Earthquake Engineering, Tenth World Conference © 1992 Balkema, Rotterdam. ISBN 90 5410 060 5

On the intensity measure of strong motions related to structural failures

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ABSTRACT: A problem in the time history analysis of structures is what is a good measure of the intensity of strong ground motions. The peak ground acceleration (PGA) or the peak ground velocity (PGV) is used for the measure in most cases. Although PGA is well correlated to the failure of short period structures and PGV is well correlated to that of long period structures, they are not always adequate measures over the wide range of frequencies. Another intensity measure related to a natural period of a structure is more adequate.

1 INTRODUCTION

In a structural design of tall buildings in Japan, the time history analysis using recorded ground motions is required to check the structural safety. However, there is a difficult problem in this analysis, which is what is a good measure of the intensity of strong ground motions. For example, the peak ground velocity (PGV) is used for the design of tall buildings in Japan, such as 25 cm/s for level 1 ground motion and 50 cm/s for level 2 ground motion in Tokyo. However, response velocity spectra of various recorded ground motions normalized by PGV is remarkably different. As a result of this, it seems that fundamental periods of designed buildings avoid some period range in which response values to the recorded ground motion at Taft or at Hachinohe are very large.

It is considered that a good intensity measure of the ground motion should be well related to a failure of structures. In general, the failure of a structure strongly depends on the frequencies of ground motion near its natural period. This shows that another intensity measure related to the natural period should be adequate. In this paper, the relationship between four intensity measures of the ground motion and the failure of structures is examined.

2 USED GROUND MOTIONS

Twelve recorded ground motions are used in this study and these characteristics are given in Table 1. These records are offered from Japan Building Center and are commonly used in Japan as induced ground accelerations in the time history analysis of tall buildings. Records from #1 to #4 in Table 1 are obtained in U.S.A. and records from #5 to #12 are obtained in Japan. Numerical values of PGA and PGV are given in Table 1. The values of PGV are evaluated from the maximum velocity response of a single degree of freedom (SDOF) system with a natural period of 14 seconds and a critical damping ratio of 0.707.

Numerical values of PGA vary from 25 cm/s^2 of #10 to 341 am/s^2 of #1. This wide range of intensity level is suitable for comparison of intensity measure. Velocity response spectra normalized to PGV of 25 cm/s are extremely scattered as shown in Fig. 1, which shows PGV may not necessarily be a good intensity measure.

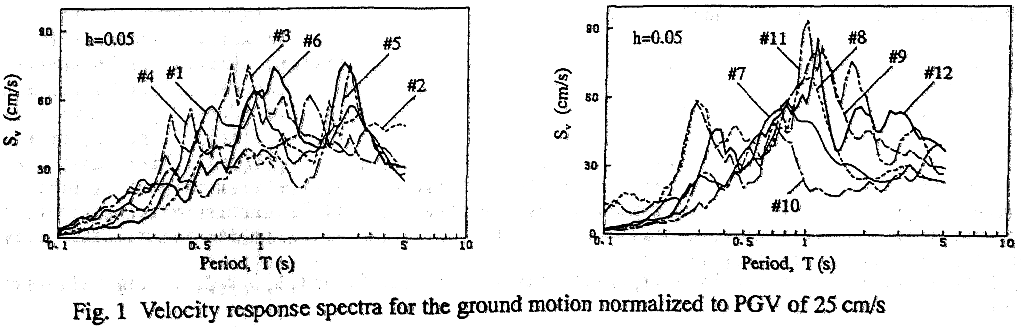

Fig. 1 Velocity response spectra for the ground motion normalized to PGV of 25 cm/s

