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ANALYSIS OF THE CORRELATION BETWEEN INSTRUMENTAL INTENSITIES OF STRONG EARTHQUAKE GROUND MOTION

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ABSTRACT

A number of parameters to assess instrumental intensity in either the frequency or in the time domain have been proposed in the past. These can be used for the scaling of natural accelerograms to define the seismic input for nonlinear analysis, or for damage potential estimations. This paper evaluates the degree of correlation between different instrumental intensity measures using a subset of a European database of natural accelerograms of strong ground motion. The degree of correlation is critically examined in terms of local site-conditions and faulting mechanism. A set of predictive equations are proposed to estimate either Arias Intensity or Cumulative absolute velocity as a function of Housner Intensity.

1. INTRODUCTION

Ground motion parameters describe characteristics of strong ground motion in quantitative form [1]. Some of these parameters can be used to assess the instrumental intensity of earthquake records. Housner Intensity [2] and Arias Intensity [3] are two good examples of instrumental intensities that have received the attention of researchers, both to describe their correlation with ductility demand [4] and in terms of the development of predictive ground motion equations[5,6].

Some ground motion parameters are associated with the frequency domain of the seismic input whereas others are with the time domain. The development of predictive equations to estimate one ground motion parameter in terms of another one is of practical interest, as this facilitates the scaling of natural accelerograms to satisfy the target instrumental intensity implicitly specified by the code.

Although a number of ground motion parameters of the time domain have been developed, so far it has not been possible to link these parameters with current seismic code provisions. Scaling procedures that can be explicitly linked to code recommendations are of practical interest. These procedures have a good balance between simplicity (in the definition of the scaling criterion) and applicability (favouring a rational use of scaled records compatible with the strength implied by the design spectrum specified by the code).

The main objective of this paper is to assess the degree of correlation between ground motion parameters considered to have a good potential for scaling in time and/or frequency domain.

2. SELECTED GROUND MOTION PARAMETERS

The ground motion parameters that were selected for this research are described below. These were considered to present a good balance between simplicity and applicability for ground motion scaling.

2.1 Housner Intensity

According to Housner [2], a precise measure of the intensity of shaking of an earthquake at a given site is given by the spectrum intensity SI_H defined by the integral :

$$SI_H = \frac{1}{2.4}\int_{0.1}^{2.5} SV(T,\xi)\,dT \tag{1}$$

where SV is the spectrum velocity curve, T is the natural period of a SDOF system and ξ is the damping ratio of the system.

It has been shown that in general there is a good correlation between Housner Spectrum intensity and displacement ductility demand [4]. This correlation is meaningful as ductility demand is a simple but at the same time very effective damage index that can be used to characterise damage potential once ductility capacity is established. Consequently, SI_H can be used as an overall measure of instrumental intensity. In view of this, recent predictive equations to estimate Housner intensity in Europe have been proposed [6]. These ground motion prediction equations estimate Housner intensity as a function of the moment magnitude, the seismic site, the distance to the fault and the style of faulting.

2.2 Arias Intensity

In order to assess the damage potential of earthquake records, Arias [3] introduced an alternative definition of instrumental intensity associated with the time domain of the seismic input. Arias intensity I_a is defined as:

$$I_a = \frac{\pi}{2g}\int_{0}^{t_d} \ddot{u}_g^2(t)\,dt \tag{2}$$

where $\ddot{u}_g(t)$ is the ground acceleration at a given time t and t_d is the total duration of the ground motion.

A recent ground motion prediction equation to estimate Arias Intensity has been proposed by Travasarau, et al. [5]. However, as acknowledged by its authors Arias intensity is of limited application in seismic structural design as it appears to correlate well with seismic demands but only for short period structures. Nevertheless, Arias intensity finds practical application in Geotechnical Earthquake Engineering as it is well correlated with liquefaction potential and slope instability triggered by earthquake ground motion.

