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EARTHQUAKE MOTION INTENSITY FROM LIQUEFACTION VIEWPOINT

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SUMMARY

The authors have studied the intensity of the earthquake motion from liquefaction viewpoint. Dissipation energy was used as a damage index of liquefaction. The dissipated energy consumed in the surface ground for various strong motions was estimated by the equivalent linear analysis using the relation between the elastic energy and a damping ratio. From the analysis, the magnitude of the dissipated energy was well consistent with the liquefaction damage due to the earthquake. It is also found that the total dissipated energy of the surface ground has good correlation with the spectrum intensity of the incident wave motion at the base ground.

INTRODUCTION

Many strong motion records over 0.5g in peak ground acceleration were observed in recent years. Examples are the 1994 Northridge earthquake, the 1994 Far-Off-Sanriku earthquake and the 1995 Hyogo-ken Nambu earthquake. However, the damage due to earthquake was not in proportion to the maximum acceleration. For example, during the 1994 Hokkaido Nansei-oki earthquake, severe liquefaction occurred in Hakodate Port in Japan due to the earthquake motion of about 120 Gals. In contrast no liquefaction observed in Muroran Port due to the earthquake motion of about 220Gals in peak ground acceleration. It indicates that liquefaction damage is independent of the maximum acceleration response of incident wave motion and that new index for evaluating the strong motion intensity to liquefaction is necessary.

So far few attempts have been made to evaluate the liquefaction potential from a ductility point of view. In recent years, however, a new idea to evaluate the ductility against liquefaction was proposed by the authors [Kazama et al. 1998a, Yanagisawa and Kazama, 1999]. The method is based on the dissipated energy consumed as a material damping. Advantages of the technique are consideration of duration effects and frequency effects of strong motions. From previous study of the liquefaction resistance of soil [Kazama et al.1998b], it was found that the stronger soil against liquefaction has the higher capacity of dissipation energy capacity. Evaluation of the dissipated energy during the earthquake means the evaluation of the strong motion intensity from liquefaction viewpoint. On the basis of the idea, we have evaluated the dissipation energy due to earthquake for various actual earthquake motions such as Hyogo-ken Nambu earthquake. We have used the array observation site on Kobe Port Island for a study site where complete liquefaction occurred during the 1995 Hyogo-ken Nambu earthquake.

EVALUATION OF DISSIAPTION ENERGY CONSUMED IN THE SURFACE GROUND

The energy consumed as a material damping is called dissipation energy. The dissipation energy is calculated by integrating the area covered with stress-strain loops and could be obtained from the equation:

$$\Delta W(t) = \oint_c \tau(\gamma)\,d\gamma = \int_0^t \tau(\gamma)\dot{\gamma}(t)\,dt \tag{1}$$

where $\Delta W(t)$ is the dissipation energy consumed until time t, γ is the shear strain, τ is the shear stress and $\dot{\gamma}(t)$ is the strain rate.

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In general the dissipation energy can be obtained from the stress-strain time history of the seismic response analysis using a non-linear constitutive relationship. However when we obtain the dissipation energy from non-linear response analysis, the results are strongly influenced by the constitutive model. Furthermore, parameter identification is sometimes difficult for applying the actual site because of complicated procedure. Therefore, in this study, we shows a simple method using equivalent linear analysis. Since the equivalent linear analysis treats the soil as an elastic material, it is impossible to calculate the dissipation energy directly from the stress-strain time histories. However, the dissipated energy is expressed by the following equation:

$$\Delta W = 2\pi h_{eq} W_E \tag{2}$$

where h_{eq} is an equivalent damping ratio and W_E is the elastic energy accumulated in loading process. Figure 1 shows a schematic diagram of the relation between the elastic energy and the dissipation energy.

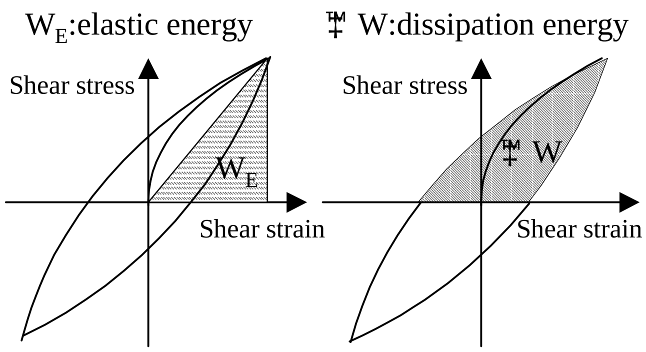

Figure 1 Schematic diagram of the elastic energy and the dissipation energy in half cycle.

