Seismic damage prediction of old Japanese-style wooden house using predominant period distribution of ground surface layer

*Hayato Nishikawa\textsuperscript{1)} and Tomiya Takatani\textsuperscript{2)}

\textsuperscript{1)} Education and Research Supporting Center, National Institute of Technology, Maizuru College, Kyoto 625-8511, Japan
\textsuperscript{2)} Department of Civil Engineering and Architecture, National Institute of Technology, Maizuru College, Kyoto 625-8511, Japan
\textsuperscript{2)} takatani@maizuru-ct.ac.jp

ABSTRACT

In general, the evaluation of a site amplification effect is very important in earthquake engineering when a seismic damage to wooden house with a low seismic performance against a strong earthquake will be predicted by an accurate estimation of the seismic intensity at ground surface. In this paper, both horizontal and vertical microtremors at 51 measuring sites in the west district in Maizuru city were measured by servo type accelerometers, and also the predominant periods at 727 sites in the same area were numerically estimated from the predominant periods measured at 51 sites using the Inverse Distance Weighting method. Moreover, a seismic damage prediction of wooden house against a strong earthquake ground motion was conducted by a relationship between a seismic damage function and a maximum drift angle of wooden house.

1. INTRODUCTION

The evaluation of a site amplification effect, that is, a predominant period of ground surface layer plays a very important key role in the earthquake engineering when a seismic damage distribution of wooden house with low seismic performance will be predicted by an accurate estimation of the seismic intensity. In general, the site amplification effect has been analytically evaluated by the multiple reflection theory using a ground surface layer model with the soil characteristics at each observation site. However, it is so difficult to uniformly and accurately evaluate the site amplification effect for a wider area, because there is a limited and available information data and this evaluation procedure needs a great amount of work. Therefore, some site amplification effects can be evaluated from a relationship between the geological features/topography obtained from much simpler information and ground amplification characteristics. S-wave
amplification spectrum at the observation site without any ground information was evaluated based on the microtremor measurements (Nishikawa and Takatani, 2014, 2015).

In this paper, both horizontal and vertical microtremors at 51 sites in the west district in Maizuru city were measured by servo type accelerometers, and also the predominant periods at 727 sites in the same area were numerically evaluated from the predominant periods measured at 51 sites. Moreover, seismic damage prediction of wooden house against a strong earthquake ground motion with the Japan Meteorological Agency seismic intensity of “5 lower to 6 upper” level was conducted by the relationship between the vulnerability function and the maximum drift angle of wooden house.

2. OUTLINE OF MICROTREMOR MEASUREMENT

2.1 Microtremor measurement System

Photo 1 shows a microtremor measurement system, which consists of a preamplifier, a data logger, three servo-type accelerometers, a rechargeable portable battery, and a PC. Sampling frequency of a microtremor measurement is 160Hz, and its measurement time is 51.2s per one set (8,192 data number). Table 1 shows an outline of the microtremor measurement instruments shown in Photo 1 which were used in the microtremor $H/V$ spectral ratio measurement at 51 measuring sites in the west district in Maizuru city.
Table 1 Outline of instruments used in microtremor measurement.

<table>
<thead>
<tr>
<th>Instrument Name</th>
<th>Outline</th>
</tr>
</thead>
<tbody>
<tr>
<td>Real Time Vibration Analysis Device (DSA-PHOTON)</td>
<td>Frequency Range : Maximum 21,000Hz</td>
</tr>
<tr>
<td></td>
<td>A/D Transformation : 24-bit resolution</td>
</tr>
<tr>
<td></td>
<td>D/A Transformation : 24-bit resolution</td>
</tr>
<tr>
<td>Real Time Vibration Wave Controlling System (DSA-RTPro)</td>
<td>Vibration Output Function, FFT Analysis Function, Long Term Vibration Recording Function, Measurement Data Editing Function</td>
</tr>
<tr>
<td>Servo-type Accelerometer (V405-BR)</td>
<td>Measurement Range : ± 30 m/s², Resolution 1 x 10⁻⁶ m/s²</td>
</tr>
<tr>
<td>Preamplifier (PA-9102)</td>
<td>Frequency Range : 0.3 – 45 Hz</td>
</tr>
</tbody>
</table>