2.3 Cummulative Absolute Velocity (CAV)

This is also a ground motion parameter specified in time domain and is given as the area under the absolute value of the ground acceleration; namely:

$$CAV = \int_0^{t_d} \left| \ddot{u}_g(t) \right| dt \tag{3}$$

CAV has been found to be well correlated with structural damage potential [1,**7**]. More recently CAV has been found to be well correlated to MSK local intensity within the range 5 to 7.5 [8]. This finding confirms the ability of CAV to correlate well with the damage potential of earthquake ground motion .

A preliminary comparison between I_a and CAV reveals that the cumulative absolute velocity treats all acceleration peaks the same, whereas in the Arias intensity higher acceleration peaks have a higher weight as the ground acceleration is squared in the integral of eqn. (2).

3. CORRELATION BETWEEN GROUND MOTION PARAMETERS

To develop predictive equations to estimate ground motion parameters for the time domain as a function of a ground motion parameter for the frequency domain, first empirical relationships between the parameters were plotted (scatter plots), then trends were identified, and finally nonlinear regression was adopted to calibrate the proposed predictive equations. For a given empirical relationship between the ground motion parameters, the degree of correlation between the parameters was assessed by the coefficient of determination R^2 of the regression.

3.1 Selected records

The family of strong motion records selected for this study are a subset of the data used by Ambraseys et al. [9] to develop predictive equations for spectral acceleration in Europe and the Middle East. The subset consists of 476 horizontal accelerograms recorded in the Greco-Italian region [10]. This was considered adequate for this preliminary study as Greece and Italy together encompass the bulk of the European seismicity. The corrected accelerograms and associated response spectra used to calculate the ground motion parameters were downloaded from the *Internet Site for European Strong-Motion Data* [11].

3.2 Observed correlations

Scatter plots were produced to observe the degree of correlation between Housner intensity and either Arias Intensity I_a or the Cumulative Absolute Velocity *CAS*. In general, the trends of the empirical relationships between ground motion parameters were sensitively linear or nonlinear, depending on the scenario under consideration. The proposed predictive equations were calibrated using nonlinear regression techniques. The truncated quadratic polynomial expressions given by equations 4 and 5 were fitted to the empirical relationships (scatter plots) between ground motion parameters.

$$I_a = A_1\, SI_H + A_2\, SI_H^2 \tag{4}$$

$$CAV = B_1\, SI_H + B_2\, SI_H^2 \tag{5}$$

where A_1, A_2, B_1 & B_2 are the fitting constants.

The regression model used in Equations (4) & (5) is rather versatile as it can work both, as a linear (when A_1 or B_1 are close or equal to zero) or as a nonlinear relationship (when all the fitting constants are different from zero). Furthermore, consistent with reality, the regression model predicts zero Housner Intensity when the parameters I_a or CAV are also equal to zero. The curve described by equation (5) showed downwards concavity; hence a regression constraint was declared to limit the fitting constants to a region consistent with a positive slope of equation (5) within the range of the observations to be fitted.

To assess the goodness of fit of the predictive equations the coefficient of determination R^2 was evaluated for every nonlinear regression. In general, it was observed that degree of correlation was a function of the ground motion parameters considered in the relationship under study, the seismic site, and the type of fault mechanism generating the ground motion.