On the other hand, the time history of elastic energy is calculated by the following equation:

$$W_E(t) = \frac{1}{2} G_{eq} \{\gamma(t)\}^2 \tag{3}$$

where G_{eq} is an equivalent shear moduli and $\gamma(t)$ is the time history of shear strain. By using the equation (3), when the time history of elastic energy can be calculated as shown in Figure 2, the total dissipation energy with time could be obtained by summing up the each dissipated energy of the corresponding loading half cycles,

$$\Delta W_{n,total} = \sum_{i=1}^{I} \Delta W_{n,i} = 2\pi h_{eq} \sum_{i=1}^{I} W_{E\,n,i} \tag{4}$$

where $\Delta W_{n,total}$ is total dissipation energy of n-th layer during the earthquake.

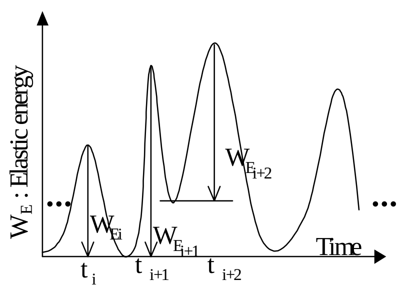

Figure 2 Schematic diagram of time history of the elastic energy.

ANALYTICAL CONDITION

Ground profile of Kobe Port Island as a study site

We studied the seismic response of Kobe Port Island as a study site. At the site, as is well known that strong motion array records were obtained at the 1995 Hyogo-ken Nambu earthquake [Kobe City report, 1995]. Table 1 shows the soil profiles used in the response analysis above K.P.-28m. K.P. is the abbreviation of Kobe Pile and it means the mean sea level of Kobe Port area.

Table 1 Soil properties used in the response analysis.

Layer No.	Elevation K.P.(m)	Soil Property	Thickness (m)	Density (t/m^3)	Shear wave Velocity (m/s)
1	4	Reclaimed Masado	2.0	1.7	170
2	2	Reclaimed Masado	2.0	1.7	170
3	0	Reclaimed Masado	1.0	2.0	210
4	-1	Reclaimed Masado	1.0	2.0	210
5	-2	Reclaimed Masado	1.0	2.0	210
6	-3	Reclaimed Masado	1.0	2.0	210
7	-4	Reclaimed Masado	1.0	2.0	210
8	-5	Reclaimed Masado	1.0	2.0	210
9	-6	Reclaimed Masado	2.0	2.0	210
10	-8	Reclaimed Masado	2.0	2.0	210
11	-10	Reclaimed Masado	2.0	2.0	210
12	-12	Reclaimed Masado	1.4	2.0	210
13	-13.4	Alluvial clay	2.6	1.6	180
14	-16	Alluvial clay	2.0	1.6	180
15	-18	Alluvial clay	2.0	1.6	180
16	-20	Alluvial clay	2.0	1.6	180
17	-22	Alluvial clay	2.2	1.6	180
18	-24.2	Alluvial clay	1.8	1.6	245
19	-26	Alluvial clay	2.0	1.6	245
20	-28	Base ground	-	See Table 2	

Earthquake motion and shear wave velocity of the base ground

Eight earthquake motions were used for comparing the intensity to liquefaction of reclaimed layer. Table 2 shows the outline of the earthquake motions used here and the shear wave velocity of the base ground. We chose larger acceleration record between two horizontal components. All motions except for Kobe array site records were converted to the incident wave at the base by using de-convolution analysis. Shear wave velocity and density of the base ground was determined on the basis of the report from the institutions obtaining the records. Figure 3 shows the time histories of the earthquake records. It should be noted that Far-Off-Sanriku earthquake motion has considerably large peak ground acceleration comparing to the others. It should be also paying attention to that the first impression of Hyogo-ken Nambu record is not so strong comparing to the others.

Table 2 Outline of the earthquake motions used here.

