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RELATIONSHIP BETWEEN JMA INSTRUMENTAL SEISMIC INTENSITY AND OTHER STRONG MOTION INDICES

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ABSTRACT : The JMA (Japan Meteorological Agency) seismic intensity (I_{JMA}) and other ground motion indices (e.g., PGA, PGV, and SI) were calculated using eight hundred and seventy nine (879) three-components acceleration records. The relationships between the JMA seismic intensity and PGA, PGV, and SI were then derived performing a two-stage linear regression analysis. Results from the analysis show that the JMA instrumental seismic intensity shows higher correlation with SI than PGA or PGV, and it shows the highest correlation with the parameters such as the product of PGA and SI or the combination of PGA and SI. The obtained relationships are also compared with the ones obtained by other studies, and it may be useful for the disaster management agencies in Japan and deployment of new SI-sensors, which monitor both SI and PGA.

KEYWORDS: JMA seismic intensity, seismometer, spectrum intensity, SI-sensor, strong motion records, ground motion indices.

1. INTRODUCTION

The JMA seismic intensity (Figure 1) has been used as a measure of strong shaking for many years in Japan [1], and is used by the disaster management agencies in Japan as the most important index to estimate structural damage due to earthquakes [2]. Other ground motion indices, e.g., Peak Ground Acceleration (PGA), Peak Ground Velocity (PGV), Spectrum Intensity (SI), etc., are also used to describe the severity of an earthquake. In Japan, the SI value (Figure 2) is used as the index to shut-off the natural gas supply after a damaging earthquake. Based on the seismic records and damage of gas pipes around the instruments due to the 1995 Kobe earthquake, a SI value of 60 cm/s was set as the level of shaking for mandatory shut-off a city gas supply. In this objective, Tokyo Gas Co. Ltd. has developed an SI-sensor [3] and a new SI-sensor [4], which calculate the SI value in the sensor using horizontal acceleration records.

Hence, it is important to know the relationship between the new JMA instrumental seismic intensity and other strong motion indices (e.g., PGA, PGV, and SI). Midorikawa *et al.* [5] and Tong and Yamazaki [6] investigated the correlation between the JMA seismic intensity and physical parameters of earthquake ground motion. However, the correlation between the seismic intensity and ground motion indices might differ depending upon the selection criteria of the records, number of records used, distribution of ground motion indices, and the method of analysis. The earthquake records used by Midorikawa *et al.* [5] were recorded mostly by SMAC-B2 type accelerometers, which requires instrumental correction. The ground motion records used by Tong and Yamazaki [6] were both JMA and non-JMA records from recent earthquakes in Japan and the United States. They used 205 selected records to give wide variability in intensity; however, the selected data may be expanded to cover a wider variation in spectral intensity and durational characteristics of seismic records. In this study, the JMA seismic intensity and other ground motion indices are calculated using 879 three-components strong motion records, and the relationships between the JMA seismic intensity and PGA, PGV and SI are then derived performing a two-stage linear regression analysis.

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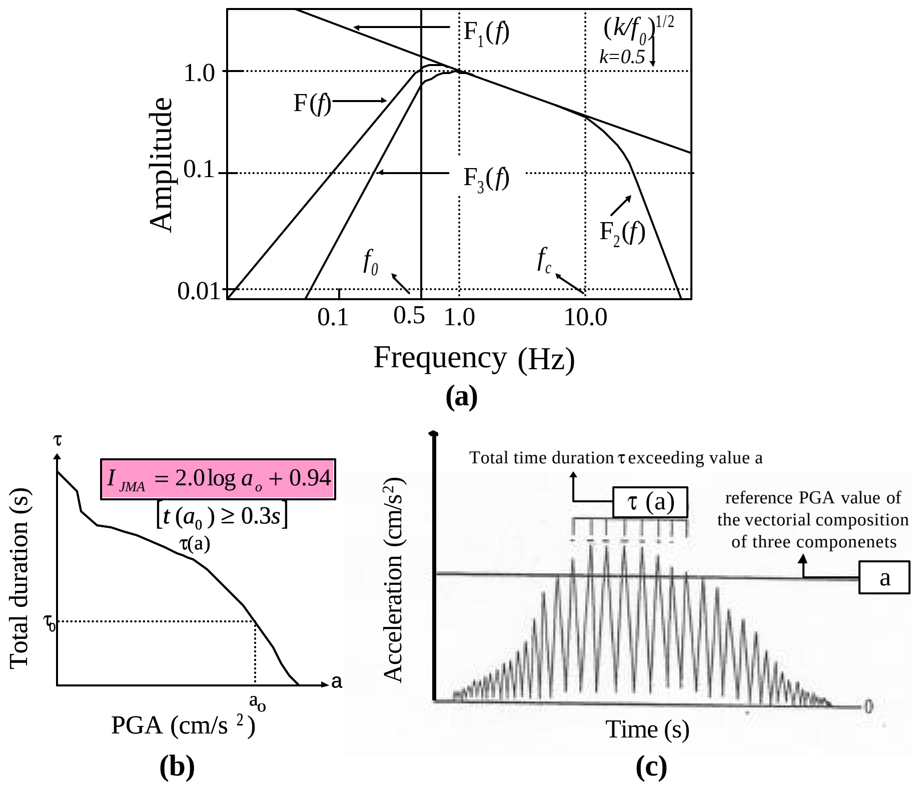