2.2 Microtremor H/V Spectral Ratio

In this paper, Fourier spectrum of a microtremor acceleration is numerically obtained from the microtremor acceleration data of 10s section selected from microtremor measurement data. Microtremor H/V spectral ratio can be obtained from both horizontal and vertical components of Fourier spectrum of microtremor acceleration, and then Fourier spectrum of microtremor can be smoothed by Parzen window with 0.4 Hz bandwidth. The microtremor H/V spectral ratio used in this paper is given by the following equation.

$$\frac{H}{V} = \sqrt{\left(\frac{H}{V}\right)_{NS-UD}^2 + \left(\frac{H}{V}\right)_{EW-UD}^2}$$  \hspace{1cm} (1)

where, $H/V$ is an average spectral ratio, $\left(\frac{H}{V}\right)_{NS-UD}$ and $\left(\frac{H}{V}\right)_{EW-UD}$ are NS and EW components of spectral ratio, respectively.

3 ESTIMATION OF H/V SPECTRAL RATIO BY THE INVERSE DISTANCE WEIGHTING METHOD

In this paper, a microtremor H/V spectral ratio at unmeasured site can be numerically estimated by the following Inverse Distance Weighting method (Shepard, 1968).

$$\frac{H}{V} = \sum_{i=1}^{N} w_i (\frac{H}{V})_i, \quad w_i = \frac{1/r_i^2}{\sum_{i=1}^{N} 1/r_i^2}$$  \hspace{1cm} (2)

where, $(\frac{H}{V})_i$ is a microtremor H/V spectral ratio at $i$-th site, $w_i$ is a weight at $i$-th measuring site, $r_i$ is a distance between $i$-th measuring site and unmeasured one, and $N$ is a total number of measured sites.

Fig. 1 shows the microtremor H/V spectral ratios at 51 measured sites, and Fig. 2 indicates a microtremor H/V spectral ratio distribution map estimated by the Inverse Distance Weighting method described above. Microtremor H/V spectral ratios at 727 estimating sites were numerically obtained from the H/V spectral ratios at 51 measured sites shown in Fig. 2. It should be noted that H/V spectral ratio at the estimating site can be obtained by Eq. (2) under the limited microtremor observations of 51 sites. It is found from Fig. 2 that the microtremor H/V spectral ratio in the seaside area in the west
Fig. 1 Microtremor measuring points in the west district in Maizuru city

Fig. 2 Predominant period interpolation result by microtremor measuring points
district in Maizuru city trends to have a long predominant period, where an extensive
damage to the old wooden structure with a low seismic performance may occur during
a strong earthquake ground motion.

4 SEISMIC DAMAGE ESTIMATION OF WOODEN HOUSE WITH LOW SEISMIC
PERFORMANCE

4.1 Transition of Japan’s Building Standards Act

In this section, the transition of Japan’s Building Standards Act is described briefly.
Table 2 shows a transition of the Building Standards Act in Japan since 1920. The
Building Standards Act has been amended based on the building damage due to a ma-
jor earthquake. After the Kanto Earthquake (M7.9) in 1923, the Urban Area Building
Standards Act has been significantly amended in 1924, and new Seismic Design
Standards Act has been enforced in 1981 after the Miyagi-ken Oki Earthquake (M7.4)
in 1978. Since 1981, wooden house has been built under a wall quantity regulation
condition. The effectiveness of this wall quantity regulation for wooden house was
proved in the Hyogo-ken Nanbu Earthquake (M7.3) in 1995. A lot of wooden houses
built before 1981 were destroyed by this earthquake, while almost wooden houses built
by new seismic design standards act after 1981 did not collapse. After the Hyogo-ken