No.	year	Name of earthquake	Observation site	Direc-tion	wave	Max. Acc.		No. of data	Density*2 $\rho(t/m^3)$	Vs*2 m/s
						Gal	*1			
1	1968	Tokachi-oki	Hachinohe Port	NS	Incident	170	153	1800	2.00	380
2	1978	Miyagi-oki	Ohfunato Port	E41S	Incident	161	158	1800	2.00	650
3			Kaihoku Bridge	W42N	Incident	293	279	1800	2.00	650
4	1993	Kushiro-oki	Kushiro Port	EW	Incident	221	221	3600	1.80	430
5	1994	Hokkaido Nansei-oki	Hakodate Port	N03W	Incident	142	142	7200	1.84	550
6			Muroran Port	EW	Incident	144	144	7200	2.00	420
7	1994	Far-Off Sanriku	Hachinohe Port	EW	Incident	1350	1350	3600	2.00	341
8	1995	Hyogoken Nambu	Kobe Port Island K.P.-28m	NS	observed	544	504	1800	2.00	305

*1: the value after 10Hz low pass filtering. *2: the value of the base ground.

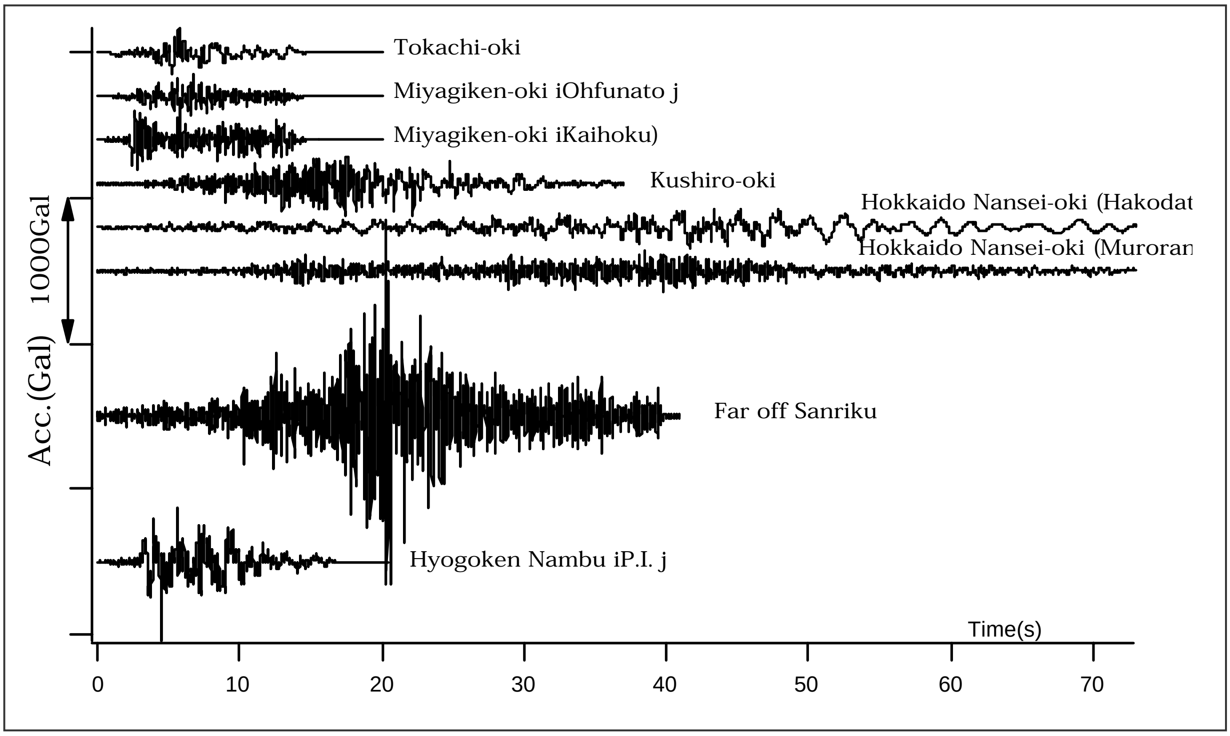

Figure 3 Time histories of the earthquake motions used in the analysis.

Dynamic properties of soils used in the analysis.

