the GMPE containing the quadratic term (Equation 4). For the first model, the mean + 1σ curve barely reaches the geometrical mean of the two components, while for the second model the geometrical mean is enveloped by mean ± 1σ curves. The aggressive NS component is covered by the mean + 1σ curve for periods up to 1.0s and between 2.0 and 3.0s, and captures well the peak value of displacement. The regression coefficients of the GMPE determined for this set, with quadratic term, are given in the Appendix.

2.5.2 Digital recordings set

This set was considered in order to expand the range of prediction to larger periods, where are expected new peaks for RDS ordinates around spectral periods of 5 – 6s. The national digital recording set was enriched with Japanese data, so the range of magnitudes covered is $5.2 \leq M_w \leq 7.1$. Unfortunately, the analysis results are blurred by lack of convergence for a large range of spectral periods, for both types of ground. For this periods single stage regression was used to determine the coefficients for the attenuation model. Up to 4.0s the increment of the regression analysis was set to 0.10s, between 4.0s and 6.0s it was increased to 0.20s, than, up to 8.0s the coefficients were determined for 0.40s increment.

![Figure 9](image)

**Figure 9. Prediction vs. calculated displacement spectra for $M_w = 6.0$ earthquake**

Calculated spectra showed a small peak present around 5s, smaller than the peak corresponding to largest amplification (which for this set occurs between 1.0 and 2.0s, as opposed to the first set where maximum amplification was near 2.20s). In Figure 9 it is shown a typical predicted spectrum for the second set of ground motions. The simulation is for 2004 $M_w = 6.0$ earthquake recorded at Piata Romana (Bucharest downtown).

2.5.3 Whole database set

This set contains 272 pairs of horizontal perpendicular components. Introducing a large number of records from smaller earthquakes results in the increase of variability. The contribution of larger earthquakes is diminished, the resulting model having usually larger plateaus and smoother peaks. In Figure 10, the predicted spectral displacements for a seismic event of $M_w = 7.0$ at epicentral distance of 120km are shown for the attenuation models corresponding to the three sets.
For ground type B, the GMPEs with coefficients determined from set 1 (strong-moderate national records) and 3 (whole database) have almost the same shape and spectral ordinates, while the digital set provides larger values and a peak around 1.40s. For ground type C, as mentioned before, digital record set determines a model with different shape, so it cannot be used to predict RDS ordinates for large earthquakes. In order to capture the displacement demand of strong earthquakes recorded in Vrancea, the GMPE with coefficients determined from the first set should be used (possibly with the quadratic term).

3. TESTING OF THE MODEL

The attenuation model was tested by assessing the residuals. Normalized residual, are defined as:

\[ z = \frac{Y_{es} - \mu_{es}}{\sigma} \]  \hspace{1cm} (5)

where \( Y_{es} \) is the logarithm of recorded amplitude of earthquake \( e \) at seismic station \( s \), \( \mu_{es} \) is the logarithm of the median provided by the GMPE and \( \sigma \) represents the standard deviation of the GMPE.

One can observe from Figure 11, both from histogram and from the QQ plot, that residuals follow a normal distribution. This is representative for all spectral periods.

In order to assess the distribution of inter-event residuals against magnitude and distribution of intra-event residuals with epicentral distance the following quantities must be calculated (Văcăreanu, Pavel, Aldea, Arion & Neagu, 2015):

\[ \text{Figure 10. Predicted displacement spectra for the models corresponding to the three sets of ground motions} \]

\[ \text{Figure 11. Histogram and QQ plot of the normalized residuals for } T = 0.70s, \text{ set 1 of records, type C ground} \]
\[ \delta B_e = \frac{1}{N_s} \sum_{s=1}^{N_s} (Y_{es} - \mu_{es}) \]  

where \( \delta B_e \) is the inter-event residual and \( N_s \) is the number of seismic stations where earthquake \( e \) was recorded.

\[ \delta W_{es} = Y_{es} - (\mu_{es} + \delta B_e) \]  

where \( \delta W_{es} \) is the intra-event residual.

Plotting these quantities at different periods gives information about the ability of the GMPE to accurately estimate the ground amplitude. Positive values of the residuals indicate an underestimation of the spectral displacement while negative values suggest an overestimation.

In Figure 12 are displayed the inter-event and intra-event residuals for \( T=1.0s \) and whole database, which are representative for the whole range of periods. The trend lines for both types of residuals indicate that the attenuation model provides an adequate description of the phenomenon. The regression lines have small slopes and the correlation of the residuals is very small indicating the GMPE is suitable for the range of magnitudes and distances used in the study. Inter-event residuals show a limited tendency of underestimation for large earthquakes while intra-event residuals have a small tendency of overestimation for large epicentral distances. Note that the model covers epicentral distances up to 300km. Using a GMPE with quadratic term showed smaller inter-event residuals.

**4. CONCLUSIONS**

Using a database of Romanian and Japanese ground motion records, an attenuation model for spectral displacements was developed. The model is applicable for Romanian sites affected by strong ground motions originating from Vrancea intermediate-depth seismic source and located on type B and C ground types, in front of the Carpathian Arch. Two-stage regression analysis was performed in order to determine the coefficients of the GMPE. Introducing a quadratic term resulted in a better estimation of spectral ordinates for large earthquakes, but doing so, the attenuation model magnitude range of applicability is limited to \( M_w = 7.6 - 7.8 \).

Using the GMPE, the impact of magnitude, soil type and epicentral distance on the RDS ordinates was assessed. Magnitude has the largest influence on the shape and size of the displacement spectra. Increasing magnitude shrinks the zone of large amplifications. Large amplifications for large magnitude earthquakes are expected on type C sites, compared to sites located on firmer ground. The soil type has also an influence on the shape and values of the RDS ordinates. Increasing epicentral distance reduces the displacement demand and flattens the peak amplification zone. There is no relevant tendency on increasing the period corresponding to maximum amplification of RDS with increasing magnitude.

The GMPEs coefficients corresponding to set 1 (strong-moderate national records) and set 3 (whole database) were used to assess the impact of soil type and magnitude on the RDS ordinates.
database) have been determined for periods up to 4.00s, due to the presence of the analogical records. This period is considered to be the limit for which computed spectra are still reliable, given the methodology used for filtering. Pushing the model to predict displacement response for periods beyond 4.0s using digital records from Romania and Japan showed small peaks and plateaus in the range of spectral periods between 4 and 8s. The expected large peaks were not highlighted, probably, because of the relatively moderate peak magnitude of the records in this set. It is well known that stronger earthquakes tend to stimulate the response of the sediment layers at large periods, while smaller earthquakes fail to do so. The model validity was tested with good results by assessing inter-event and intra-event residuals, according to procedures available in literature.

5. ACKNOWLEDGMENTS

The authors would like to express their gratitude to National Research Institute for Earth Science and Disaster Resilience (NIED, http://www.kyoshin.bosai.go.jp/) for granting access to K-NET and Kik-net ground motion record database. We thank Cristian Neagu for his kind support on $V_{s30}$ – based site classification in Romania.

6. REFERENCES


APPENDIX

Table 1. Coefficients of the GMPE for set 1, Equation 4, ground type B.

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<th>T (s)</th>
<th>a</th>
<th>b</th>
<th>c</th>
<th>d</th>
<th>h</th>
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Table 2. Coefficients of the GMPE for set 1, Equation 4, ground type C.

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