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PREDICTION OF DAMAGE TO STRUCTURES THROUGH FATIGUE RESPONSE SPECTRA CONSIDERING NUMBER OF EARTHQUAKE RESPONSE CYCLES

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SUMMARY

In general, peak ground acceleration (PGA), peak ground velocity (PGV), maximum response acceleration (A_{max}) and spectral intensity (SI) have been used as the indices of destructive power on earthquake motion. However, it is quite important to consider the number of earthquake response cycles in the vicinity of the maximum response and natural period of structures for predicting damage to structures. Moreover, the deterioration with life time also plays a vital role in the damage. In this study, an index for predicting damage to structures is proposed using the parameters of the fatigue life and the natural period. This index, which is called as Fatigue response Spectral Intensity (FSI), is defined as integrated value on tripartite coordinates: natural period of wooden structures or RC structures, pseudo-response velocity spectra and number of seismic response cycles. In addition, it is calculated the square of the response velocity of 1-DOF structure. This index is called as Velocity Power (VP). VP and FSI were calculated by using the response to recent earthquakes in Japan such as the 1994 Hokkaido Toho-Oki earthquake, the 1994 Sanriku Haruka-Oki earthquake, the 1995 Hyogoken-Nambu earthquake, the 2000 Tottoriken-Seibu Earthquake, 2001 Geiyo Earthquake and so on. Compared with the damage by the recent earthquakes, it was clarified that these indices represent reasonably the damage ratio to wooden structures and RC structures during earthquakes. Especially, the effect of fatigue on the damage was indicated reasonably, since the number of cycles of the large seismic response was considered in these VP and FSI values. Based on this study it is concluded that VP and FSI values demonstrate the damage ratio more accurately than alternative indices such as PGA, PGV, A_{max} and SI value.

1. INTRODUCTION

Many of the dead at the Hyogoken-Nambu earthquake are presumed to be squeezed by collapse of wooden houses. The destructive power index of the earthquake motion predicts structural damage quickly, correctly and immediately after that[1)], and this index is useful for mitigation of earthquake disaster. The purpose for using this is classified into early detection and urgent correspondence of earthquake damage, practical use for aseismic design and retrofit of the structure, and so on. In general, seismic intensity, PGA, PGV, and spectral intensity (SI) are used as the indices which show the destructive power of an earthquake motion. However, these indices do not take the concept of the structural response cycles into

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consideration. It is true that the spectral intensity uses the maximum seismic response for structures with natural periods within the range of 0.1s and 2.5s. However this index does not take into account the fatigue effect. Since the damage to structure becomes larger with the number of earthquake response cycles, it is necessary to take this fact into consideration in order to express the structure damage by the actual earthquake motion.

In this study, the fatigue response spectrum intensity (FSI) and velocity power (VP) indices which take the number of seismic response cycles into consideration are proposed. It is discussed that the effect by the number of seismic response cycles to the wooden structure. And it is discussed that FSI and VP are effective indices in representing as the destructive power of an earthquake strong motion.

2. EVALUATION OF DESTRUCTIVE POWER INDEX ON EARTHQUAKE MOTIONS

2.1 Outline of destructive power index

The FSI value in which the number of seismic response cycles is considered has been proposed so far by researchers[2), 3)]. It is expectable that the FSI value serves as an accurate index since it takes into account the structure action. However, the FSI cannot be used for the real-time evaluation because this index is incalculable unless an earthquake motion is completed. In this study, the destructive power index considering the real-time evaluation and seismic response cycles is investigated. By the way, the destructive power of an earthquake motion is calculated integrating the square of acceleration in the time duration by Kuwamura[4)], which is called acceleration power. However, acceleration power does not take the structural response into account. Then, the ground acceleration is not good parameter as for correlation with damage interpretation of an earthquake. In this study as an evaluation index, the square of 1-DOF structural response velocity to an earthquake motion is calculated and integrated in the time duration. This is called as velocity power (VP). It is thought that VP will be applicable to grasping the damage in real-time.