Dynamic properties of alluvial clay layer was studied by Kobe City government after the earthquake [Kobe City report, 1995]. The dynamic properties of reclaimed Masado layer was also investigated by Zen and Yamazaki [1996]. They obtained dynamic properties of reclaimed Masado using undisturbed frozen sample. Since the curve was obtained until 0.2% strain amplitude, therefore, we expanded the dependency of properties on shear strain amplitude beyond 0.2% considering the liquefaction. This treatment has done considering the degradation of stiffness with cyclic loading. Figure 4 a) and b) shows the dependency of the shear modulus and damping with effective shear strain used here. In the figure, the property of alluvial clay and reclaimed land above see level were the almost same curve as the one proposed by the handbook on liquefaction [1997]. However, the property of reclaimed land under the sae level is definitely different from the one already proposed. Figure 5 shows the variation of the shear stress ratio on the basis of the shear stress at very small strain level 10^{-6}. It is found that the curve considering the liquefaction shows the strain softening behaviour in the larger strain level over 0.1%. From previous study, the calculation results using the curve considering the liquefaction showed better agreement with actual array record than that using ordinary curve without consideration of the liquefaction [Kazama et al. 1999b].

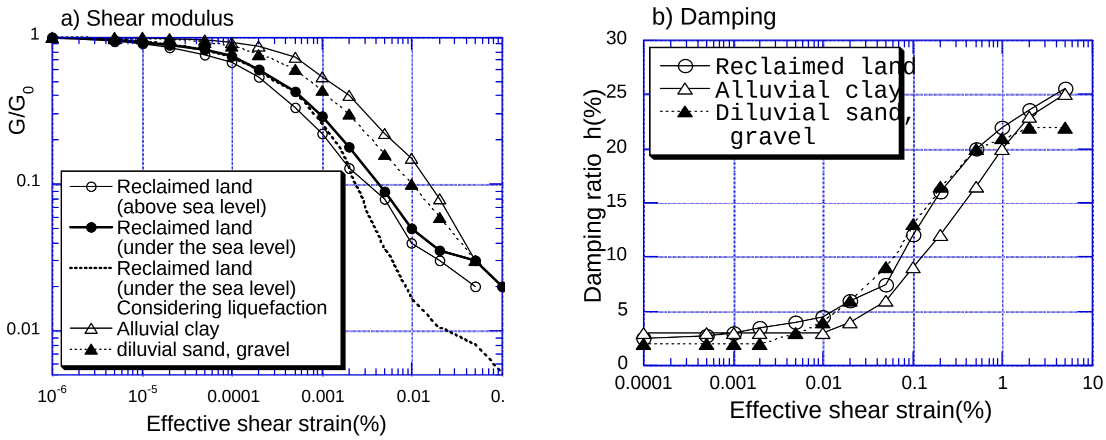

Figure 4 Dynamic properties of soil used in this study

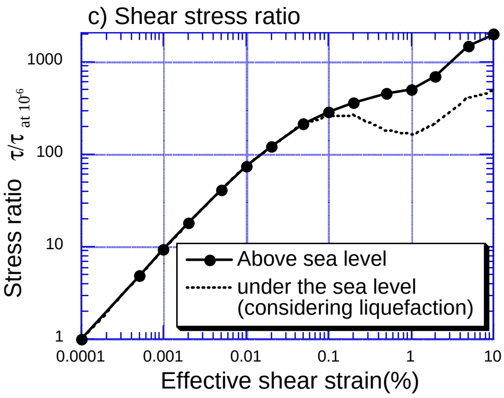

Figure 5 Variation of the shear stress ratio

RESULTS OF ANALYSES

Distribution of Maximum Acceleration Response and Shear Strain Response

Figure 6 shows the distribution of the maximum acceleration and shear strain response in depth direction for various earthquakes. From the figure, a little amplification of acceleration was developed in case of Tokachi-oki, Miyagi-ken-oki, Kushiro-oki, Nansei-oki earthquake. In contrast, in case of Far-Off-Sanriku and Hyogo-ken Nambu earthquake, acceleration response of surface ground decreased considerably. As shown in the maximum shear strain response, in case of Far-Off-Sanriku and Hyogo-ken Nambu earthquake, large shear strain developed over 1% in reclaimed layer. This would be the reason of decrease of acceleration response.