Table 1 Used recorded ground motions

Data number #	Year Site Component		Data duration (s)	Time increment (s)	Used duration (s)	PGA (cm/s^2)	PGV (cm/s)
1	1940 El Centro	NS	53.7	0.02	30.0	341.7	34.53
2	1940 El Centro	EW	53.5	0.02	30.0	210.1	34.36
3	1952 Taft	N21E	54.4	0.02	30.0	152.7	14.51
4	1952 Taft	N69E	54.4	0.02	30.0	175.9	17.62
5	1968 Hachinohe	NS	36.0	0.01	30.0	225.0	34.06
6	1968 Hachinohe	EW	36.0	0.01	30.0	182.9	34.16
7	1956 Tokyo	NS	11.4	0.02	11.0	74.0	7.52
8	1962 Sendai	NS	14.0	0.02	14.0	57.5	3.77
9	1962 Sendai	EW	14.2	0.02	14.0	47.5	3.49
10	1963 Osaka	EW	15.0	0.02	14.0	25.0	5.22
11	1978 Tohoku Univ.	NS	40.9	0.02	30.0	258.2	39.72
12	1978 Tohoku Univ.	EW	40.9	0.02	30.0	202.6	27.67

3 DAMAGE OF A SDOF NONLINEAR STRUCTURE

In general, a degree of a damage of structures to the ground motion is evaluated by a ductility factor, μ, or a cumulative plastic deformation factor, η (Akiyama 1975). In this paper, the damage level is evaluated by these parameters of a SDOF system with a damping ratio, h, of 5% and a bilinear restoring characteristic as shown in Fig. 2. A strain hardening ratio, γ (ratio of plastic stiffness to elastic stiffness), is assumed to 0.5.

$$\mu=\frac{y_{max}}{y_y},\quad \eta=\frac{\Sigma E_p}{Q_y y_y}=\frac{\Sigma \Delta y_{pi}}{y_y},$$

where, y_{max} is the maximum displacement,
Q_y is the shear force at yielding,
y_y is the displacement at yielding,
ΣE_p is the total plastic energy stored by hysteresis loop,
$\Sigma \Delta y_{pi}$ is the total plastic deformation of hysteresis loop.

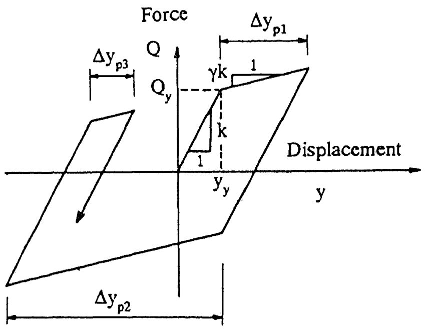

Fig. 2 Bilinear hysteresis model

In the calculation of time history analysis, a time increment, Δt, of 0.01 second is used except for near corner points of hysteresis curve, where Δt of 0.001 second is used.

Sixty-eight natural periods, T, of SDOF system between 0.1 and 5.0 seconds are selected to examine the influence of frequencies, which are equally spaced in logarithmic scale. First, numerical values of μ and η are calculated for about sixteen various values of Q_y. Next, values of Q_y that are required to reach the specified levels of failure of structures, such as μ=1, 2, 3, 4, 5 or η=0.5, 1, 2, 5, 10, are interpolated using these values. Fig. 3 shows an example of the relation between log(μ) and log(Q_y/m), where, m is a mass of a structure. This indicates they are almost a linear relationship. Fig. 4 shows an example of the relation between log(η) and log(Q_y/m). This indicates the relation is approximately a quadratic curve. Nevertheless, the interpolation equation is assumed quadratic functions for both relationships. In the figures 3 and 4, a circle means a calculated value by the time history analysis and a dotted line illustrates the interpolation function determined by the least square method. A symbol plus means the estimated values of Q_y using the interpolation function.

Fig. 5 shows examples of the nonlinear response spectra of Q_y required for μ=1, 2, 3, 4, 5, and Fig. 6 shows examples for η=0.5, 1.0, 2.0, 5.0, 10.0.

