LONG-PERIOD GROUND MOTION EVALUATION FROM A LARGE WORLDWIDE DIGITAL STRONG MOTION DATABASE

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ABSTRACT :

The reliability of long-period ground motion from digital strong motion data is first explored using records from co-located broadband and digital strong motion instruments. It is shown that displacement waveforms obtained by double integration of the accelerogram need not be free of unrealistic baseline drift to yield reliable spectral ordinates up to at least 10 s. These findings are further corroborated by considering a set of synthetic accelerograms contaminated by random long-period noise. The results of this study suggest that high-pass filtering the digital acceleration record from a cut-off period selected to suppress baseline drifts on the displacement waveform appears to be in most cases too conservative and unduly depletes reliable information on long-period spectral ordinates. Based on these results, new predictive equations for long-period ground motions are obtained and implemented in probabilistic seismic hazard analyses. To illustrate some representative results, ground motion hazard maps in terms of long-period spectral displacements for the Southern Calabrian Arc (Italy) are shown.

KEYWORDS: Attenuation relationships, digital accelerograms, displacement-based design, displacement response spectra, ground motion prediction, long-period ground motion

1. INTRODUCTION

The developments of the last decade have led to placing strong emphasis on displacement considerations and *capacity design* concepts, and the earthquake resistant design of structures has increasingly become *performance-based*. In this process, the primary descriptor of the seismic demand is the relative displacement of the structure caused by the imposed ground motion, quantified through the Displacement Response Spectrum (hereafter *DRS*). Among the different methods for *displacement-based* design proposed in recent years, the direct displacement-based design approach (Priestley *et al.*, 2007) replaces the actual structure (a nonlinear multi-degree-of-freedom system) with an equivalent linear 1 *DOF* system, in which energy dissipation due to nonlinear response is accounted for through a large (up to 30%), equivalent viscous damping factor. Since design involves the response of the damaged structure, equivalent linearization may require the determination of displacement response spectral ordinates at periods well beyond the typical 0 -to- 4 s range of current norms like Eurocode 8 (CEN, 2004). Furthermore, adequately considering long-period ground motions is fundamental for large-scale structures, such as super high-rise buildings, suspension bridges and oil-storage tanks (see e. g. Koketsu and Miyake, 2008), the number of which is rapidly increasing. At such long periods, the lack of accuracy of traditional strong motion data has long been considered as a major limitation to determine reliable displacement spectra.

As widely recognized (see e. g. Boore, 2005; Boore and Bommer, 2005), digital strong-motion accelerographs allow the recovery of ground motions at periods much longer than those allowed by analog instruments and, while removal of low-frequencies by filtering is sometimes still required, the filter cutoffs with digital data can be set so low that little information of engineering interest is lost (see below and Paolucci *et al.*, 2008). This has been hailed by Boore (2005) as the basis for *"a new era in engineering seismology"*, characterized by the possibility of recovering reliable long-period ground motions from digital recordings.

With few remarkable exceptions (e. g. the work by Tolis and Faccioli, 1999, and Faccioli *et al.*, 2004 on *DRS* at long periods), the previous findings have been only scarcely translated into practice till today. That is, even the most recent empirical prediction equations for spectral ordinates either cover a limited range of vibration periods (see e. g. Akkar and Bommer, 2007), or are poorly constrained (PEER, 2007), or are plainly unreliable

(e. g. Berge-Thierry *et al.*, 2003) at long periods. This is mainly (but not only) due to the massive and penalizing high-pass filtering applied in the processing of analog accelerometer data.
With this background, we illustrate herein a new set of empirical prediction equations for *DRS* ordinates, aimed at overcoming the previous restrictions. We start from the results of Cauzzi and Faccioli (2008) and explore the dependence of predicted *DRS* on the upper and lower magnitude (M_W) bounds of the reference dataset. Furthermore, since the use of the focal distance R (km) as predictor variable could be questionable in the near field of large earthquake sources, we introduce prediction equations that use the fault distance R_f, i.e. the distance from the site to the ruptured fault. The said equations are easily introduced in computational tools for probabilistic seismic hazard analysis, such as the CRISIS2003 (Ordaz *et al.*, 1991) computer program. The results are displayed as spectral displacement hazard maps, with particular attention to a high seismicity zone in Southern Italy (Southern Calabrian Arc). Prior to that, the reliability of long-period spectral ordinates from digital accelerograms is briefly discussed in the next Section.