<table>
<thead>
<tr>
<th>Year</th>
<th>Details of Transition</th>
</tr>
</thead>
<tbody>
<tr>
<td>1920</td>
<td>The Urban Area Building Standards Act Enforcement (New Building Standard Act in Japan)</td>
</tr>
<tr>
<td>1924</td>
<td>Significant Amendment of the Urban Area Building Standards Act (Seismic Intensity Design)</td>
</tr>
<tr>
<td>1950</td>
<td>Establishment of the Building Standards Act (Wall Quantity Regulation, Allowable Stress Design method)</td>
</tr>
<tr>
<td>1959</td>
<td>Amendment of the Building Standards Act (Fire-proof Regulation, Strengthening of Wall Quantity Regulation)</td>
</tr>
<tr>
<td>1971</td>
<td>Amendment of the Building Standards Act Enforcement Order (Wooden House Foundation Regulation: Concrete or RC Strip Footing)</td>
</tr>
<tr>
<td>1981</td>
<td>Significant Amendment of the Building Standards Act Enforcement Order (New Seismic Design Standards Act, Overhaul of Wall Quantity Regulation)</td>
</tr>
<tr>
<td>1987</td>
<td>Amendment of the Building Standards Act (The Lifting of the Ban of Three-story Wooden House Construction)</td>
</tr>
<tr>
<td>1995</td>
<td>Amendment of the Building Standards Act (Encouragement of Joint Metal or Hardware between Frame members)</td>
</tr>
<tr>
<td>2000</td>
<td>Amendment of the Building Standards Act (Mandatory of Ground Investigation, Specification of Joint and Connecting Metals, Balance Calculation of Seismic Wall Arrangement)</td>
</tr>
<tr>
<td>2006</td>
<td>Modified Seismic Retrofit Promotion Act (Promotion of Intentional Seismic Retrofit, Strengthening of Guidance for Building, Expansion of Financial Supporting Action)</td>
</tr>
</tbody>
</table>
Nanbu Earthquake in 1995, the Building Standards Act has been amended in 1995 so as to use the joint and connecting metals at the connection point between wooden frame members. The Building Standards Act has been amended in 2000, and the mandatory of ground investigation, the specification of joint and connecting metals, and the balance calculation of seismic wall arrangement in wooden house were conducted after 2000. Moreover, seismic retrofit for wooden house built before 1981 has been strongly promoted in 2006 in order to reduce seismic damage of wooden house with a low seismic performance against a strong earthquake ground motion.

In 2016, the Kumamoto Earthquake (M7.3) occurred on April 16 after a fore earthquake (M6.5) occurred on April 14. A lot of buildings over 100,000 were damaged by twice strong earthquakes, and so many wooden houses in Mashiki town were destroyed, where was experienced the JMA seismic intensity of “7” level twice. It was found that 17 wooden houses built after 2000 may be collapsed by two earthquake motions in a newsletter on the seismic damage investigation by the Architecture Institute of Japan on May 14. Seismic damage of wooden house may be caused by the weak ground, the construction date, and the insufficiency of seismic performance. At the present time, the seismic design of a wooden house is not conducted not to collapse against twice strong earthquake motions with the JMA seismic intensity of “7” level under the Building Standards Act. Therefore, seismic design regulation in the Building Standards Act will be amended in near future.

4.2 Seismic Damage Collapsing Ratio of Japanese-style Wooden House

Fig. 3 illustrates a relationship between the Japan Meteorological Agency seismic intensity and the collapsing rate of Japanese-style wooden house against a strong earthquake ground motion.
earthquake. There are three wooden house construction stages, that is, “Stage 1”: before 1960; “Stage 2”: 1961- to 1980; “Stage 3”: after 1981. A lot of marks with three marks and colors shown in Fig. 3 are plotted for every construction stage based on many seismic damage reports on Japanese-style wooden house. It is obvious from this figure that wooden house collapsing rate of each construction stage increases with the JMA seismic intensity. Collapsing rate of “Stage 1” in the JMA seismic intensity of “6 upper” level has a wide range of 19% to 83%. Each collapsing rate in “Stage 1”, “Stage 2”, and “Stage 3” at the instrumental seismic intensity 6.4 (the JMA seismic intensity of “6 upper” level) is 70%, 50%, and 11%, respectively. This implies that even a wooden house built in “Stage 3” may have a high possibility of the collapse against a strong earthquake ground motion with the JMA seismic intensity of “6 upper” level.

4.3 Seismic Performance of Wooden House and Its Maximum Drift Angle

In general, there is a certain significant relationship between a predominant period of the ground surface layer and a seismic damage to wooden house in many past earthquakes in Japan. In addition, a yielding base shear coefficient $C_y$ for wooden structure may be greatly related with the seismic damage against a strong earthquake ground motion. Based on the seismic fragility (damage) function for a yielding base shear coefficient $C_y$, the seismic damage estimation of the wooden house with a low seismic performance against a strong earthquake is conducted using a predominant period of ground surface layer evaluated in the previous section.

