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Displacement damping modification factors for pulse-like and ordinary records

Fabrizio Mollaioli *, Laura Liberatore, Andrea Lucchini

Department of Structural Engineering and Geotechnics, "Sapienza" University of Rome, Via Gramsci, 53, 00197 Rome, Italy

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A B S T R A C T

In seismic codes, elastic response spectra are usually defined by assuming a conventional value for the critical damping ratio equal to 5%. damping modification factors (*DMF*s), i.e. scaling factors, are then applied to account for the effect of damping values higher or lower than the nominal 5%. Usually, code-mandated *DMF*s depend neither on ground motion characteristics nor on structural properties. However, the influence of such factors on the *DMF* was highlighted by different studies.

In this paper, records from 110 near-fault pulse-like ground motions and 224 ordinary ground motions are used to calculate elastic displacements and *DMF* spectra corresponding to different values of the damping ratio ranging from 2% to 50%. The effect on *DMF*s of pulse period of the ground motion, earthquake magnitude, site-to-source distance, and period of vibration of the structure is discussed. By rotating the pulse-like records according to different directions with respect to the fault, including the fault-normal and the fault-parallel one, the influence of the angle of rotation is also investigated. Based on results of regression analyses, equations for the prediction of the *DMF* for near-fault pulse-like ground motions are finally proposed.

1. Introduction

The development of performance-based seismic engineering brought to a growing interest in the definition of displacement response spectra (e.g. see [1–4]). In the performance-based philosophy, in fact, the design criteria are expressed in terms of achieving different performance objectives for different levels of seismic hazard [5,6]. Such objectives may be related to damage levels which in turn may be associated to displacement demands. In this case, differently from conventional force-based seismic design procedures, seismic actions are defined using displacement spectra rather than pseudo-acceleration spectra. If an equivalent linear system is used to model the structure (e.g. see [7–9]), then an equivalent damping value and effective period of vibration must be identified and the displacement demand calculated with a simple elastic spectrum. Moreover, in case of structures protected with base isolation systems or supplementary damping devices, response spectra corresponding to high damping levels have to be defined. Even though the energy dissipation characteristics of isolation and damping devices may not be ideally viscous, also for this type of structures equivalent linear models can be used to evaluate with different degrees of accuracy the seismic demand [10].

Elastic spectra with damping ratios different from 5% are usually derived from the conventional 5%-damped response spectrum by applying a simple scaling factor that is usually named damping modification factor (*DMF*). Starting from the '80s, many different equations have been proposed for the *DMF* (e.g. [11–13]), and some of them have been also adopted in seismic code provisions and guidelines, as highlighted by Lin et al. [14] and Cardone et al. [15]. Often, the *DMF* is given by codes as a function of the damping ratio only. However, various studies showed that different parameters, e.g. period of vibration, magnitude of the earthquake, site conditions and distance from the fault, may affect, to different extents, the *DMF* [16–18].

It is well known that at locations close to the fault, forward directivity may produce large-amplitude velocity pulses, which may affect the response of structures [19–25]. In particular, Priestley [26] observed that in the presence of velocity pulses the effectiveness of damping might be reduced. On the other hand, Hatzigeorgiou [27] found that *DMF* evaluations using near-fault and far-fault ground motions lead to similar results. In the present study, a review of the state of the art on *DMF* is made and the main parameters influencing its value are identified. Then, records from 110 near-fault pulse-like ground motions and 224 ordinary records are used to calculate elastic displacement spectra and *DMFs* corresponding to seven different values of damping ratio equal to 2%, 5%, 10%, 20%, 30%, 40% and 50%. The influence on *DMF* spectra of

* Corresponding author. Tel.: +39 06 49919186.
E-mail address: fabrizio.mollaioli@uniroma1.it (F. Mollaioli).

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pulse period of the ground motion (for pulse-like records), earthquake magnitude and site-to-source distance (for ordinary records), and period of vibration is discussed. For the case of the pulse-like records, components corresponding to different angles with respect to the fault direction are considered. Finally, based on results of regression analyses, an equation for the estimation of the *DMF* for pulse-like ground motions is proposed, and predictions are compared with those obtained using models developed by other researchers.

2. Factors influencing the *DMF*

Reduction of spectral ordinates due to damping is influenced by various factors [28]. In this section, a state of the art review on the main parameters that have been found to affect the *DMF* is reported. The influence on *DMF* of period of vibration of the structure, earthquake magnitude, ground motion duration and number of cycles, distance to the fault, site condition and near-fault condition is presented and discussed here.

In the studies cited below, the *DMF* is estimated based on displacement or pseudo-acceleration spectra, with the exception of the study of Lin and Chang [16] in which both pseudo-acceleration and acceleration spectra are considered, and that of Hatzigeorgiou [27] where *DMF*s are evaluated from acceleration, velocity and displacement spectra. More insight into this issue is provided at the beginning of Section 4.