2. ON THE RELIABILITY OF LONG-PERIOD SPECTRAL ORDINATES FROM DIGITAL ACCELEROGRAMS

Relying on doubly integrated displacement traces free from unrealistic baseline drifts has generally been regarded as a pre-requisite for accurate processing of strong motion records at long periods. This stems, however, from the untested assumption that physically unrealistic trends should be removed from the velocity or displacement traces, before long-period spectral displacements are computed. Feeling that this assumption may be overly restrictive, some available examples (see also Jousset and Douglas, 2007) of earthquake ground motions recorded by co-located digital strong motion (SM) and broadband (BB) instruments were investigated by Paolucci *et al.* (2008). They used (1) data from the M_W 4.5 Vallorcine earthquake (September 8 2005, France – Switzerland border), recorded in NW Italy at about 17 km epicentral distance R_E, and (2) a larger set of data made available by the Mexican National Seismological Survey (www.ssn.unam.mx). All the cited data were simultaneously recorded at the same sites by a triaxial BB seismometer and by a triaxial digital accelerometer. The example of Figure 1 is representative of the worst cases, for which Paolucci *et al.* (cit.) could not find a suitable baseline correction (hereafter BC) procedure for generating a physically sound displacement waveform. Nevertheless, the spectral ordinates practically coincide up to 10 s and are in good agreement up to over 20 s.

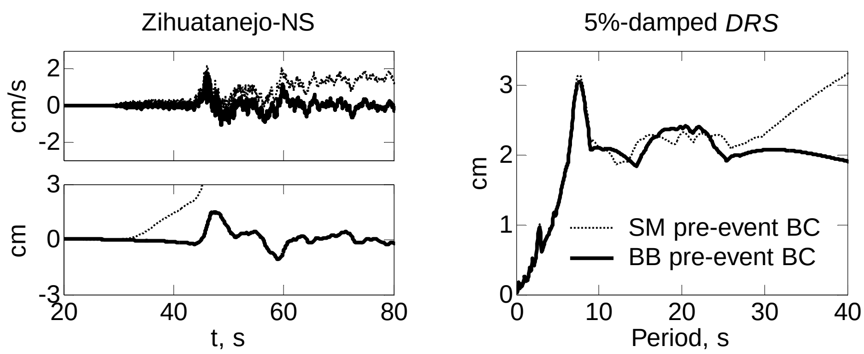


Figure 1 Comparison of velocity and displacement time histories (lhs) and 5%-damped *DRS* (rhs) obtained by Paolucci *et al.* (2008) for the Zihuatanejo record (NS component) of the Jan 11, 1997 Michoacán earthquake (M_W 7.1, R_E = 143 km).

To decide whether, and in which period range, the correction of records at long periods may alter the spectral displacements, Paolucci *et al.* (cit.) applied to the previous records, in addition to a trivial pre-event BC procedure, 4th order acausal filters (Boore and Bommer, 2005), with cutoff frequency f_C = 0.05 and f_C = 0.1 Hz, respectively. After processing, the geometric average of the *DRS* of the horizontal components of each SM record was calculated, along with the ratio with respect to the corresponding average BB unfiltered spectral ordinates. Both pre-event BC records and those filtered with T_C = 20 s showed a nearly flat spectral ratio, demonstrating a negligible influence of the long-period noise on the spectral ordinates. The spectral ratios for the 10 s filtered records tended to decay on average after 6 - 7 s, with few exceptions. Similar results were found for the vertical components. Thus, the results showed that the common high-pass filtering of digital acceleration records from a cutoff period selected to avoid baseline drifts on the displacement traces is in most cases too conservative and unduly depletes long-period spectral ordinates of physically meaningful information.

Due to the scarcity of co-located SM and BB records available for the analyses, Paolucci *et al.* (cit.) extended their study through the use of synthetic accelerograms, for the purpose of discriminating between the target correct spectrum, and the spectrum affected by long-period noise. A noise index I_V (based on the velocity time history) associated to each accelerogram was introduced and related to the probability of observing a certain level of long-period noise in the displacement spectra. Since I_V can easily be calculated not only on the synthetic contaminated accelerograms, but on real accelerograms as well, the described procedure was applied to a worldwide digital strong motion database consisting of about 1300 triaxial records (see Faccioli *et al.*, 2007). By applying a simple pre-event BC procedure, 54% of the whole dataset was found to be reliable up to long periods. Furthermore, high-pass filtering with T_C = 20 s all the records in the database sufficed for the noise index to become so small that all records in the dataset could be considered reliable up to 10 -12 s at least.