Generally the maximum response drift angle of wooden house may be estimated for several yielding base shear coefficients $C_y$ using an equivalent-performance acceleration response spectrum $S_{ae}$ (Hayashi, Y., 2002). In this paper, a target wooden house is assumed to be one degree of freedom system with the same mass as two-story wooden house, and its first natural mode is done to be linear. Also, a wooden house may contract one degree of freedom system with an equivalent height $H_e$ and an equivalent mass $M_e$.

Fig. 4 indicates a relationship between a yielding base shear coefficient $C_y$ and a drift angle $R$. Several signs of $Q$, $R_y$, and $M_e g C_y$ in Fig. 4 mean a horizontal load, a maximum drift angle, and a yielding load, respectively.

Equivalent-performance acceleration response spectrum $S_{ae}$ can be converted the
seismic performance of wooden house into an equivalent response spectrum, and is written by the following equation.

\[ S_{ae} = \frac{(2\pi T_e^2 H_e R)}{F_h} \]  

(3)

where, \( T_e \) is an equivalent natural period and \( F_h \) is a reduction rate of acceleration response spectrum.

Generally, a simplified restoring force characteristics of wooden house model can be assumed to be a bi-linear type, and the yielding shear force for the response drift angle \( R \), at the yielding point can be given by \( M_{eg} C_y \). Equivalent natural period \( T_e \) can be given by the following equation.

\[ T_e = 2\pi \sqrt{\frac{\mu RH_e}{C_y g}} \quad (R > R_y) \]  
\[ T_e = 2\pi \sqrt{\frac{(1+9(R/R_y)^{0.3}) \mu RH_e}{10 C_y g}} \quad (R \leq R_y) \]  

(4.a) (4.b)

where, \( \mu \) is a ratio of the equivalent mass of a single degree of freedom system to the mass of two-story wooden house.

Reduction rate of acceleration response spectrum \( F_h \) and damping coefficient \( h \) can be given by the following equations.

\[ F_h = 1.5 / (1+10h) \]  
\[ h = 0.05 + 0.2(1 - (1/\sqrt{R/R_y})) \]  

(5) (6)

Equivalent-performance acceleration response spectrum \( S_{ae} \) can be easily obtained from Eqs.(3) to (6) when the values of \( \mu \), \( R \) and \( C_y \) are assumed. Fig. 5 indicates a relationship between an input acceleration response spectrum \( S_a \) and an equivalent-performance acceleration response spectrum \( S_{ae} \). An intersection point between \( S_a \) and \( S_{ae} \) is an estimated response value, that is, a maximum drift angle \( R \) of wooden house at one yielding base shear coefficient \( C_y \) for the input earthquake ground motion.

Fig. 5 Comparison of equivalent-performance spectrum with response spectrum (Hayashi, Y., 2002)
Equivalent-performance acceleration response spectrum $S_{ae}$ can be numerically calculated for a yielding base shear coefficient $C_y$ and a drift angle $R$ from Eq. (3).

Fig. 6 shows three components of acceleration waves measured at Mashiki town in the Kumamoto Earthquake (M7.3) occurred on April 16, 2016 and their response spectra $S_a$ and equivalent-performance acceleration response spectra $S_{ae}$ calculated for several values of drift angle $R$ and yielding acceleration response spectra $S_{ae}$ calculated for several values of drift angle $R$ and yielding base shear coefficient $C_y$ (Sugino, M., et. al, 2016). In general, equivalent-performance spectrum $S_{ae}$ has a tendency to move from long period region to short one with the decrease of a yielding base shear coefficient $C_y$ as shown in Fig. 6(b). The natural period of $S_n(T)$ having a significant effect on the drift angle $R$ may change by a yielding base shear coefficient $C_y$. It is noted from Fig. 6(b) that seismic performance of wooden house may be higher with the increase of a yielding base shear coefficient $C_y$.

As stated above, there may be a significant relationship between the predominant period of ground surface layer and the maximum drift angle of wooden house against a strong earthquake ground motion. Accordingly, the predominant period of ground surface layer can be analytically estimated from the microtremor measurement. Therefore, the microtremor measurement may be an effective and significant system in evaluating the predominant period of ground surface layer.

4.4 Seismic Fragility Function of Wooden House

Seismic fragility function for a two-story Japanese-style wooden house can be evaluated for three yielding base shear coefficients $C_y=0.2$, $0.3$, and $0.4$ in this paper as mentioned in the previous section.