2.1. Period of vibration

Due to the specific properties of the elastic response spectra, at very short and very long periods the effect of viscous damping is not significant. At very short periods, in fact, the pseudo-acceleration response of an elastic SDOF system tends to the Peak Ground Acceleration (PGA) whereas the displacement response points toward zero; at long periods, instead, the displacement response tends to the Peak Ground Displacement (PGD) while the pseudo-acceleration reduces almost to zero. Therefore, it is expected that in the range of very short and very long periods the *DMF* value tends to unity. On the contrary, the most significant influence of damping is in the intermediate period range.

Several studies (e.g. [17]) report that at periods ranging between approximately 1 s and 3 s the *DMF* varies slightly. In general, the range within which the *DMF* value strongly depends on the period extends with the increase of the damping ratio. Cameron and Green [18] estimated that for rock sites, magnitude in the range of 5–6, and period of vibration equal to 0.5 s, the mean value of the *DMF* is equal to 0.961 and 0.808 for $\xi = 7\%$ and 30%, respectively, whereas it is equal to 0.935 and 0.643 for a period of 1.5 s. This finding indicates that for small to medium magnitudes the influence of period on the *DMF* should be accounted for, at least for higher damping values. For larger earthquakes, the effect of period is less marked especially in the intermediate period range.

2.2. Magnitude, duration and distance from the fault

The strong influence of magnitude on the *DMF* was recognized by different researchers. In general, the effect of damping is more pronounced for large earthquakes [17]. However, this trend is well-defined only for periods greater than 0.5 s, whereas for shorter periods the opposite may occur [18]. An indirect correlation between *DMF*, magnitude and focal distance is given by the following equation suggested by Rosenblueth [29]:

$$DMF(\xi, T, D) = \frac{\left(1 + 4.93\xi \frac{D}{T}\right)^{-0.41}}{\left(1 + 4.93 \times 0.05 \frac{D}{T}\right)^{-0.41}} \quad (1)$$

where *D* is the duration in seconds estimated as a function of magnitude and focal distance.

More recently Bommer and Mendis [17] observed that the influence of magnitude and distance may be taken into account by considering the effect of the duration (or of the number of cycles). Based on this observation Stafford et al. [30] developed the following model to evaluate in the period range 1.5–3.0 s the *DMF* as a function of duration or number of cycles:

$$DMF(\xi, x) = 1 - \frac{\beta_1 + \beta_2 ln(\xi) + \beta_3 ln(\xi)^2}{1 + exp\left[-\frac{ln(x)+\beta_4}{\beta_5}\right]} \quad (2)$$

In Eq. (2), the variable x is either the significant duration or the number of cycles, and β_i are coefficients whose value depends on the used predictor variable. A comparison between the *DMF* calculated with Eq. (1) (for $T = 1.5$ s) and Eq. (2) (with x equal to the significant duration from 5% to 75% of the Arias Intensity) is presented in Fig. 1. Even though the definition of duration is different in the two models, a very good match can be noted when the damping ratio is equal to 10%; differences between the two models increase with increasing damping. In both cases the influence of duration seems to be negligible when the duration is greater than about 20 s.

As observed by Stafford et al. [30], the duration of motion (or the number of cycles) is an important parameter affecting the *DMF*. However, the direct inclusion of duration in a prediction model is not practical because duration is not generally specified in earthquake design scenario. Therefore it seems more convenient to capture the effect of duration implicitly, through the use of other predictor variables such as magnitude and distance [31].

2.3. Site conditions

The effect of site conditions was deeply investigated by Cameron and Green [18]. They considered two different databases: one representative of earthquake motions in active seismic regions and one representative of motions in stable continental regions. The accelerograms used in the study were grouped according to the site classification (rock or deep soil). For motions in active seismic regions little influence of site condition on *DMF* was found at all the investigated periods (ranging from 0 s to 10 s), whereas a greater effect was noted for motions in stable continental regions but only at periods $T \leqslant 0.2$ s. In the latter case, the effect of soil conditions increases with increasing magnitude.

According to Hatzigeorgiou [27], the *DMF* values for soil types B, C and D (corresponding to very dense, stiff and soft soil, respectively, in accordance with the USGS site classification system) are very similar, whereas for soil type A (rock) they are different.

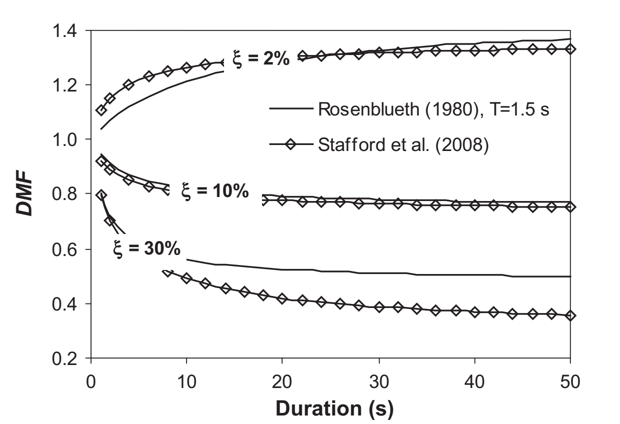

Fig. 1. Influence of duration on *DMF*, comparison between Eq. (1) (Rosenblueth [29]) and Eq. (2) (Stafford et al. [30]).