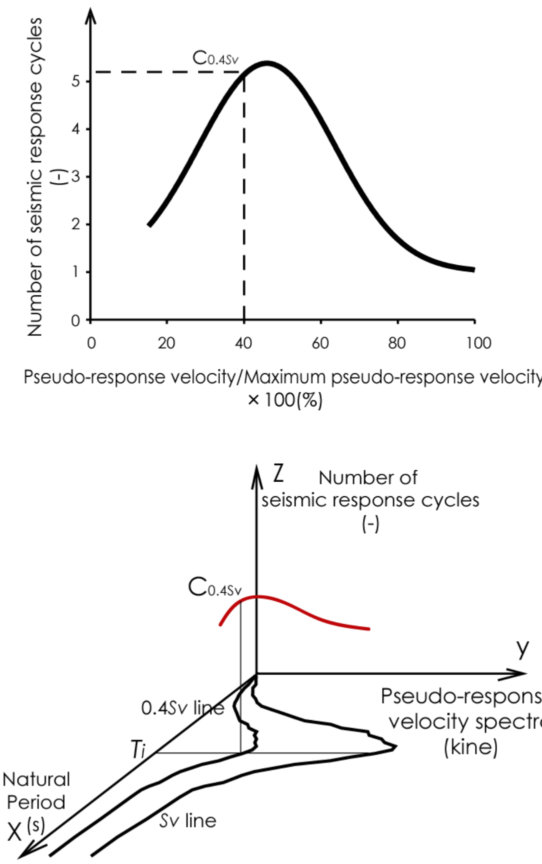

Fig.1 Conceptual diagrams of *FSIv*

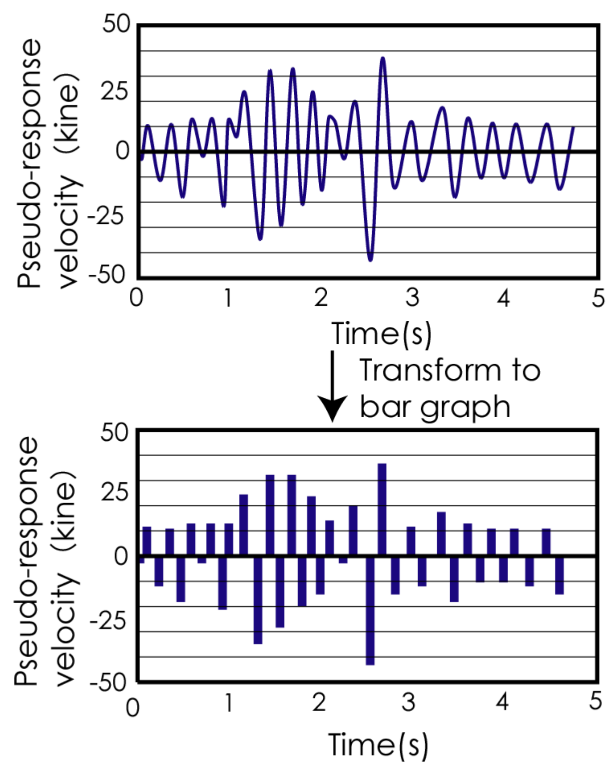

Fig.2 Conceptual diagram of *FSIv*
(Bar graph of response velocity)

The conceptual diagram of FSI_v (the fatigue response spectral intensity using pseudo-velocity response) is shown in Fig. 1. This index is defined as integrated value on tripartite coordinates; natural period of wooden houses (T) as x-axis, pseudo-response velocity spectra (S_v) as y-axis and number of seismic response cycles (C_v) as z-axis. The number of seismic response cycles is counted by using the bar graph of pseudo-response velocity as shown in Fig. 2. For the purpose of comparing with SI value, the natural period of wooden structures is considered in the range from 0.1s to 2.5s, and damping ratio h is 0.05 in this study. The indices SI and FSI_v are defined by the following formulas:

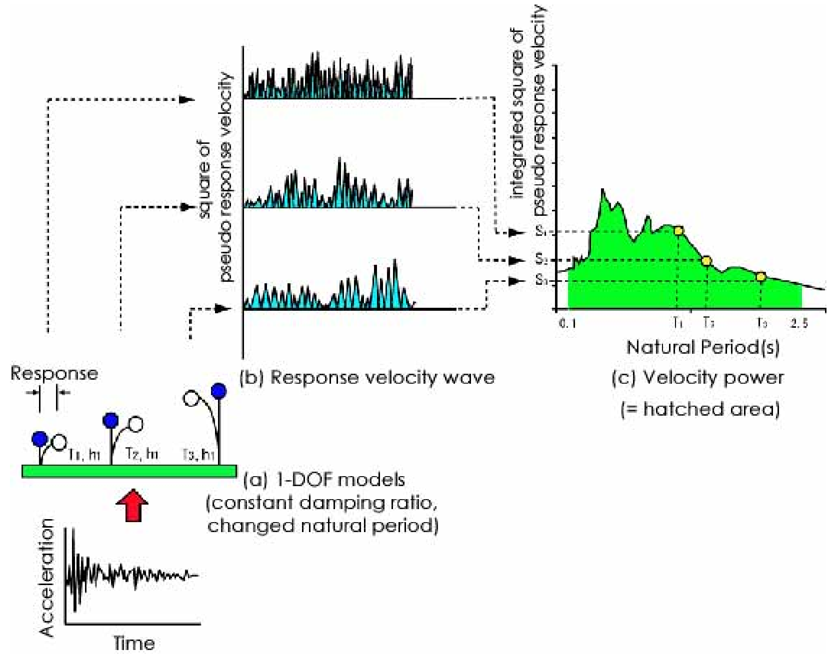

Fig. 3 Conseptual diagram of velocity power (*VP*)

$$SI = \int_T S_v dT$$

$$FSI_v = \int_T \int_{S_v} C_{S_v} {S_v}^2 dS_v dT$$

The conceptual diagram of *VP* is shown in Fig. 3, and is defined by the following formula. This index pays its attention to the time duration of an earthquake motion like FSI_v, and computes using 25 pseudo-velocity responses for the natural periods in the range of T=0.1s to 2.5s at intervals of 0.1s with 5% damping ratio. The amplitudes of 25 pseudo-velocity responses are squared, respectively, and squared values are integrated from the beginning of the record to the end (t). This integrated value is called as velocity power (*VP*). The area of the hatch portion shown in Fig. 3 (c) is *VP*. In this study, the relation between the wooden structure damage and destructive power indices (that is *PGA*, *PGV*, seismic intensity, *SI* value, *FSI* value, and *VP* value) is considered.

$$VP = \int_T \int_0^t v^2(t) dt dT$$

2.2 Relationship between damage to wooden structures and destructive power indices

The relationship between damage ratio of wooden structures and each index is shown in Fig.4. Damage ratio D of wooden structures is defined by the following equation:

$$D = \frac{D_1 + D_2/2}{h_a} \times 100$$

In which, D_1 is the amount of serious damaged structures; D_2 is the amount of medium damaged structures and h_a is the total amount of wooden structures. It is shown that the relationship between damage ratio of wooden structures and *PGA* has no good correlation. However, *PGV*, *SI*, FSI_v, and *VP*