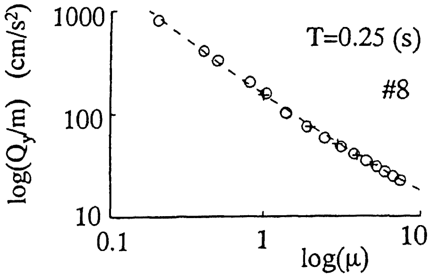

Fig. 3 The relation between log(η) and log(Q_y)

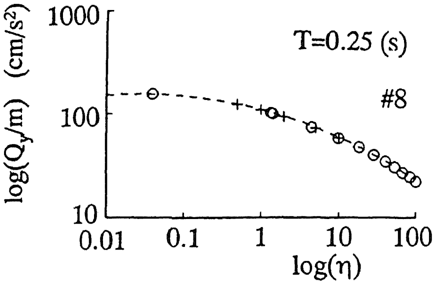

Fig. 4 The relation between log(μ) and log(Q_y)

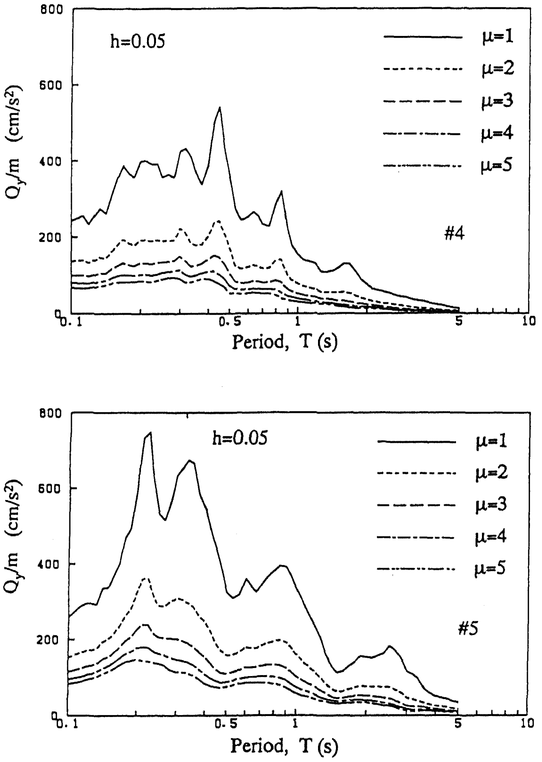

Fig. 5 Nonlinear response spectra for μ=1,2,3,4,5

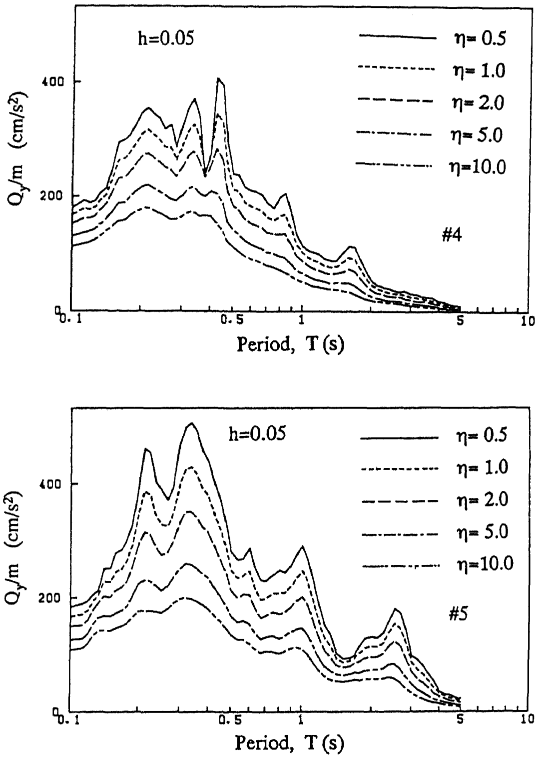

Fig. 6 Nonlinear response spectra for η=0.5,1,2,5,10

4 RELATION BETWEEN THE INTENSITY OF GROUND MOTION AND THE DAMAGE OF STRUCTURES

Following four measures of the intensity of ground motion are used to examine the correlation between the measure and the damage of structures using the time history analysis.

1) PGA : Peak ground acceleration.
2) PGV : Peak ground velocity.
3) SI : Mean velocity spectral intensity between T and 2T, where T is the natural period of a target SDOF structure with a damping ratio of 5%.
4) Ve : Mean equivalent velocity converted from the input energy, E_I, between T and 2T, where T is the natural period of a target SDOF structure with a damping ratio of 5%, and the conversion is done by $Ve=\sqrt{2E_I/m}$.