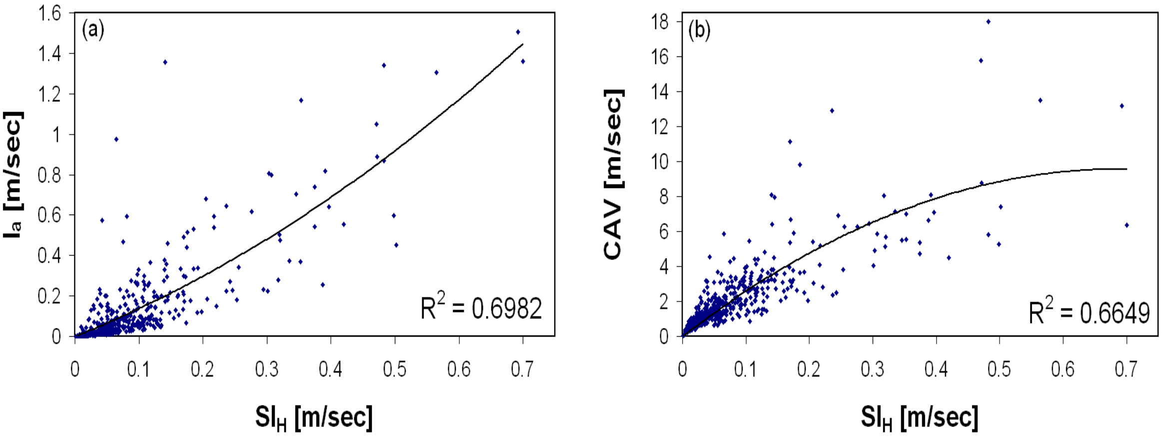

Figure 1. Correlation plots for all the accelerograms considered together

Figure 1 shows an example of the empirical relationships between ground motion parameters when all accelerograms are considered together (*i.e.* the influence of seismic site or type of faulting is neglected). In this example it is evident that I_a is slightly better correlated with SI_H than CAV is.