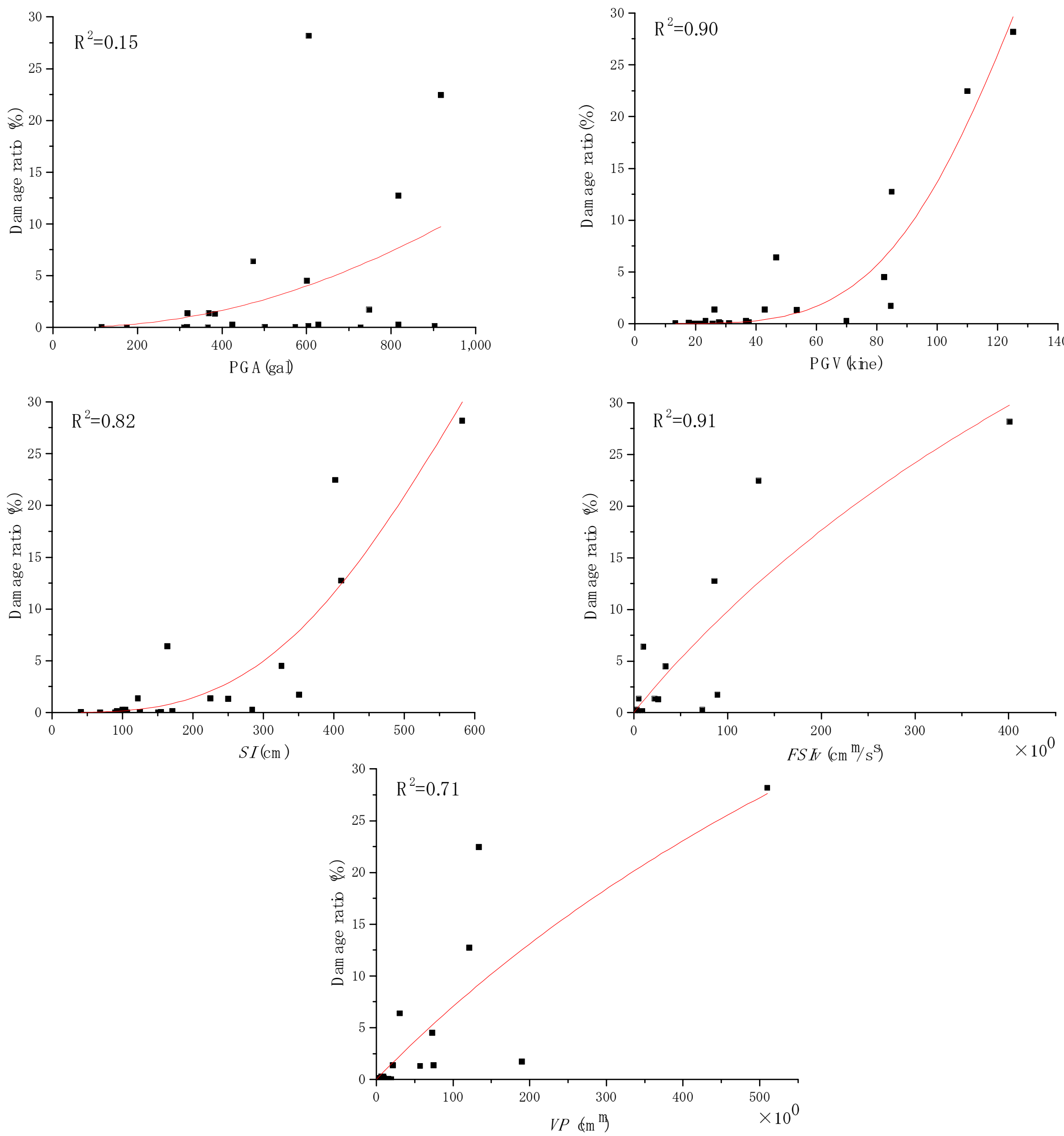

Fig.4 Relationship between damage ratio of wooden structures and destructive power indices

have good correlation with damage ratio. The coefficients of determination R^2 which show approximate accuracy are 0.15 for *PGA,* 0.90 for *PGV*, 0.82 for *SI*, 0.91 for FSI_v, 0.71 for *VP*, respectively.