Two measures, PGA and PGV, are independent of the frequency characteristics of the ground motion. The others, SI and Ve, depend on the magnitude of the frequencies of the ground motion between T and 2T.
In this paper, the mean values of SI and Ve are evaluated by twelve values of periods between T and 2T.

Figures, 7, 8, and 9 show examples of the relation between four measures of the intensity and Q_y required to $\mu=2$ for natural period of 0.25, 0.5 and 1.0 second, respectively. In the figures, a circle indicates a value obtained from a recorded ground motion.

To clarify a degree of correlation among four measures, following linear relationship between Q_y/m and an intensity measure, X, is assumed and the correlation coefficients, r, for this relationship are calculated.

$$Q_y/m=\alpha(X+\beta) \ ,$$

where α and β are constants. α, β and correlation coefficients are given in the figures.

Tables 2, 3, 4, and 5 show the correlation coefficients between the measures and Q_y required to μ or η for target natural periods of 0.126, 0.25, 0.5, 1.0 and 2.0 second. Tables 2 and 3 are for the μ of 1 and 2, respectively. Tables 4 and 5 are for the η of 1 and 2, respectively.
From the figures and the tables, following results are obtained.

A) Relationship between Q_y and μ

1) PGA is a very good measure in short and moderate period range ($T\leq 0.5$ second), but is not so good in long period range ($T\geq 1.0$).
2) PGV is a good measure in long period range, but is not good in short and moderate period range.
3) Ve is a good measure in the wide range of period.
4) SI is a good measure in the wide range of period, but the correlation coefficient is a little lower than that of Ve.

B) Relationship between Q_y and η

1) PGA is a good measure in short and moderate period range, but is a bad measure in long period range.
2) PGV is a good measure in long and moderate period range ($T\geq 0.5$ second), but is a bad measure in short period range ($T\leq 0.25$ second).
3) Ve is a very good measure in the wide range of period.
The correlation coefficient is higher than that in the case of μ.
4) SI is a good measure in the wide range of period, but the correlation coefficient is a little lower than that of Ve.

It is considered that the cumulative plastic deformation is better measure than the ductility factor on the damage of structures. Then, the measure considered the influence of frequency of ground motion, such as Ve or SI, should be used for the normalizing the intensity of the ground motion.