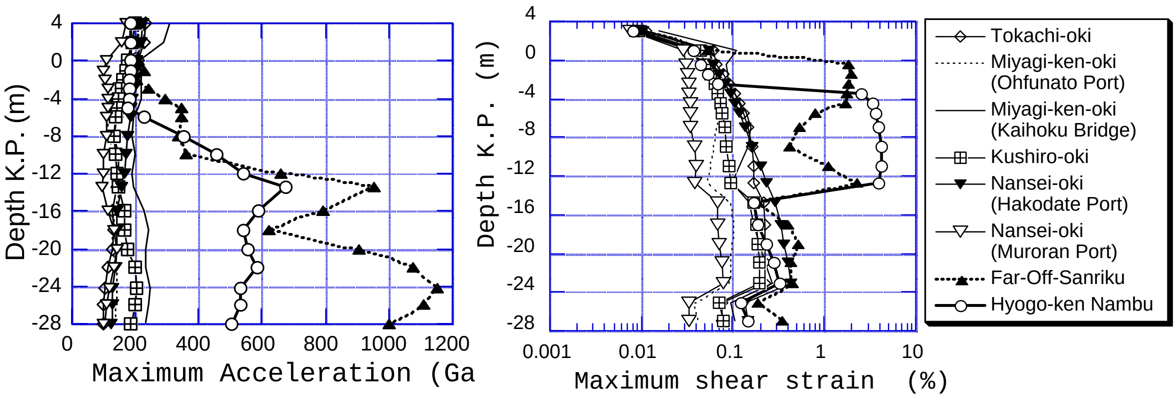

Figure 6 Distribution of the maximum acceleration response and shear strain response

Distribution of the dissipation energy in depth direction

Figure 7 shows the dissipated energy consumed at the each layer during earthquakes. The dissipated energy was normalized by the effective vertical pressure at the mid depth of the layer. It is found that large energy was dissipated as a material damping in reclaimed layer for Far-Off-Sanriku and Hyogo-ken Nambu earthquake. On the other hand, for the other earthquake, the dissipated energy in alluvial layer is much larger than the one consumed in reclaimed layer.

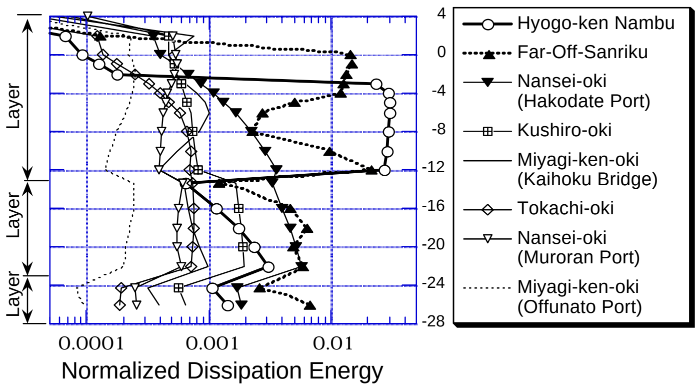

Figure 7 Distribution of the dissipated energy during earthquakes in depth direction.

These distributions correspond to the maximum shear strain distributions as shown in Figure 6. When paying attention to the dissipated energy in reclaimed layer, its values are from 0.02 to 0.03. These values are well consistent with the dissipated energy evaluated from the array data analysis [Kazama et al. 1998a] and the one evaluated from the cyclic tri-axial test for Masado [Kazama et.al, 1998c].

Table 3 shows the total dissipated energy consumed in the surface ground and its distributions. The total dissipation energy was defined by the following equation:

$$(\Delta W/\sigma'_v)H_{total} = \sum_{n=1}^{N} \frac{\Delta W_{n,total}}{\sigma'_{v,n}} H_n \qquad (5)$$

where H_{total} is the total thickness of the surface ground. From Table 3, for the Hyogo-ken Nambu earthquake, about 92% of total dissipation energy were consumed in the reclaimed layer. In contrast, for Far-Off-Sanriku earthquake, about 67% of total dissipation energy were consumed in reclaimed layer. The difference between two earthquakes would depend on the frequency content. The total dissipated energy can be regarded as an index to represent the seismic intensity against liquefaction. When we estimate the earthquake intensity from liquefaction viewpoint, it can be said that Hyogo-ken Nambu earthquake motion is the most severe earthquake for Kobe Port Island site and the second one is Far-Off-Sanriku earthquake motion.