3. EFFECT OF EARTHQUAKE RESPONSE CYCLES ON ANALYSIS OF WOODEN STRUCTURES

3.1 Outline of earthquake response analysis

The wooden structure is modified by 2-DOF shear type. Hysteretic restoring force of the analytical model is interlaced by poly-linear type and slipped type at the rate of 0.4:0.6 as shown in Fig. 5, and the point for 1/6,000rad is added to the poly-linear type hysteretic restoring force for giving the initial rigidity corresponding to the predominant period during vibration with small amplitude. Moreover, framework rigidity of wooden structure begins to fall at 1/30rad [5]. Then, the point is added to poly-linear type hysteretic restoring force so that stability may decline from 1/30rad. It is said that the wooden structure will disintegrate due to P-⊿ effect if deformation angle of a layer exceeds 1/15rad. So, the inclination is introduced after 1/30rad so that scaling stability may become zero at 1/15rad. The resonant frequency of this model is 3.0Hz with base shear coefficient C_0=0.2.

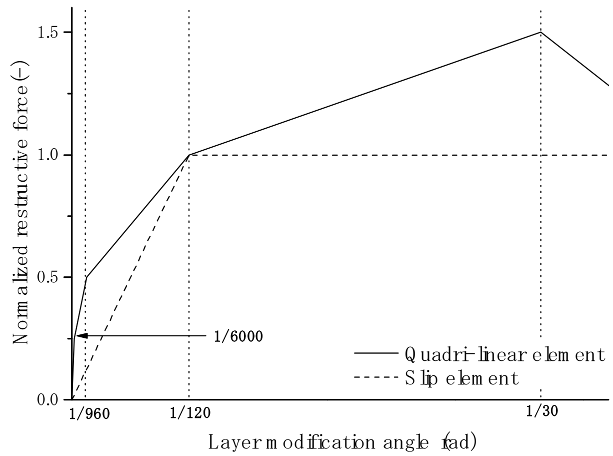

Fig.5 Hysteresis of analytical model

3.2 Generation of artificial earthquake motion

In the analysis, artificial earthquake motions are used as an input, and the effect of the number of seismic response cycles on the damage of the wooden structure is considered. The wooden structure's model is the same as that of Section 3.1. An artificial earthquake motion is generated using a function of Jenning's type envelope curve as shown in Fig. 6, such artificial earthquake motions with different time length of main motion (*TE*) are used. In this chapter, for example, the analysis was performed using the JMA-Kobe record of the 1995 Hyogoken-Nambu earthquake and the K-Net Matsue record of the 2000 Tottoriken-Seibu earthquake as Type II (inland type) earthquake motions, and the Hachinohe harbor record of the 1968 Tokachi-Oki earthquake as type I (plate-boundary type) earthquake.

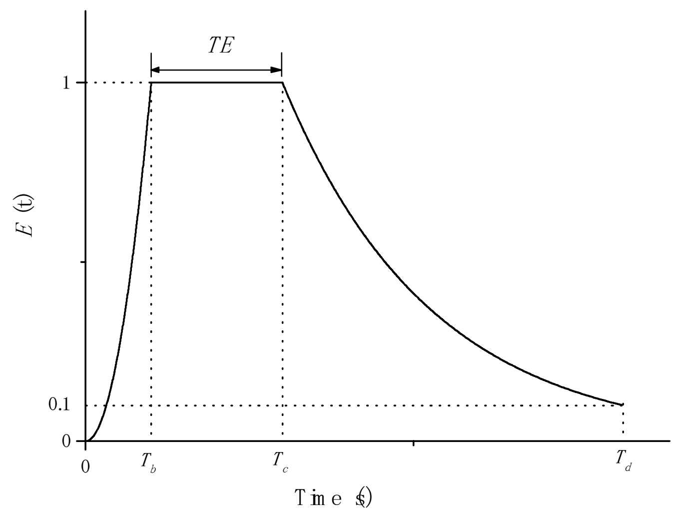

Fig.6 Function of Jenning's type envelope curve

3.3 Analytical results

In the analysis, the length of main motion *TE* of the artificial earthquake is changed from 5s to 30s at intervals of 5s, and the maximum acceleration A_{max} is changed from 100gal to 800gal at intervals of 100gal. Each motion has almost equal power spectrum and equal frequency content. The artificial earthquake motions with different time length of main earthquake are used for estimating the damage to the wooden structure. Measurement of structural damage is evaluated by the maximum displacement and the displacement at first floor.