3. A WORLDWIDE DIGITAL DATABASE FOR *DRS* PREDICTION UP TO VERY LONG PERIODS

Following Paolucci *et al.* (cit.), Cauzzi and Faccioli (2008) assembled a database containing only spectra having a probability $P \geqslant 0.9$ of the long period ordinate drifts to be less than 15%. To satisfy this criterion, the simple removal of the acceleration offset calculated on the pre-event window of the digital records, proved to be sufficient for 57% of the data. For the remaining data, high-pass filtering both horizontal components of each record with a T_C = 20 s cutoff made the noise index small enough to result in a probability > 90% for the influence of long period noise on the *DRS* ordinates to be within about 15%. A substantial effort was made to reliably classify the majority of stations in the database according to the four main Eurocode 8 (CEN, 2004) ground categories, though few stations with unknown site conditions were retained in the dataset.

The key resource for creating the database were the data from the Japanese K-net network (www.k-net.bosai.go.jp), because of the high quality and uniformity of the available accelerograms and the detailed information provided for each recording site. This made K-net the largest contributing source to the dataset, while the rest of accelerograms were from California, Europe, Iran, and Turkey. The most uniform possible coverage of the data space was sought in terms of the main predictor variables of *DRS*, i. e. magnitude and distance. Thus, non Japanese data were mainly used to cover those magnitude and distance intervals where the Japanese data available were not considered sufficient. The Iran data were taken from the Iran Strong Motion Network, ISMN (www.bhrc.ac.ir/ISMN/Index.htm). For California earthquakes data available from the USGS National Strong-Motion Project, NSMP (nsmp.wr.usgs.gov) were mainly used and, for the 1999 Hector Mine event, digital data from the Engineering Strong Motion Data Center, CISN (www.quake.ca.gov/cisn-edc) and from the Southern California Seismic Network, SCSN (www.scsn.org). Concerning Europe and Turkey, most records came from the strong-motion data archive at the Imperial College of London (Ambraseys *et al.* 2002; www.isesd.cv.ic.ac.uk/ESD). The resulting database consisted of about 1160 3-component acceleration records (from 60 earthquakes), of which 84% from Japan, 6% from Iran, 5% from the United States, 5% from Europe and Turkey. All data were entered in the database in the form of uncorrected acceleration time histories and subsequently processed as previously described, with the exception of 9 accelerograms of the 1980 Irpinia (Italy) M_W 6.9 earthquake, which are the only analog recordings present in the database and were inserted in it only after a careful scrutiny of their long period characteristics.

The use of analysis of variance (see e.g. Douglas, 2007) and the deterministic comparisons with other recent studies in Europe and in the United States documented in Cauzzi and Faccioli (cit.) showed that the evidence of regional dependence of the *DRS* ordinates is very weak. These results lend strong support to the use of worldwide data, predominantly from Japan, to derive *DRS* attenuation relationship for a European region, such as Italy, where the available digital data are not enough to develop a reliable prediction model over a broad period range. In addition to the above explanation, the main characteristics of the dataset are selectively summarized as follows: (i) selection of crustal (focal depth < 22 km) earthquakes worldwide; (ii) $5.0 \leqslant M_W$

⩽ 7.2 range (see also Faccioli *et al.*, 2007); (iii) focal mechanism classification according to Boore and Atkinson (2008); (iv) exclusion of subduction zone events; (v) use of the focal (hypocentral) distance, R, as the source-to-site distance measure (R < 150 km); (vi) use of both V_{S30} and ground type classes as predictor variables.

The previous database (available also at progettos5.stru.polimi.it) is enlarged in the present study in order to test the sensitivity of the predictions to the lower and upper magnitude bounds of the reference dataset (see also Bommer *et al.*, 2007). The extended version of the database contains about 1630 three-component records from 77 earthquakes worldwide: 75% of the additional data are from Japan, 9% from Europe and the Middle-East, and 16% from Taiwan. The extended dataset includes well known events, such as the 1999 M_W 7.6 Izmit (Turkey) earthquake, the 1999 M_W 7.6 Chi-Chi (Taiwan) mainshock and the very recent M_W 6.9 Iwate (Japan) 2008 event. Focusing on the 5%-damped horizontal *DRS*, the following question will be answered: how much are the median *DRS(T;5%)* for (say) M_W 6 affected, if the lower magnitude bound of the reference dataset is decreased to 4.5 and the upper one increase to 7.6? Furthermore, using a significant subset of events with well identified source geometry in the assembled database, a set of empirical relationships that uses the fault distance R_f (rather than the focal distance R) as a predictor will be introduced.