Figure 1. Calculation of JMA instrumental seismic intensity, which is obtained by (a) applying a band pass filter in the frequency domain and (b) considering the durational effect t(*a*) of *PGA,* which is obtained in the time domain by (c) summing the time segments exceeding a reference *PGA* value of the vectorial composition of the three-components of acceleration records.

2. EARTHQUAKE DATA

The earthquake data set used in this study consists of 879 three-components acceleration records selected from thirteen (13) major earthquake events that occurred mostly in Japan, two in the United States, and one in Taiwan, and the magnitude for the selected earthquake events ranges from 5.1 to 8.1. The data set of the strong motion records is limited to

1. Acceleration records only from free-field sites were selected
2. Only the non-liquefied records were included in the data set
3. Acceleration records with a PGA greater than or equal to 10 cm/s^2 in one of the horizontal components were included in the data set
4. The acceleration records include both far-field and near-field ones
5. In case of closely located stations, only one record was selected and others were omitted.

3. STRONG MOTION PARAMETERS

JMA seismic intensity

The JMA seismic intensity scale was revised recently. First, the Fourier Transform (FT) is applied for the selected time window for the three-components of acceleration time histories. Then, a band-pass filter Equation (1) is applied in the frequency domain as shown in Figure 1(a).

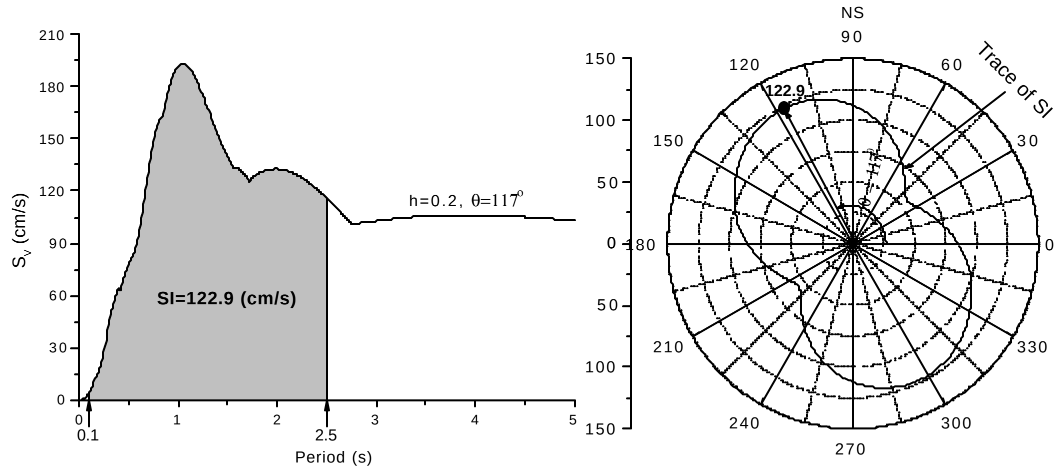
$$F(f) = F_1(f)F_2(f)F_3(f) \tag{1}$$

in which, Period-effect Filter:

$$F_1(f) = \left(1/f\right)^{1/2} \tag{2}$$

High-cut Filter:

$$F_2(f) = \left(1 + 0.694x^2 + 0.241x^4 + 0.0557x^6 + 0.009664x^8 + 0.00134x^{10} + 0.000155x^{12}\right)^{-1/2} \tag{3}$$



(a) **(b)**

Figure 2. (a) Definition of Spectrum Intensity (*SI*), which is calculated as the area under the relative-velocity response spectrum with 20% damping ratio between the periods of 0.1s and 2.5s, divided by the period interval, and (b) trace of *SI*, which is computed from the EW and NS components of acceleration records of the JMA Kobe station of the 1995 Kobe earthquake. The maximum value of *SI* is shown on the trace with a solid circle, which is obtained at q=117^0.