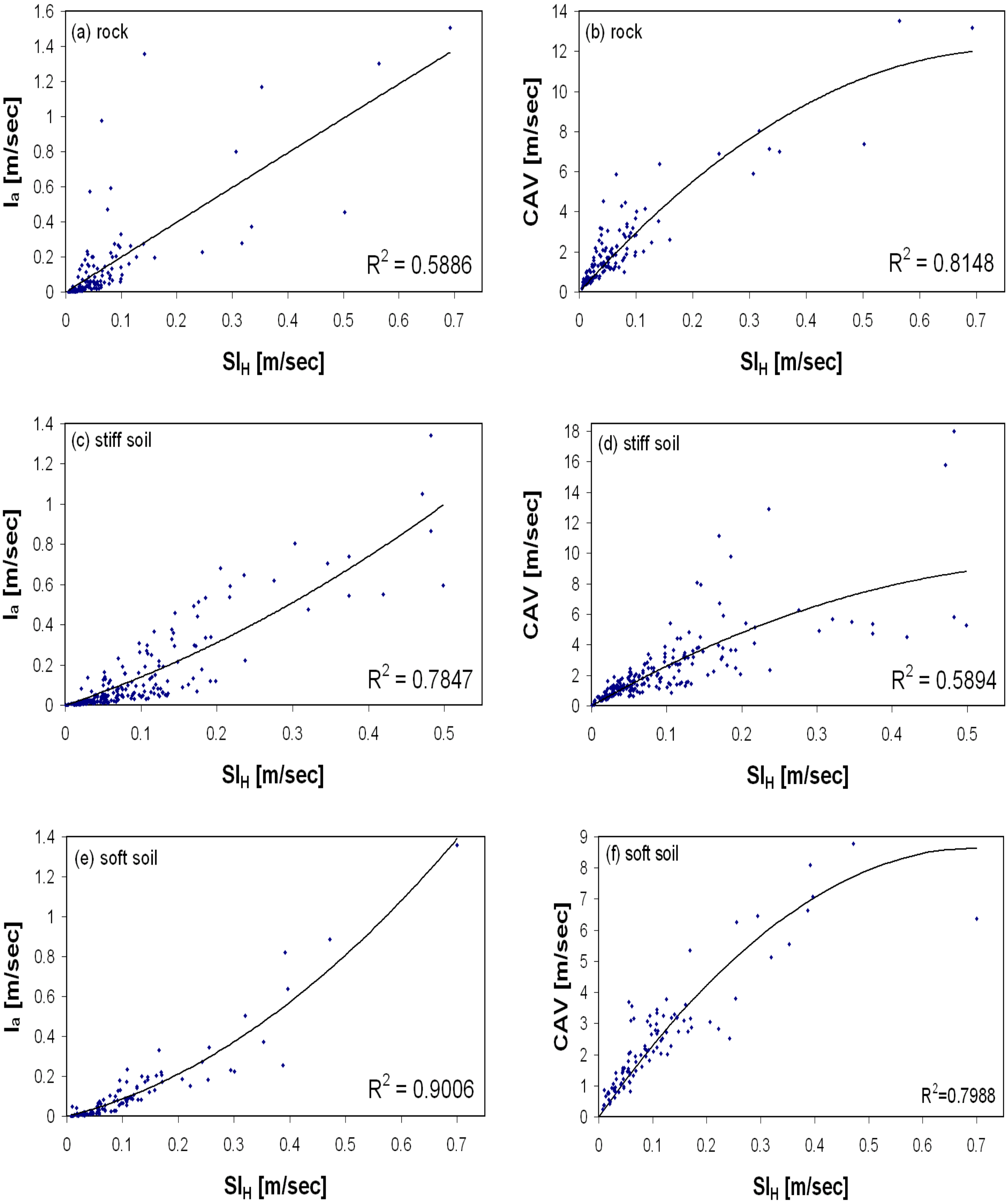

Figure 2. Correlation plots to account for seismic site

Figure 2 gives examples of the observed correlations when the influence of the seismic site is taken into account (but the influence of the faulting style is neglected). It is observed that in most cases the degree of correlation is improved when the seismic site is accounted for.

3.3 Analysis of correlation

Tables 1 and 2 summarise the results for all the nonlinear regressions (such as those exemplified in Figures 1 and 2) for all the combinations between ground motion parameters, seismic site and type of faulting. Note that Tables 1 and 2 include the ranges of variation of the observed SI_H values. Strictly speaking the proposed predictive equations should not be applied outside these ranges. The type of faulting denoted by Ambraseys et al.[9] as 'odd' was not taken into account while considering the effect of type of faulting mechanism. This is because 'odd' faulting was used by Ambraseys et al. [9] in cases where the style of faulting was difficult to assess precisely as a result of a combination of normal, thrust and strike-slip faulting.

Table 1. Predictive equations for the relationship SI_H vs. I_a

Seismic Site	Fault Mechanism	N	SI_H range [m/sec]	$I_a = A_1\, SI_H + A_2\, SI_H^2$		R^2
				A_1	A_2	
All	All	476	[0.001;0.70]	1.26	1.55	0.6982
Rock	All	146	[0.005;0.69]	2.00	-0.04	0.5886
Stiff soil	All	222	[0.001;0.50]	1.26	1.48	0.7847
Soft soil	All	108	[0.008;0.70]	0.69	1.86	0.9006
All	Normal	286	[0.001;0.69]	1.22	1.17	0.6526
All	Strike-slip	50	[0.003;0.14]	0.35	11.67	0.7870
All	Thrust	76	[0.008;0.70]	1.48	0.89	0.8164
Rock	Normal	98	[0.007;0.69]	1.93	-0.08	0.5230
Rock	Strike-slip	12	[0.005;0.10]	0.78	-0.65	0.5968
Rock	Thrust	22	[0.008;0.35]	0.96	6.22	0.9835
Stiff soil	Normal	126	[0.001;0.50]	1.22	1.57	0.7908
Stiff soil	Strike-slip	24	[0.003;0.14]	0.50	10.43	0.7847
Stiff soil	Thrust	38	[0.017;0.48]	1.41	1.08	0.749
Soft soil	Normal	62	[0.009;0.47]	0.41	2.65	0.8585
Soft soil	Strike-slip	14	[0.013;0.11]	-0.37	20.73	0.9514
Soft soil	Thrust	16	[0.019;0.70]	0.64	1.89	0.9868