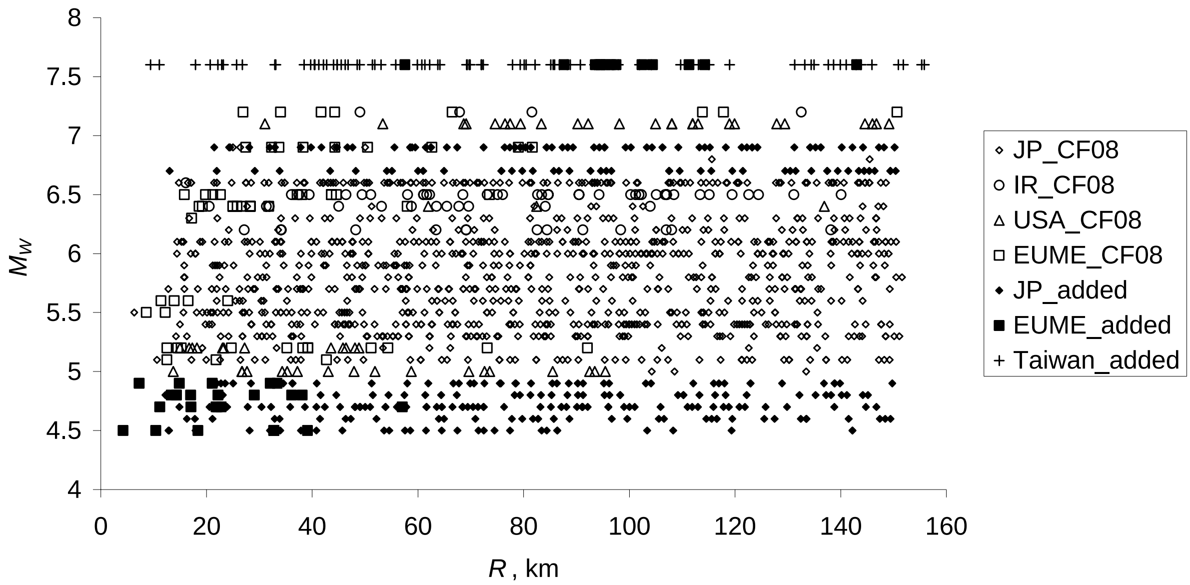


Figure 2 Distribution of magnitude, distance and geographical origin of the acceleration records in the present database. Japan (JP), Iran (IR), United States (USA), Europe and Middle East (EUME). Hollow symbols are the data already used in Cauzzi and Faccioli (2008). Note the rather uniform distribution of data with respect to magnitude and distance.

The distribution of records in terms of magnitude, focal distance and geographical origin is shown in Figure 2. Stations on ground type A are 6% of the whole database, those on type B are 45%, on type C 36%, and on type D 11%. The remaining 2% consists of Iran and California recording stations with unknown local site conditions. The reader is referred to Boore (2004), Figini and Paolucci (2008), Faccioli *et al.* (2007) and Cauzzi and Faccioli (2008) for details regarding the V_{S30} assessment of K-net data.

4. REGRESSIONS AND RESULTS

The *DRS* ordinates for damping ratios ζ = 5%, 10%, 20% and 30% were computed up to 20 s period for both horizontal and for the vertical (ζ = 5% only) component of each accelerogram, at period spacing of 0.05 s. We focus here on 5%-damped horizontal *DRS(T)*, while the reader is referred to Cauzzi and Faccioli (2008) for details regarding the prediction equations for arbitrarily damped *DRS*. The chosen long period limit of 20 s is well beyond the range needed for displacement-based design of current structures, the inelastic vibration periods of which hardly exceed 10 s. However, it is necessary to explore a very broad period range to adequately represent the *DRS* and its trends at large magnitudes. The horizontal seismic action is represented in this study by the geometric mean of the *DRS* ordinates of the two recorded horizontal components at a given period. Having found that the logarithmic transformation of the *DRS* is justified by the results of pure error analyses, the empirical equations for the prediction of the *DRS(T;ζ)* ordinates is taken in the form:

$$\log_{10}DRS(T;\zeta) = a_1 + a_2M_W + a_3log_{10}R + a_BS_B + a_CS_C + a_DS_D + \varepsilon \qquad (4.1)$$

where T(s) is the vibration period, ζ is the damping ratio and a_i (i=1,…,D) are numerical coefficients function of period and damping ratio to be determined through regressions. ε denotes a random error term, assumed as normally distributed with zero mean and standard deviation $\sigma_{\log DRS}$. S_B, S_C, S_D are dummy variables accounting for the main ground categories contemplated in the current European Norms (CEN, 2004). The use of different functional forms, e.g. including inelastic attenuation with distance and a magnitude saturation term ($\div M_W^2$), was also explored. However, no significant improvement in the total standard error of the prediction was observed with respect to (4.1). An additional advantage of the latter is that it allows, at long periods, an immediate comparison with the far-field theoretical attenuation relation for maximum ground displacement derived by Faccioli *et al.* (2004) from the Brune's model, i. e.:

$$\log_{10}d_{max} = -4.3 + M_W - log_{10}R \qquad (4.2)$$

where $d_{\max}$ (cm) is the maximum ground displacement and R (km) the focal distance. Furthermore, the scaling with a ($\div M_W^2$) term was found to be statistically significant (α = 5%) only for T < 0.1 s and 2 s < T < 8 s and meaningless (positive from regressions) for T > 12 s. For brevity, the reader is referred to Cauzzi and Faccioli (cit.) for details on the effects of style of faulting factors and V_{S30} predictor variables. Thanks to the innovative procedure for the assessment of long-period reliability of the spectral ordinates, the whole database of Figure 2 was used for each value of the vibration period T. The results, obtained through a two-stage maximum likelihood method (Joyner and Boore, 1993 and 1994), are depicted for ground type A in Figure 3 along with the *DRS*(T;5%) predicted by Cauzzi and Faccioli (cit). The median spectral shapes predicted by (4.1) on ground type A change smoothly with M_W and exhibit the same general behaviour, i. e. a strongly increasing initial branch up to a *corner* period varying from a few s to almost 10 s (depending on magnitude and damping factor), followed by a branch that smoothly tends to the maximum ground displacement with a nearly constant or moderately decreasing trend. The spectral ordinates exhibit a ten-fold increase for a unit increase in magnitude, in general agreement with (4.2). In particular, at T = 10 s, we obtained a_1 = -4.72, a_2 = 1.07, a_3 = -0.99, a_B = 0.09; a_C = 0.20; a_D = 0.34, σ_{logDRS} = 0.26. Around their maximum value, the 5%-damped *DRS* are characterized by a "transition" over a period range that becomes wider with magnitude.

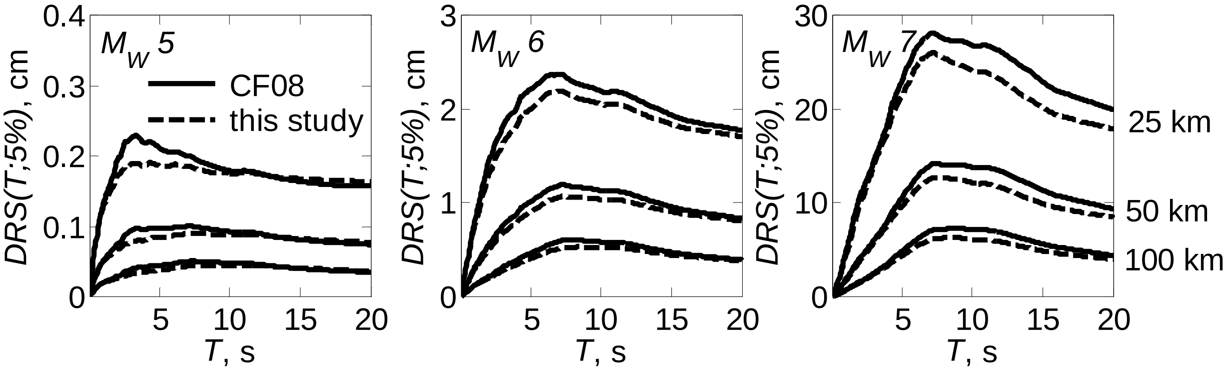


Figure 3 Median *DRS(T;5%)* predicted on rock by (4.1). The results of the present study are compared with those obtained by Cauzzi and Faccioli (2008), who used data in the 5.0 ≤ M_W ≤ 7.2 range.