$$\left(x = {}^{f}\!/_{f_c}\right)$$

Low-cut Filter:

$$F_3(f) = \left(1 - \exp\left({}^{-f}\!/_{f_o}\right)^3\right)^{1/2} \tag{4}$$

After taking the Inverse Fourier Transform (IFT), the effect of the duration (τ) was considered for a vectorial composition of the three-components that is made in the time domain (Figure 1(b)). Considering an acceleration value a_0 having total duration τ satisfying $\tau(a_0) \geq 0.3$s (Figure 1(c)), the JMA seismic intensity (I_{JMA}) is calculated by using Equation (5) as a real (continuous) number

$$I_{JMA} = 2.0 \log a_o + 0.94 \tag{5}$$

Note that some of the largest intensities calculated for the 879 records used in this study are 6.44 for the JMA Kobe station of the Kobe earthquake, 6.48 for the TCU084 station of the Chi-Chi earthquake, and 6.55 for the Tarzana station of the Northridge earthquake.

PGA and PGV

The peak value for Peak Ground Acceleration (PGA) and Peak Ground Velocity (PGV) are defined as the maximum of the resultant of the two horizontal components in the directions as originally recorded and denoted by PGA_R and PGV_R

Spectrum intensity

The Spectrum Intensity (SI) is calculated as the area under the relative-velocity response spectrum with 20% damping ratio between the periods of 0.1s and 2.5s, divided by the period interval (Figure 2(a)), and it is defined as

$$SI = \tfrac{1}{2.4} \int_{0.1}^{2.5} S_v(T, h = 0.2)\, dT \tag{6}$$

where *SI* is the spectrum intensity defined as the maximum of *SI* calculated from 0 to 180 degree in the horizontal plane with one-degree interval, S_v is the relative-velocity response spectrum, T is the period, h is the damping ratio taken as 20%, and dT is the period interval taken as 0.1s. Figure 2(b) shows the trace of *SI*, which is computed from the EW and NS components of acceleration records of the JMA Kobe station of the 1995 Kobe earthquake by rotating the two horizontal components of acceleration records from 0 to 180 degree with 1-degree interval. One can see that the maximum value of *SI* is obtained as 122.9 cm/s at θ=117^0, which is shown on the trace (Figure 2(b)) with a solid circle.

4. ESTMATION OF THE JMA SEISMIC 1NTENSITY AND ITS CORRELATION WITH GROUND MOTION PARAMETERS

The JMA seismic intensity is calculated using the selected data set and the linear relationships between the JMA seismic intensity and ground motion indices are derived performing a two-stage linear regression analysis [7]. The linear relationships are derived in this study as:

$$I_{JMA} = -0.79 + 0.20M + 1.81\log_{10} PGA_R \quad (\sigma = 0.292,\ R^2=0.942) \tag{7}$$

$$I_{JMA} = 3.38 - 0.14M + 1.82\log_{10} PGV_R \quad (\sigma = 0.344,\ R^2=0.937) \tag{8}$$

$$I_{JMA} = 2.65 - 0.04M + 1.92\log_{10} SI \quad (\sigma = 0.158,\ R^2=0.982) \tag{9}$$

The relationships are also derived using other parameters, such as, the product of two ground motion indices or the combination of two ground motion indices. In this case, the relationships are derived as:

$$I_{JMA} = 1.31 + 0.01M + 0.98\log_{10}(PGA_R * PGV_R) \quad (\sigma = 0.203,\ R^2=0.975) \tag{10}$$

$$I_{JMA} = 0.87 + 0.07M + 0.98\log_{10}(PGA_R * SI) \quad (\sigma = 0.125,\ R^2=0.987) \tag{11}$$

$$I_{JMA} = 1.59 + 0.02M + 1.38\log_{10} SI + 0.59\log_{10} PGA_R \quad (\sigma = 0.104,\ R^2=0.991) \tag{12}$$

$$I_{JMA} = 1.25 + 0.01M + 0.95\log_{10} PGV_R + 1.00\log_{10} PGA_R \quad (\sigma = 0.202,\ R^2=0.975) \tag{13}$$

where I_{JMA} is the JMA intensity, M is the magnitude, PGA_R and PGV_R are the resultant of the two horizontal components, and SI is the maximum of SI calculated from 0 to 180 degree in the horizontal plane with one-degree interval. For a comparison with other studies, the relationships from Equations (7) to (13) are normalized for a magnitude of 7, and the new relationships take into the following forms:

$$I_{JMA} = 0.62 + 1.81\log_{10} PGA_R \tag{14}$$

$$I_{JMA} = 2.43 + 1.82\log_{10} PGV_R \tag{15}$$

$$I_{JMA} = 2.39 + 1.92\log_{10} SI \tag{16}$$

$$I_{JMA} = 1.38 + 0.98\log_{10}(PGA_R * PGV_R) \tag{17}$$

$$I_{JMA} = 1.36 + 0.98\log_{10}(PGA_R * SI) \tag{18}$$

$$I_{JMA} = 1.74 + 1.38\log_{10} SI + 0.59\log_{10} PGA_R \tag{19}$$

$$I_{JMA} = 1.31 + 0.95\log_{10} PGV_R + 1.00\log_{10} PGA_R \tag{20}$$

Figure 3 shows the comparison of the relationships between I_{JMA} and PGA_R, PGV_R and SI, which are obtained in this study with the ones obtained in other studies [5, 6]. It should be noted that the linear relationships obtained by Tong and Yamazaki [6] were based on the larger of the two horizontal components of the acceleration records (PGA_L, PGV_L, SI_L). To compare the results with this study, the relationships obtained by Tong and Yamazaki [6] were converted from larger to resultant of the two horizontal components using the mean ratio of larger/resultant obtained in this study. One can see that the relationship between the JMA seismic intensity and SI (Figure 3(c)) obtained in this study is very similar comparing to the one obtained by Tong and Yamazaki [6]. One can also see that the relationship between the JMA seismic intensity and PGA_R (Figure 3(a)) obtained in this study is very similar comparing to the ones obtained by Midorikawa *et al.* [5] and Tong and Yamazaki [6], however, some difference is observed with respect to PGV_R (Figure 3(b)). This difference comes might be due to the difference of the data sets and method of analysis. The data set used by Tong and Yamazaki [6] is well distributed and contains smaller values of intensity and the data set used by Midorikawa *et al.* [5] was recorded mostly by SMAC-B2 type accelerometers, which requires instrumental correction. On the other hand, the data set used in this study is well distributed, however, the range of the JMA intensity is between 1.52 and 6.55. Comparing the correlation coefficient between the JMA seismic intensity with other ground motion parameters, it is observed that the JMA seismic intensity shows the highest correlation with the combination of *PGA* and *SI* (Equation (12)), and it shows the lowest correlation with *PGV* (Equation (8)). Midorikawa *et al.* [5] pointed out that if long period contents are dominated in the records, correlation between the JMA intensity and *PGV* becomes bad. Since, some records used in this study contains long period motion, especially in the Chi-Chi earthquake records [8], the JMA seismic intensity and *PGV* has rather low correlation.