Table 2. Predictive equations for the relationship SI_H vs. CAV

Seismic Site	Fault Mechanism	N	SI_H range [m/sec]	$CAV = B_1\, SI_H + B_2\, SI_H^2$		R^2
				B_1	B_2	
All	All	476	[0.001;0.70]	27.86	-20.31	0.6649
Rock	All	146	[0.005;0.69]	31.73	-22.83	0.8148
Stiff soil	All	222	[0.001;0.50]	28.26	-21.25	0.5894
Soft soil	All	108	[0.008;0.70]	24.68	-17.63	0.7988
All	Normal	286	[0.001;0.69]	27.78	-16.58	0.6705
All	Strike-slip	50	[0.003;0.14]	32.80	-35.71	0.8332
All	Thrust	76	[0.008;0.70]	22.31	-15.94	0.7406
Rock	Normal	98	[0.007;0.69]	33.98	-23.88	0.8109
Rock	Strike-slip	12	[0.005;0.10]	36.14	-174.76	0.7668
Rock	Thrust	22	[0.008;0.35]	29.91	-30.60	0.9054
Stiff soil	Normal	126	[0.001;0.50]	27.98	-17.51	0.5854
Stiff soil	Strike-slip	24	[0.003;0.14]	34.01	-45.97	0.7885
Stiff soil	Thrust	38	[0.017;0.48]	25.21	-29.40	0.6802
Soft soil	Normal	62	[0.009;0.47]	24.97	-17.83	0.7965
Soft soil	Strike-slip	14	[0.013;0.11]	32.08	-7.35	0.9422
Soft soil	Thrust	16	[0.019;0.70]	18.78	-13.96	0.8782

The influence of seismic site and type of faulting on the degree of correlation is not easy to establish because as seen in Tables 1 and 2, the number of accelerograms *N* vary for a given combination of ground motion parameters and type of ground motion (controlled by seismic site and fault mechanism).

In general, Tables 1 and 2 reveal that the seismic site has a slightly bigger effect on the degree of correlation than the fault mechanism does. It is also observed that on the average, the degree of correlation between ground motion parameters improves when both the effect of seismic site and type of faulting are taken into account.

To compare the efficiency of the ground motion parameters I_a or CAV in terms of their degree of correlation with SI_H a weighted average of the coefficient of determination R^2 was evaluated. The weighting accounted for the number of accelerograms *N* associated with the nonlinear regressions as indicated in Tables 1 and 2. It was found that the I_a correlates better with SI_H than CAV does; however, the difference in the degree of correlation is very small. In fact the weighted R^2 average values were found to be 0.72 for the SI_H *vs.* I_a relationship, and 0.70 for the SI_H *vs.* CAV relationship. In principle, this finding indicates that one could use I_a or CAV to estimate the target ground motion intensity in time domain as a function of the target SI_H specified in the frequency domain.

4. CONCLUDING REMARKS

This paper introduced a set of predictive equations to estimate cumulative absolute velocity and Arias intensity as a function of the Housner intensity. The proposed equations take into account the seismic site as well as the type of faulting. Strictly speaking, the proposed predictive equations are only applicable for the Greco-Italian region. It is also recommended that the proposed equations are used only within the Housner intensity ranges for which they were calibrated. A detailed description of the variability of the proposed predictive equations as required in probabilistic seismic hazard studies was beyond the scope of this research.

In general, it was found that both the seismic site and the faulting mechanism affect the degree of correlation between the ground motion parameters considered in the study. The seismic site has a slightly higher influence on the degree of correlation than the faulting mechanism has. It was also evident that, on the average, the Arias Intensity and the cumulative absolute velocity show nearly the same degree of correlation with Housner spectrum intensity.

More than a decade ago Martinez-Rueda [4] made the observation that ground motion parameters developed for the time domain had limited application for the scaling of natural accelerograms, if these are expected to be consistent with the design spectrum specified by the code. Results obtained in this work make the above observation no longer valid as now one can derive the target Housner intensity from the *PSA* spectrum specified by the code and then the target CAV or the target I_a can be estimated directly from the proposed predictive equations calibrated for the seismic region of interest.

By using the full dataset of earthquake records used by Ambraseys et al. [9] a more robust set of predictive equations for CAV or I_a can be calibrated for Europe and the Middle East. Such work is currently under development by the authors.

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