As apparent from Figure 3, the differences between the present *DRS* predictions and those by Cauzzi and

Faccioli (cit.) are of minor impact, especially for M_W 5 and M_W 6, and R > 25 km. Practically negligible differences (not shown here for brevity) have been observed in the site amplification terms: this was expected since the site coefficients are determined within the first stage of the regressions, while the scaling with magnitude in the second one. These results confirm the soundness of the predictive tool and the general adequacy of the reference dataset provided by Cauzzi and Faccioli (cit.).
Nevertheless, the use of the focal distance R could be inappropriate for *DRS* prediction in the near-field, especially for large earthquakes, due to the dimensions of the ruptured fault. To overcome this possible limitation, we performed separate regressions on a significant (443) subset of data with $M_W \geq 5.9$ and with know values of R_f, the distance from the site to the ruptured fault. The prediction equation now takes the form:

$$\log_{10}DRS(T;\zeta) = a_1 + a_2M_W + a_3\log_{10}(R_f^2+h^2)^{0.5} + a_BS_B + a_CS_C + a_DS_D + \varepsilon \qquad (4.3)$$

where all the symbols have been already introduced but the saturation term h, the value of which was obtained within the first stage of the regressions. Illustrative results are shown in Figure 4 for a M_W 7 event, and three values of R_f, i.e. 5 km, 15 km and 50 km. The results yielded by (4.3) are compared in the figure with those given by (4.1), where focal distance has been converted into fault distance by using the correlation:

$$R = 10.7 + 0.99R_f \qquad (4.4)$$

proposed by Cauzzi and Faccioli (cit.).

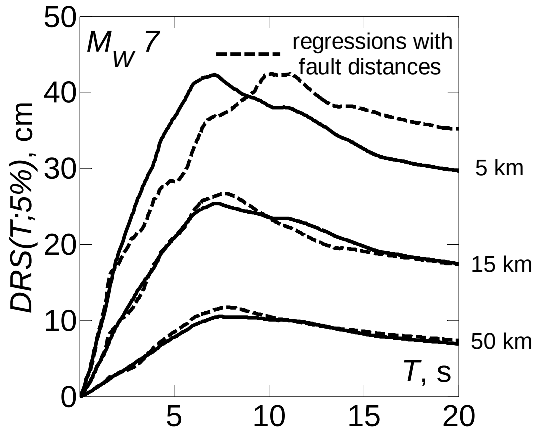
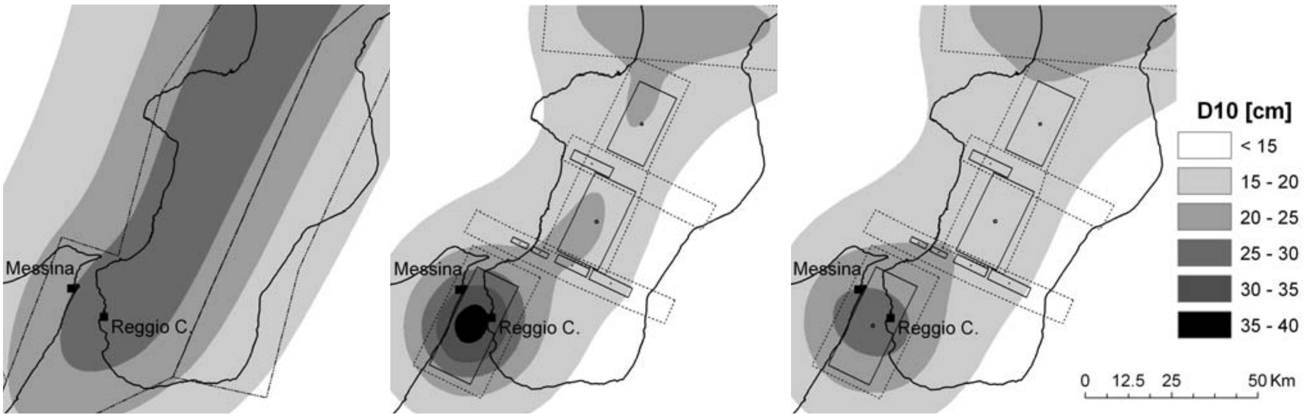


Figure 4 Comparison between the median *DRS(T;5%)* predicted on rock by (4.3), dashed curves, and those yielded by (4.1), solid curves. The focal distance R to be used with (4.1) has been converted into R_f using (4.4).

