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Empirical equations for the prediction of displacement spectrum intensity and its correlation with other intensity measures

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A B S T R A C T

Displacement spectrum intensity (*DSI*), defined as the integral of a ground motion's displacement response spectrum from 2.0 to 5.0 s, is proposed as an indicator of the severity of the long period content of a ground motion. It is demonstrated how the distribution of *DSI* can be predicted using existing ground motion prediction equations for (pseudo) spectral accelerations, which is necessary for it to be a useful intensity measure (IM) in either probabilistic or deterministic seismic hazard analysis. Empirical correlation equations between *DSI* and other common ground motion IMs are developed for active shallow crustal earthquakes using a dataset of ground motions from active shallow crustal earthquakes. The ability of *DSI* to account for near-source ground motions exhibiting forward directivity, potentially damaging far-source long-period ground motion, and its use with other spectrum intensity parameters to characterise short, medium, and long period severity of ground motions is discussed. The developed ground motion prediction and correlation equations enable *DSI* to be utilised in rigorous ground motion selection frameworks such as the generalised conditional intensity measure (GCIM) approach.

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1. Introduction

Recently there has been a significant increase in the perceived importance of long period ground motions, both because of the increasing number of critical structures which are sensitive to such aspects of ground motions (e.g. high-rise buildings, tall and long-span bridges, dams, and containment tanks, among others), and also an improved scientific understanding of how such long period ground motions are generated.

Long period ground motions are known to apply severe seismic demands to structures in the near-fault region, primarily as a result of so-called forward directivity source effects [1–4]. In addition, the long period content of ground motions exhibit less anelastic attenuation and wave scattering than the short period content, and potentially significant amplification of these motions in sedimentary basins makes such motions also damaging at very large distances. The damageability of such long period motions has been both witnessed in historical events [e.g. 5,6], and is expected to occur in future events based on findings from analytical and experimental investigations [e.g. 4,7].

For the purposes of probabilistic seismic performance assessment, ground motions which are used in seismic response analysis are typically quantified via the use of a single ground motion intensity measure (IM) [8,9]. The common use of a response spectral ordinate (either pseudo-acceleration, velocity, or displacement) [10] at a single vibration period provides one approach to characterise long period ground motion intensity, but requires the specification of a single vibration period. The specification of such a period is problematic as it is well recognised that: (i) the determination of the fundamental period of structures cannot be precisely estimated; and (ii) in addition to the response spectral ordinate at the fundamental (elastic) period of a structure, response spectral shape [11] (i.e. the response spectral intensity at other similar vibration periods) is also important in influencing structural response due to the effects of higher modes and lengthening of the equivalent (secant) fundamental period due to inelastic behaviour. Therefore, rather than using response spectral ordinates for a specific vibration period, it may be desirable to have an average measure of the severity of a ground motion to structures which are sensitive to long period vibration.

This manuscript defines a new ground motion intensity measure (IM), displacement spectrum intensity (*DSI*), as the integral of a ground motion's displacement response spectrum from 2.0 to 5.0 s, as an indicator of the severity of the long period content of a ground motion. Firstly, an analytical methodology for the prediction of *DSI* using existing ground motion prediction equations for

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(pseudo) spectral accelerations is presented. Secondly, empirical correlation equations between *DSI* and other common ground motion IMs are developed based on ground motion records from the Next Generation Attenuation (NGA) database [12]. Finally, discussion is given to the ability of *DSI* to account for velocity pulses from ground motions exhibiting forward directivity, and its use with other spectrum intensity parameters.

2. Definition and prediction of displacement spectrum intensity

2.1. Definition of displacement spectrum intensity, DSI

In order to develop a ground motion intensity measure (IM) representing the severity of the long period content of a ground motion, it is necessary to have a measure which accounts for such long period intensity in an average sense, rather than a more specific measure which may be appropriate for only a small proportion of ground motions. Similar to acceleration spectrum intensity, *ASI* [13], and (Housners) spectrum intensity, *SI* [14], which represent the severity of the short and moderate period content of a ground motion, respectively, displacement spectrum intensity, *DSI*, is defined here as the integral of the displacement response spectra of a ground motion. Specifically:

$$DSI = \int_{2.0}^{5.0} Sd(T,5\%)dT \approx \sum_{i=1}^{n} w_i Sd_i \tag{1}$$

where $Sd_i = Sd(T_i, 5\%)$ is the 5% damped spectral displacement at vibration period T_i, n is the number of periods (from 2.0 to 5.0 s) that Sd is computed at, and w_i is integration weights which depend on the integration scheme and vibration period discretization used. It is to be noted that the adopted limits of integration of T are intended to capture specific features of long period ground motion severity, including that due to forward directivity, as well as attempting to be not strongly correlated with *ASI* and *SI* (which, as previously noted, are proxies for short and moderate period severities). These specific features, and hence the logic behind the selection of these integration limits is elaborated upon in later sections. It is worth noting that the phrase "long-period ground motion" as used herein is intended to represent the components of a ground motion with vibration periods in the range of 1–10 s, similar to the definition adopted by others [15].