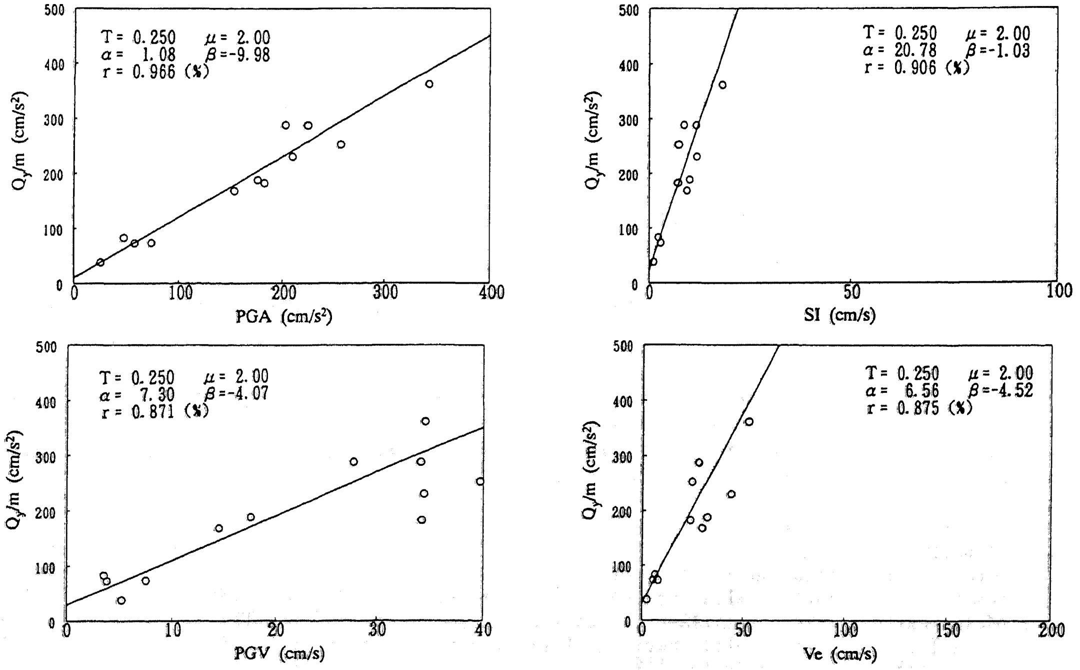

Fig. 7 Relation between damages and intensity measures for T=0.25 second

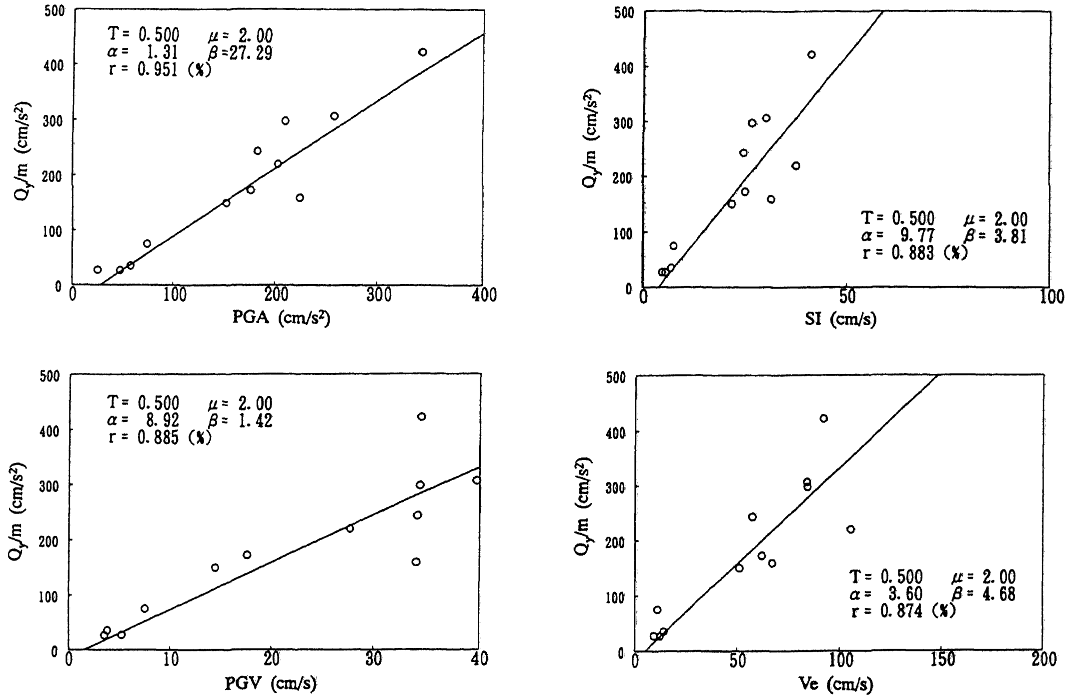

Fig. 8 Relation between damages and intensity measures for T=0.5 second

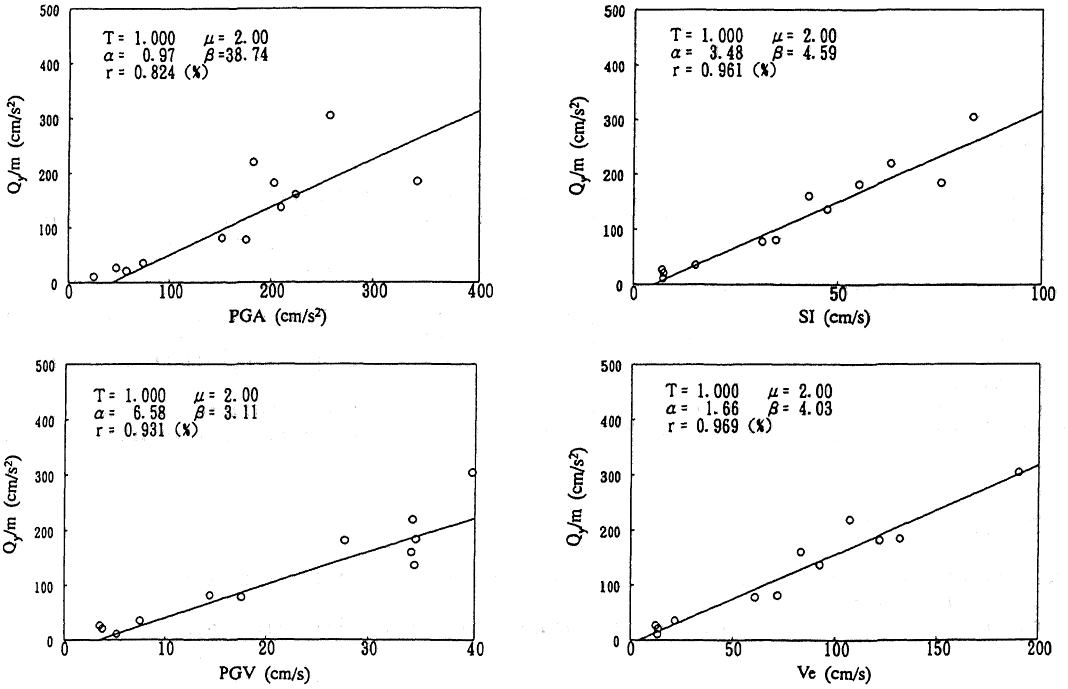

Fig. 9 Relation between damages and intensity measures for T=1.0 second

Table 2 Correlation coefficients r(%) between intensity measures and Q_y required to $\mu=2$

Intensity	Natural Period , T (s)				
measure	0.126	0.25	0.50	1.0	2.0
PGA	95.7	96.6	95.1	82.4	86.9
PGV	81.1	87.1	88.5	93.1	99.0
SI	91.9	90.6	88.3	96.1	90.9
Ve	93.0	87.5	87.4	96.9	94.5

Table 3 Correlation coefficients r(%) between intensity measures and Q_y required to $\mu=3$

Intensity	Natural Period , T (s)				
measure	0.126	0.25	0.50	1.0	2.0
PGA	97.5	96.1	95.3	82.7	85.2
PGV	85.4	88.9	88.5	94.4	97.9
SI	89.1	88.8	89.1	96.0	85.8
Ve	91.7	86.1	87.9	96.6	89.8

Table 4 Correlation coefficients r(%) between intensity measures and Q_y required to $\eta=1$

Intensity	Natural Period , T (s)				
measure	0.126	0.25	0.50	1.0	2.0
PGA	92.7	94.5	95.0	75.4	82.9
PGV	73.8	82.1	93.3	86.4	97.0
SI	96.2	91.8	89.6	92.2	86.9
Ve	96.8	92.4	90.0	95.5	92.4

Table 5 Correlation coefficients r(%) between intensity measures and Q_y required to $\eta=2$

Intensity	Natural Period , T (s)				
measure	0.126	0.25	0.50	1.0	2.0
PGA	94.8	94.4	95.2	75.4	81.7
PGV	77.6	83.3	93.7	86.9	96.9
SI	94.1	90.5	90.7	92.2	86.0
Ve	95.8	92.2	91.3	95.6	91.2

5 CONCLUSIONS

Four measures of intensity of ground motion are used to examine the relation to the failure of structures, that is defined the yield shear force required to reach the specified ductility factor or the cumulative plastic deformation. Two measures, PGA and PGV, are independent of the frequency of ground motion. The others, mean velocity spectral intensity, SI, and mean equivalent velocity of input energy, Ve, depend on the frequencies between T and 2T, where T is a natural period of a structure.

PGA is well correlated to the failure of the short period structures and PGV is well correlated to that of the long period structures, especially for μ. However, they are not good measure in other frequency range.

Ve and SI are good measures in the wide range of frequency, especially for η. The correlation coefficient to Ve is higher than that to Ve.

These results suggest that the measure of the intensity of the ground motions should be used, that is considered the influence of frequencies of ground motion near the fundamental period of structure, such as Ve or SI in this paper.

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