As apparent from Figure 4, (4.4) performs well, at least for M_W 7, for R_f higher than, say, 10 km. On the other hand, for R_f = 5 km, a significant difference due to the different distance measures can be observed, especially for T > 2 s.

5. HAZARD MAPS IN TERM OF SPECTRAL DISPLACEMENTS

The prediction models introduced in the previous Section have been easily (due to the simple functional forms adopted) implemented into the computer program CRISIS2003 (Ordaz *et al.*, 1991) for probabilistic seismic hazard analyses (PSHA). To illustrate some representative results, following Faccioli and Villani (2008), we show in Figure 5 ground motion hazard maps in terms of spectral displacements at T = 10 s (D_{10}) for the Southern Calabrian Arc, Italy, with 975 yr return period. The region in question includes the Messina Strait zone, which has been the seat of destructive historical earthquakes, notably the M_W 7.1 1908 event. On one hand, a conventional Seismic Source Zones (SSZs) model for Italy, the so-called ZS9 model (Meletti *et al.*, 2008), was used in Figure 5a, along with the attenuation relationship (4.1). On the other hand, an alternative representation of the main seismogenic features in terms of active faults was used in Figures 5b and Figure 5c. The latter rely on the fault database DISS3 (DISS3 Working Group, 2007; Basili *et al.*, 2008). In the region at study the ZS9 model contains the 2 source zones outlined in Figure 5a while the individual sources and seismogenic areas (SA) of DISS3 are outlined in Figure 5b and 5c. The SA (larger areas enclosed within dashed rectangles) are susceptible of a Poissonian characterization and associated to (4.1), while the smaller rectangles (with solid lines) are surface projections of faults assumed to display a characteristic earthquake behavior and associated to (4.1) and (4.3) in Figures 5b and Figure 5c, respectively.



(a) (b) (c)

Figure 5 Maps of D_{10} calculated for 975 yr return period, in the Southern Calabrian Arc, Italy: (a) based on the ZS9 model, (b and c) using the DISS3 model of individual faults and seismogenic areas, as explained in the text. The map in (c) is based on attenuation equation (4.3).

While the influence of the adopted seismic source model on the results of PSHA is beyond the scope of this study, some practical indications of interest can be gathered from Figure 5. As expected (see Figure 3), the results in Figure 5a are close to those obtained by Faccioli and Villani (2008) based on Cauzzi and Faccioli (2008), though the predicted spectral displacements are slightly lower. On the other hand, Figure 5b suggests that the spectral ordinates are likely to be overestimated in the near-field region, if an attenuation relationship using the focal distance R is associated to a 3D fault model of a large earthquake (such as the cited M_W 7.1 1908 event).

REFERENCES

Akkar, S., Bommer, J.J. (2007). Prediction of elastic displacement response spectra in Europe and the Middle East. *Earthquake Engineering & Structural Dynamics* **36:10,** 1275-1301.

Ambraseys, N., Smit, P., Sigbjornsson, R., Suhadolc, P. and Margaris, B. (2002). Internet-Site for European Strong-Motion data. European Commission, Research-Directorate General, Environment and Climate Programme, www.isesd.cv.ic.ac.uk/ESD.

Basili, R., Valensise, G., Vannoli, P., Burrato, P., Fracassi, U., Mariano, S. and Tiberti, M.M. (2008). The database of individual seismogenic sources (DISS), version 3: summarizing 20 years of research in Italy's earthquake geology. 2nd version. *Tectonophysics*, in press.

Berge-Thierry, C., Cotton, F., Scotti, O., Griot-Pomniera, D.A. and Fukushima, Y. (2003). New empirical spectral response attenuation laws for moderate European earthquakes. *Journal of Earthquake Engineering* **7:2,** 193-222.

Bommer, J.J., Stafford, P.J., Alarcón, J.E. and Akkar, S. (2007). The influence of magnitude range on empirical ground-motion prediction. *Bull Seism Soc Am* **97:6,** 2152-2170.

Boore, D.M. (2004). Estimating $V_S(30)$ (or NEHRP Site Classes) from Shallow Velocity Models (Depths < 30 m). *Bull Seism Soc Am* **94:2,** 591-597.