For example, the relationship between *TE* and maximum displacement at first floor in JMA-Kobe, K-Net Matsue and Hachinohe harbor are shown in Fig. 7. These figures are the result for JMA-Kobe with the maximum value of 400gal, 600gal and 800gal, K-Net Matsue with the maximum value of 100gal, 200gal and 300gal, and Hachinohe Harbor with the maximum value of 400gal, 600gal and 800gal. And these indicate the effect of non-linear characteristic of wooden structure on the response. According to these figures, maximum displacement of the first floor becomes larger as *TE* becomes longer, and the difference of displacement has produced damage grade. Therefore, it is suggested that structural damage also becomes larger as the repetition cycles of near the maximum response to an earthquake motion increases.

4. EVALUATION OF THE DESTRUCTIVE POWER INDEX BY AN ARTIFICIAL EARTHQUAKE MOTION

The relationships between maximum displacement of first floor and each index are shown in Fig.8~Fig.10. These figures are obtained from the earthquake response analysis to artificial earthquake motions as input. Fig.8 shows the relationship for JMA-Kobe, Fig.9 shows the relationship for K-Net Matsue, and Fig.10 shows the relationship for Hachinohe Harbor. These figures show that the relationships between maximum displacement of first floor and *SI*, FSI_v, and *VP* have good correlation, and that these indices correspond well with damage. In Fig. 8, the coefficients of determination R^2 for each index which show approximate accuracy are 0.87 for *SI*, 0.87 for FSI_v and 0.76 for *VP*, respectively. In Fig. 9, those are 0.99 for *SI*, 0.98 for FSI_v and 0.97 for *VP*, respectively. In Fig. 10, those are 0.89 for *SI*, 0.92 for FSI_v and 0.86 for *VP*, respectively. Therefore, it is suggested that the number of seismic response cycles influences strongly structure damage.

5. CONCLUSIONS

The conclusions of this study are summarized below.

(1) The damage to wooden structure becomes large, as the repetition cycles of near the maximum response to an earthquake motion increases. Therefore, the number of seismic response cycles influences strongly structure damage.

(2) In the relationship between damage ratio of wooden structures and each destructive power index, FSI_v and *VP* are effective parameters and should be considered as the destructive power indices of an earthquake motion.

Acknowledgment

The digital data of strong ground motion accerelograms employed in this study are those published by National Research Institute for Earth Science and Disaster Prevention (K-Net, KiK-Net), Japan Meteorological Agency, Port and Harbor Research Institute, Kansai Earthquake Observation Research Association and West Japan Railway Company. Mr. Hiroshi Kurahashi of CTI Engineering Co., Ltd. helped us in calculating earthquake responses. The authors would like to thank these organizations and him.