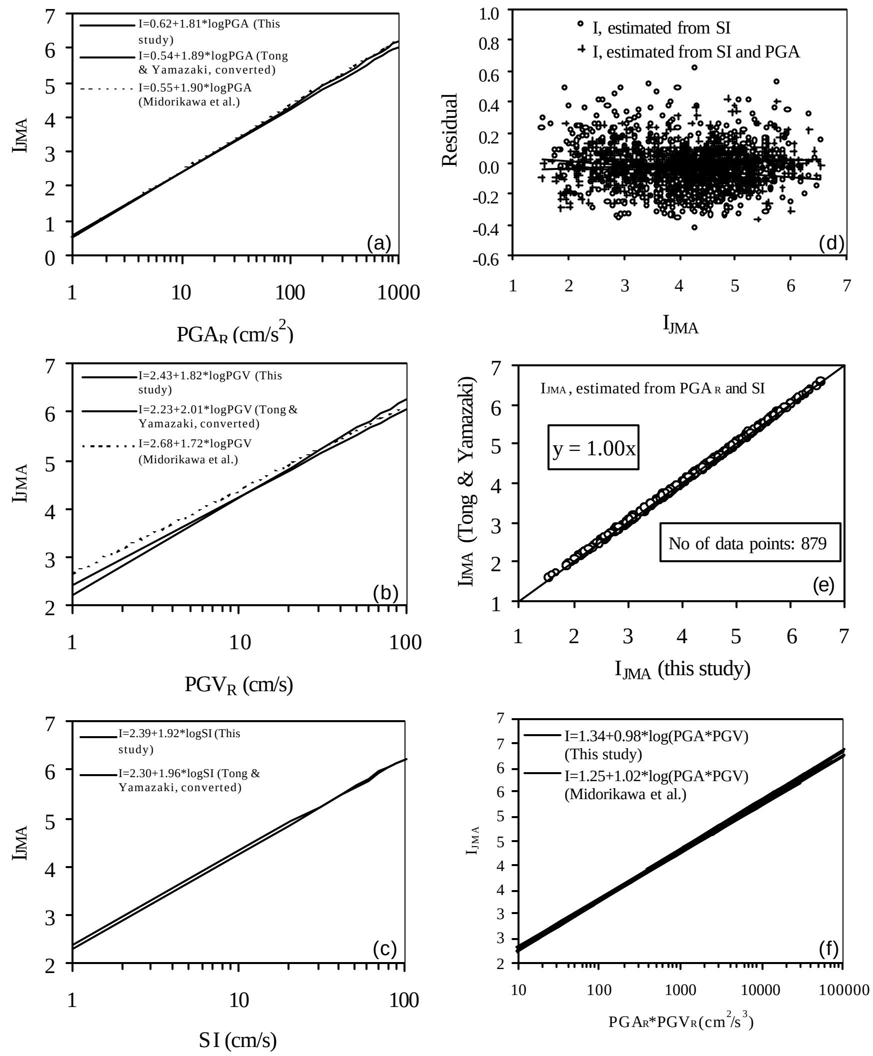


Figure 3. Comparison of the relationships between the JMA seismic intensity and ground motion indices obtained in this study with the ones obtained by other studies [5, 6]. The plots of the residuals of I_{JMA} obtained from single and multiple ground motion indices are also shown in the figure (d) at the top right corner.

Figure 3(d) shows the plots of the residuals of I_{JMA} obtained from: 1) two-stage single variable linear regression analysis, and 2) two-stage multiple variables linear regression analysis. It can be seen that the linear fit of the residuals, in the case when I_{JMA} is estimated from both *SI* and *PGA*, is more or less close to the zero line. On the other hand, the linear fit of the residuals, in the case when I_{JMA} is estimated from only *SI*, has the tendency to be away from the zero line for higher values of I_{JMA}. This clearly indicates a better estimation of JMA intensity considering more than one ground motion indices rather than single ground motion index. Figure 3(e) shows the relationship between the JMA seismic intensity estimated in this study using *SI* and *PGA* and the JMA intensity estimated by Tong and Yamazaki [6]. It can be seen that the ratio of JMA intensity estimated in this study to the JMA intensity estimated by Tong and Yamazaki [6] is 1.00. It means, the JMA intensity estimated for the two cases is the same. This good agreement was also observed in case of single ground motion index *SI* (Figure 3(c)) that is explained earlier. The JMA seismic intensity is also estimated using other parameter, such as, the product of two ground motion indices. Figure 3(f) shows the comparison of the relationship between the JMA seismic intensity and the product of *PGA* and *PGV* obtained in this study to the one obtained by Midorikawa *et al.* [5]. One can see that the relationships obtained in the both studies are very similar, however, it was observed that the JMA intensity shows higher correlation with the product of *PGA* and *SI* than the product of *PGA* and *PGV*.

5. CONCLUSIONS

The JMA instrumental seismic intensity was calculated using 879 three-components strong motion records. The relationships between the JMA seismic intensity and other ground motion indices, i.e., *PGA*, *PGV*, and *SI* were derived performing a two-stage linear regression analysis. The major findings are as follows:

1. The relationship between the JMA seismic intensity and strong motion parameters obtained in this study showed a very similarity with the ones obtained by Tong and Yamazaki and Midorikawa *et al.* with respect to both *PGA* and *SI*, however, some difference was observed with respect to *PGV*.
2. In case of single ground motion parameter, Midorikawa *et al.* concluded that JMA intensity shows higher correlation with *PGV* than *PGA*. However, in this study, it was observed that it shows higher correlation with *SI* than *PGA* or *PGV*. Moreover, it was also observed that JMA intensity shows higher correlation with *PGA* than *PGV*.
3. The relationship between the JMA intensity and other ground motion parameter such as the product of *PGA* and *PGV* shows a very similarity comparing to the one obtained by Midorikawa *et al.*, however, in this study, it was observed that the JMA intensity shows higher correlation with the product of *PGA* and *SI* than the product of *PGA* and *PGV*.
4. In case of multiple ground motion parameters, very good agreement was observed between the relationship obtained in this study comparing to the one obtained by Tong and Yamazaki, and the JMA intensity shows the highest correlation with the parameter such as the combination of *PGA* and *SI* than the combination of *PGA* and *PGV*.
5. Comparing the correlation coefficients between the JMA intensity with all strong motion parameters, it follows as: (a) the JMA intensity shows the highest correlation with the parameter such as the combination of *PGA* and *SI*, (b) it shows the second highest correlation with the parameter such as the product of *PGA* and *SI*, and (c) it shows the next higher correlation with *SI*.

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