Table 3 Total dissipated energy consumed in the surface ground and its distributions

	Dissipated energy	Percentages of dissipation energy in each layers			
Earthquake motion	$(\Delta W/\sigma'_v)H_{total}$	above sea level	Reclaimed	Alluvial clay layer	Diluvial
Hyogo-ken Nambu (100%)	0.322	0	93	6	1
Hyogo-ken Nambu (95%)	0.272	0	92	6	1
Hyogo-ken Nambu (90%)	0.265	0	92	6	1
Hyogo-ken Nambu (80%)	0.218	0	92	6	1
Hyogo-ken Nambu (70%)	0.178	0	92	6	1
Hyogo-ken Nambu (60%)	0.153	0	92	7	1
Hyogo-ken Nambu (50%)	0.125	0	90	6	1
Far-Off-Sanriku (100%)	0.198	0	67	24	9
Far-Off-Sanriku (90%)	0.156	0	66	25	9
Far-Off-Sanriku (80%)	0.142	0	73	21	6
Nansei-oki (Hakodate Port)	0.080	1	30	61	8
Kushiro-oki (Kushiro Port)	0.032	3	28	63	7
Miyagi-ken-oki (Kaihoku Bridge)	0.020	8	46	42	7
Tokachi-oki (Hachinohe Port)	0.016	2	42	50	5
Nansei-oki (Muroran Port)	0.014	9	43	44	7
Miyagi-ken-oki (Muroran Port)	0.006	9	45	40	6

Factor of the strong motion having good correlation with dissipated energy

In this section, we studied what kind of index of strong motion has good correlation with the dissipated energy. Indices used in this study were peak ground acceleration (PGA), peak ground velocity (PGV) and spectrum intensity (SI) of both the surface ground acceleration and the incident wave motion at the base ground. Spectrum intensity was defined by the following equation:

$$SI = \frac{1}{2.4}\int_{0.1}^{2.5} Sv\,dT \qquad [cm/s] \qquad (6)$$

where Sv is the velocity response spectra, and SI value has the same dimension as the velocity.

Figure 8 to Figure 11 shows the relation of indices with the total dissipated energy consumed in the surface ground. The best correlation with the dissipated energy was given by the SI value of the incident wave motion at the base ground. It is also found that the correlation between the dissipated energy and PGV is not so bad. For incident wave motion, the correlation coefficient was 0.979 for SI value and 0.969 for PGV. On the other hand, there is positive correlation with PGA for an earthquake motion varying with its amplitude, but no positive correlation with PGA exists for various earthquake motions. It indicates that the contribution of the higher frequency content of earthquake motion to the dissipation energy is considerably small comparing to the lower frequency content.

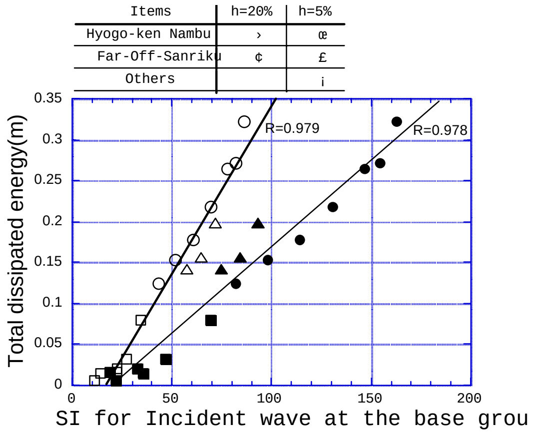

Figure 8 **Relation between the total dissipated energy and SI values for incident wave at the base**

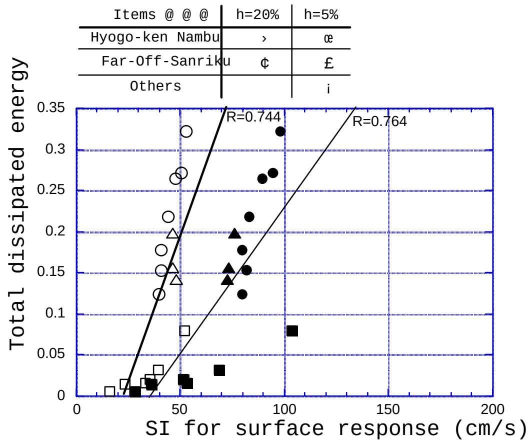

Figure 9 **Relation between the total dissipated energy and SI values for surface wave**