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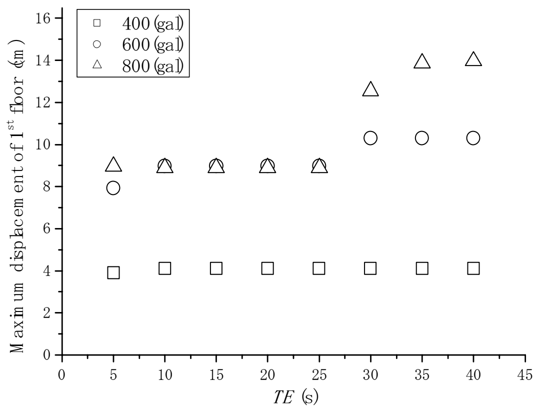
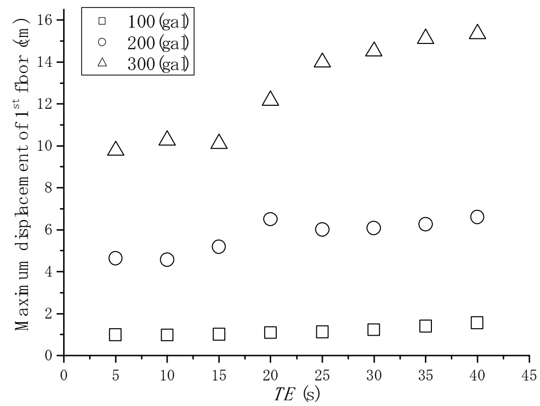
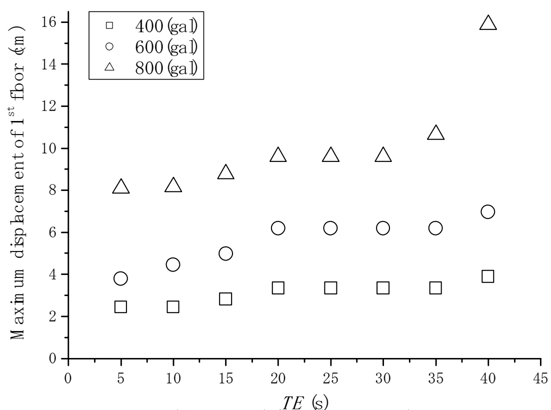


(a) JMA-Kobe

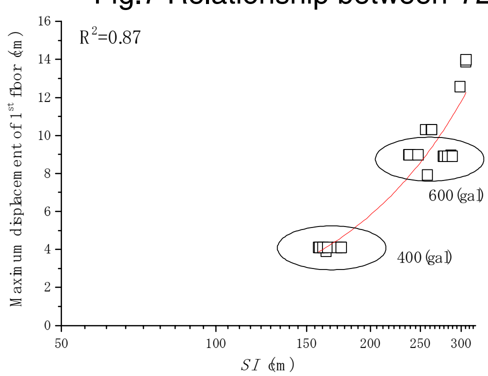


(b) K-NET Matsue

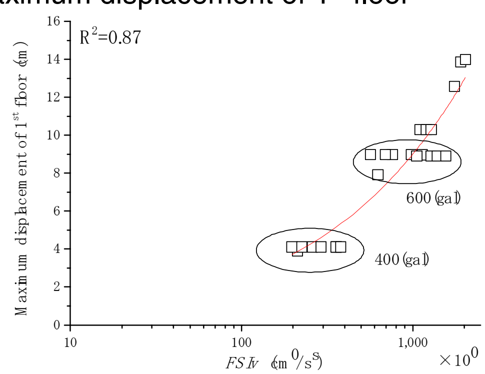


(b) Hachinohe Harbor

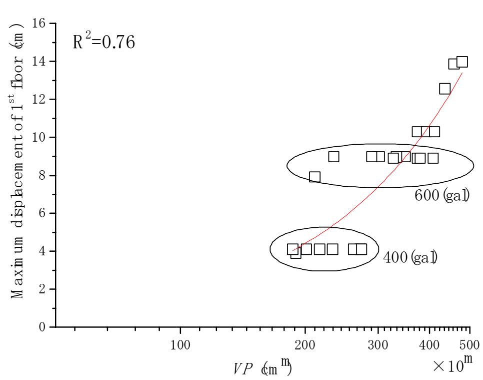
Fig.7 Relationship between *TE* and maximum displacement of 1st floor