2.2. Prediction of DSI from spectral acceleration predictions

In order for *DSI* to be useful as an IM in seismic performance assessments it is necessary to have a means by which the distribution of *DSI* can be predicted at a given location due to the occurrence of a specific earthquake rupture (so-called ground motion prediction equations, GMPEs). In this section, the theoretical basis behind the prediction of *DSI* using existing GMPEs for *SA* is presented. The method employed is similar to that used by Bradley et al. [16], and therefore only key features are presented herein.

In general, GMPEs for spectral accelerations, (*SA*'s), provide the median (50th percentile) spectral acceleration and an associated lognormal standard deviation. In order to compute a GMPE for *DSI*, it is necessary to make use of the non-log form for the (statistical) moments of spectral acceleration ordinates. Thus, Eqs. (2) and (3), which are the properties of the lognormal distribution, can be used to obtain the non-log moments from log-moments given by spectral acceleration GMPEs:

$$\mu_{SA} = SA_{50}\exp\left(\tfrac{1}{2}\sigma_{lnSA}^2\right) \tag{2}$$

$$\sigma_{SA} = \mu_{SA}\sqrt{\exp(\sigma_{lnSA}^2) - 1} \tag{3}$$

where SA_{50} and σ_{lnSA} are the median and lognormal standard deviation of the spectral acceleration, determined directly from *Sa* GMPEs; and μ_{SA} and σ_{SA} are the (non-log form) mean and standard deviation of the spectral acceleration, respectively.

Noting that $Sd_i = SA_i(T_i/2\pi)^2$, the mean and variance of *DSI* can then be computed from the discrete form of Eq. (1) by:

$$\mu_{DSI} = \sum_{i=1}^{n}\left[w_i \mu_{SA_i}\left(\frac{T_i}{2\pi}\right)^2\right] \tag{4}$$

$$\sigma_{DSI}^2 = \sum_{i=1}^{n}\sum_{j=1}^{n}\left[w_i w_j \rho_{Sd_i,Sd_j}\sigma_{SA_i}\sigma_{SA_j}\left(\frac{T_i T_j}{4\pi^2}\right)^2\right] \tag{5}$$

where ρ_{Sd_i,Sd_j} is the correlation between Sd_i and Sd_j, i.e. the correlation between the spectral displacements at vibration periods T_i and T_j. Note that Eqs. (4) and (5) give the exact statistical moments of *DSI* (as defined by the discrete approximation in Eq. (1)), but no information on the resulting distribution.

The following relationship also exists between the correlation of log and non-log variables (e.g., Bradley et al. [16]):

$$\rho_{Sd_i,Sd_j} = \rho_{SA_i,SA_j} = \frac{\exp\left(\rho_{lnSA_i,lnSA_j}\sigma_{lnSA_i}\sigma_{lnSA_j}\right) - 1}{\sqrt{\exp\left(\sigma_{lnSA_i}^2\right) - 1}\sqrt{\exp\left(\sigma_{lnSA_j}^2\right) - 1}} \tag{6}$$

where ρ_{SA_i,SA_j} is the correlation between spectral accelerations at vibration periods i and j; and $\rho_{lnSA_i,lnSA_j}$ is the correlation between the logarithm of spectral accelerations at vibration periods T_i and T_j. Eq. (6) is useful in that several models that are available for the correlation between logarithmic spectral accelerations at different vibration periods, i.e. $\rho_{lnSA_i,lnSA_j}$ [e.g., 17,18].

Eqs. (4) and (5) give the two (non-log) moments for *DSI* and if it is assumed that the distribution of *DSI* can be adequately represented by the lognormal distribution (which is shown to be the case in the following section) then the median and lognormal standard deviation of *DSI* can be computed from rearranged forms of Eqs. (2) and (3):

$$DSI_{50} = \frac{\mu_{DSI}^2}{\sqrt{\sigma_{DSI}^2 + \mu_{DSI}^2}} \tag{7}$$

$$\sigma_{lnDSI} = \sqrt{\ln\left\{\left(\frac{\sigma_{DSI}}{\mu_{DSI}}\right)^2 + 1\right\}} \tag{8}$$

where μ_{DSI} and σ_{DSI} are obtained from Eqs. (4) and (5), respectively, and DSI_{50} and σ_{lnDSI} are the median and lognormal standard deviation (dispersion) of the displacement spectrum intensity of a ground-motion for a given scenario, respectively, which can be used directly in conventional probabilistic seismic hazard analysis (PSHA) computer programs. As elaborated by Bradley et al. [16], the principal benefit of computation of *DSI* directly from spectral acceleration prediction equations comes from the significantly advanced state of *SA* prediction equations in regard to quantification of faulting styles and site conditions, and large databases of empirical data used for their calibration [e.g., 19–21]. Thus, using Eqs. (2)–(8), state-of-the-art ground-motion predictions of *DSI* can be obtained, incorporating differences in worldwide ground-motion prediction (e.g., different tectonic regimes, site classification, etc.).

2.3. Distribution of DSI

Eqs. (7) and (8) provide the median and lognormal standard deviation of *DSI*, but do not provide any information on its

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