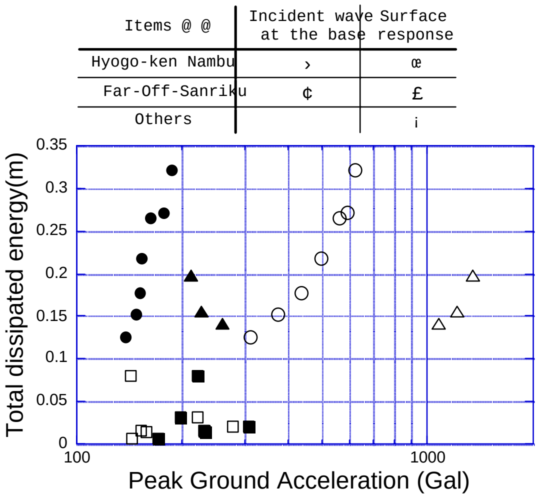

Figure 10 **Relation between the total dissipated energy and PGA**

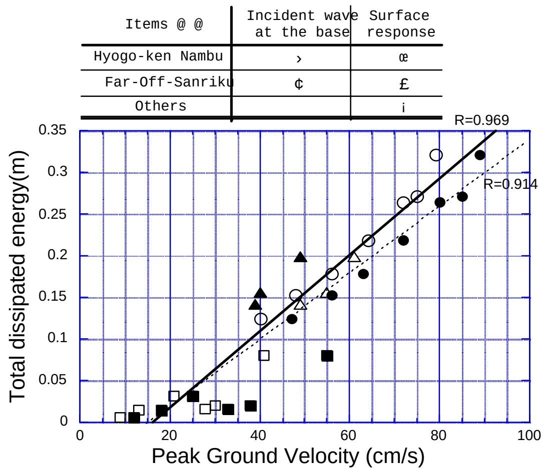

Figure 11 **Relation between the total dissipated energy and PGV**

Figure 12 shows the SI ratio between the surface response and the incident wave at the base ground. The larger value means the larger amplification from the base ground to the surface ground. As shown in Figure 12, the larger the total dissipated energy was consumed, the smaller SI ratio becomes. It indicates that the consuming the energy as a material damping play an isolation effects on the super-structures.

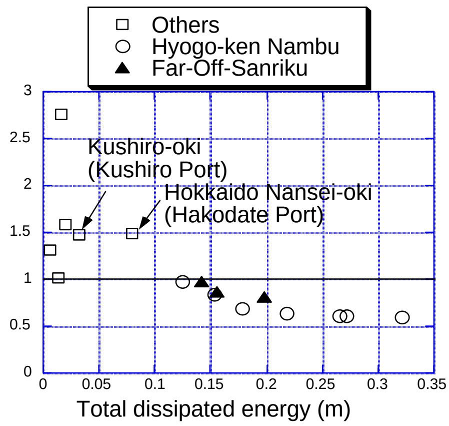

Figure 12 **SI ratio between the surface response and the incident wave at the base ground**

CONCLUSIONS

We have studied strong motion intensity from the dissipated energy consumed in the surface ground. The dissipated energy is the effective factor in relation to liquefaction damage. The results obtained from this study summarised as follows:

1. We proposed a simple method for evaluating the dissipated energy by using equivalent linear analysis.
2. The distributions of the dissipation energy correspond to those of maximum shear strain response in the surface ground but the maximum acceleration. When we evaluate the strong motion intensity from the dissipated energy consumed in the surface ground, it can be concluded that the strong motion records of the 1995 Hyogo-ken Nambu earthquake is the most severe for Kobe Port Island as a study site, and the second one is the 1994 Far-Off-Sanriku earthquake. This ranking is good correspondence to the actual liquefaction damage due to the earthquakes.
3. The total dissipation energy has good correlation with peak ground velocity and spectrum intensity. However, no positive correlation exists between the dissipated energy and PGA. It is also found that indices of the incident wave motion at the base ground have better correlation with the dissipated energy than the surface ground response.
4. In conclusion PGA is not effective index to explain the liquefaction damage due to earthquake and evaluation of the dissipated energy is very important for the design work of liquefaction countermeasures.

ACKNOWLEDGEMENT

This research was conducted by sponsorship of Toray science foundation and the Maeda foundations, and was financially supported by Grand-in-Aid for scientific research No.08558037 from The Ministry of Education of The Japanese Government. The strong motion records at Kobe Port Island were originally obtained by the Development Authority of Kobe City. The other strong motions used in this study were presented by the Port and Harbour Research Institute, The Ministry of Transport. The authors express sincerely appreciation to these organizations.

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