(a) *SI*

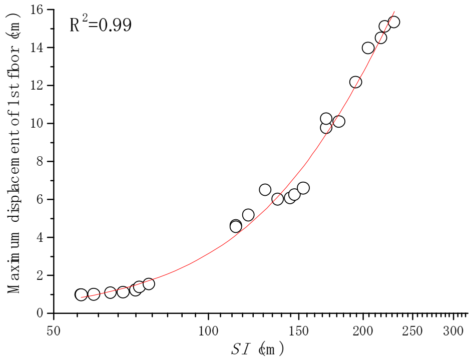


(b) *FSIv*

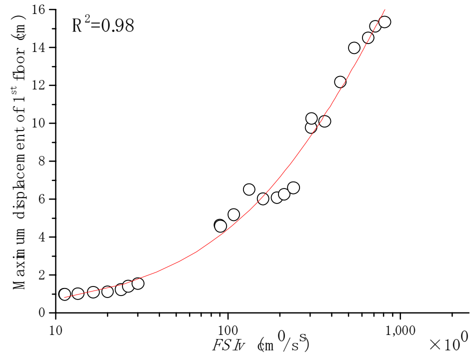


(c) *VP*

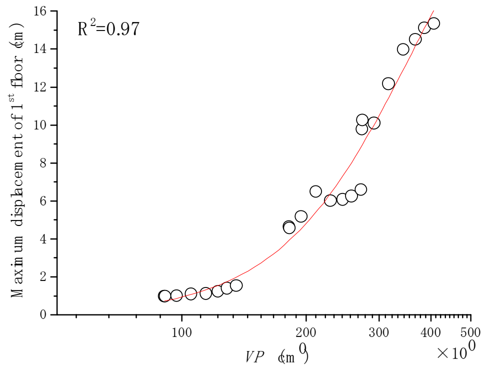
Fig.8 Relationship between destructive power indices and maximum displacement of 1st floor (JMA-Kobe)



(a) *SI*

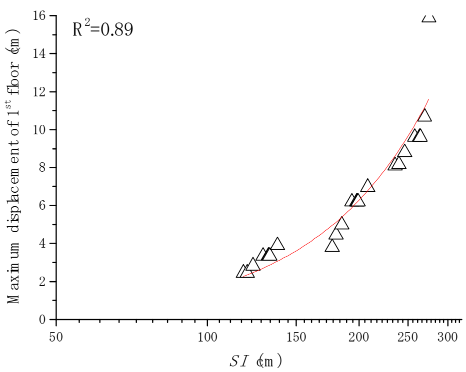


(b) *FSIv*

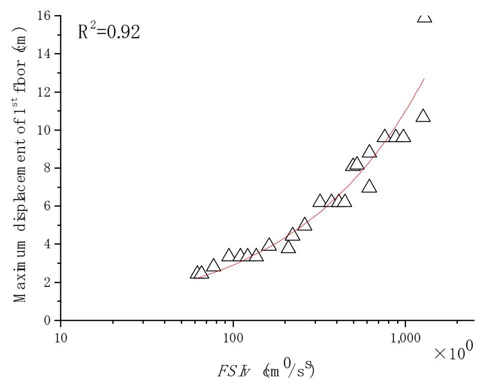


(c) *VP*

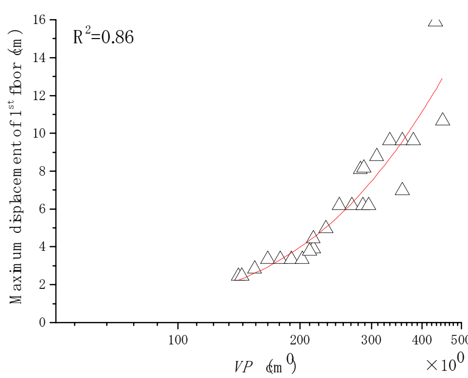
Fig.9 Relationship between destructive power indices and maximum displacement of 1st floor (K-NET Matsue)



(a) *SI*



(b) *FSIv*



(c) *VP*

Fig.10 Relationship between destructive power indices and maximum displacement of 1st floor (Hachinohe Harbor)