Boore, D.M. (2005). Long-period ground motions from digital acceleration recordings: a new era in engineering

seismology. In Gülkan, P. and Anderson, J.G. (eds) Directions in strong motion instrumentation. NATO Science Series 58. Springer Netherlands.
Boore, D.M. and Bommer, J.J. (2005). Processing of strong-motion accelerograms: needs, options and consequences. *Soil Dyn Earthquake Eng* **25**, 93–115.
Boore, D.M. and Atkinson, G.M. (2008). Ground-motion prediction equations for the average horizontal component of PGA, PGV, and 5%-damped PSA at spectral periods between 0.01 s and 10.0 s. *Earthquake Spectra* **24:1,** 93-138.
Cauzzi, C. and Faccioli, E. (2008). Broadband (0.05 to 20 s) prediction of displacement response spectra based on worldwide digital records. *Journal of Seismology* **12** (in press). DOI : 10.1007/s10950-008-9098-y.
CEN, European Committee for Standardization (2004). Eurocode 8: Design of structures for earthquake resistance – Part 1: General rules, seismic actions and rules for buildings, Bruxelles.
DISS Working Group (2007). Database of Individual Seismogenic Sources (DISS), Version 3.0.4: A compilation of potential sources for earthquakes larger than M 5.5 in Italy and surrounding areas. http://www.ingv.it/DISS/, © INGV 2007 - Istituto Nazionale di Geofisica e Vulcanologia - All rights reserved.
Douglas, J. (2007). On the regional dependence of earthquake response spectra. *ISET Journal of Earthquake Technology* **44:1,** 71-99.
Faccioli, E., Paolucci, R. and Rey, J. (2004). Displacement spectra for long periods. *Earthquake Spectra* **20**, 347-376.
Faccioli, E., Cauzzi, C., Paolucci, R., Vanini, M., Villani, M. and Finazzi, D., (2007). Long-period strong ground motion and its use as input to displacement based design. In: Pitilakis K (ed) Earthquake Geotechnical Engineering. 4th International Conference on Earthquake Geotechnical Engineering – Invited Lectures. Springer Netherlands.
Faccioli, E. and Villani, M. (2008). Seismic hazard mapping for Italy in terms of broadband Displacement Response Spectra. *Earthquake Spectra* (submitted for possible publication).
Figini, R. and Paolucci, R. (2008). Site effects at long periods from digital strong motion records of the KiK-net, Japan. *Journal of Earthquake Engineering* (accepted for publication).
Jousset, P. and Douglas, J. (2007). Long-period earthquake ground displacements recorded on Guadeloupe (French Antilles). *Earthquake Engineering and Structural Dynamics* **36:7,** 949-963.
Joyner, W.B. and Boore, D.M. (1993). Methods for regression analysis of strong-motion data. *Bulletin of the Seismological Society of America* **83:2,** 469-487.
Joyner, W.B. and Boore, D.M. (1994). Errata: Methods for regression analysis of strong-motion data *Bulletin of the Seismological Society of America* **84,** 955-956.
Koketsu, K. and Miyake, H. (2008). A seismological overview of long-period ground motion. *Journal of Seismology* **12:2,** 133-143.
Meletti, C., Galadini, F., Valensise, G., Stucchi, M., Basili, R., Barba, S., Vannucci, G. and Boschi, E. (2008). A seismic source model for the seismic hazard assessment of the Italian territory. *Tectonophysics* **450,** 85-108.
Ordaz, M., Jara, J.M. and Singh, S.K., (1991). Riesgo sísmico y espectros de diseño en el estado de Guerrero. Technical Report, Instituto de Ingenieria, UNAM, Mexico City.
Paolucci, R., Rovelli, A., Faccioli, E., Cauzzi, C., Finazzi, D., Vanini, M., Di Alessandro, C. and Calderoni, G. (2008). On the reliability of long period spectral ordinates from digital accelerograms. *Earthquake Engng Struct Dyn* **37,**697–710.
PEER, Pacific Earthquake Engineering Research Center (2007). Next Generation Attenuation of Ground Motions (NGA) Project. Web site: peer.berkeley.edu/products/nga_project.html
Priestley, M.J.N, Calvi, G.M. and Kowalsky, M.J. (2007). Displacement –based seismic design of structures, IUSS Press, Pavia.
Tolis, S.V. and Faccioli, E. (1999). Displacement design spectra. *Journal of Earthquake Engineering* **3:1,**107–125.