The maximum drift angle of a two-story Japanese-style wooden structure is analyt-
Yielding base shear coefficient $C_y = 0.2$

Yielding base shear coefficient $C_y = 0.3$

Yielding base shear coefficient $C_y = 0.4$

Fig. 7 Seismic fragility function for base shear coefficient and predominant period
Fig. 8 Seismic damage of old Japanese-style wooden house
(Yielding base shear coefficient $C_y = 0.2$)

Fig. 9 Seismic damage of old Japanese-style wooden house
(Yielding base shear coefficient $C_y = 0.3$)
Fig. 10 Seismic damage of old Japanese-style wooden house (Yielding base shear coefficient $C_y=0.4$)

ically calculated using a simulated earthquake ground motion wave due to a ground boring data in this paper. Based on a calculation result for each predominant period of ground surface, a total collapse ratio of wooden structure in this paper is defined as a percentage that the maximum drift angle is over 1/30.

A seismic fragility function for each yielding base shear coefficient $C_y$ of wooden structure can be obtained from a curve fitting technique. Seismic fragility function, that is, a cumulative distribution function given by a logarithmic normal distribution may be applied to the relationship between the predominant period of ground surface layer and the total collapse ratio of wooden structure.

Fig. 7 indicates a relationship between the seismic fragility function and the predominant period of ground surface layer for three yielding base shear coefficients $C_y$. The larger the yielding base shear coefficient $C_y$ becomes, the higher the seismic fragility function of wooden house is with the increase of a predominant period $T_g$.

4.4 Seismic damage prediction of old Japanese-style wooden house

Seismic damage prediction of old Japanese-style wooden house in the west district in Maizuru city can be numerically evaluated using the seismic fragility functions of wooden structure shown in Fig. 7, which were obtained from the procedure previously mentioned.

Fig. 8 shows seismic damage prediction result of old Japanese-style wooden
house with a yielding base shear coefficient $C_y=0.2$ against a strong earthquake ground motion with the JMA seismic intensity of over “6 upper” level. This seismic damage prediction was numerically evaluated from the seismic fragility function for a yielding base shear coefficient $C_y=0.2$ shown in Fig. 7(a). Seismic damage of $D>80\%$ for old Japanese-style wooden house covers a wide range of the west district of Maizuru city, and also is distributed in the range of the predominant period of $T>0.3s$ shown in Fig. 2.

Fig. 9 indicates seismic damage prediction result of old Japanese-style wooden house with a yielding base shear coefficient $C_y=0.3$ against a strong earthquake ground motion with the JMA seismic intensity of over “6 upper” level. This seismic damage prediction was numerically evaluated from the seismic fragility function for a yielding base shear coefficient $C_y=0.3$ shown in Fig. 7(b). It is found that seismic damage of $D>60\%$ for old Japanese-style wooden house is distributed in the range of the predominant period of $T>0.5s$ shown in Fig. 2.

Fig. 10 illustrates seismic damage prediction result of old Japanese-style wooden house with a yielding base shear coefficient $C_y=0.4$ against a strong earthquake ground motion with the JMA seismic intensity of over “6 upper” level. This seismic damage prediction was numerically evaluated from the seismic fragility function for a yielding base shear coefficient $C_y=0.4$ shown in Fig. 7(c). It is found that seismic damage of $D>20\%$ for old Japanese-style wooden house is distributed in the range of the predominant period of $T>0.5s$ shown in Fig. 2. Consequently, because the old Japanese-style wooden house with a yielding base shear coefficient $C_y=0.4$ has a high seismic performance against a strong earthquake ground motion, its seismic damage is a narrow range and also is limited within the range of predominant period of $T>0.5s$.

5. CONCLUSIONS

The evaluation of a site effect is very important in the earthquake engineering when a seismic damage distribution of wooden house will be predicted by an accurate estimation of seismic intensity. In this paper, both horizontal and vertical microtremors at 51 sites in the west district in Maizuru city were measured by servo type accelerometers, and also the predominant periods at 727 sites in the same area were numerically evaluated from the predominant periods measured at 51 sites. Moreover, seismic damage prediction of wooden house against a strong earthquake ground motion with the Japan Meteorological Agency seismic intensity of “5 lower to 6 upper” level was conducted by the relationship between the seismic fragility function and the maximum drift angle of old Japanese-style wooden house.

The summary obtained in this paper is as follows.

(1) A predominant period at the site without any ground information can be easily evaluated from microtremor $H/V$ spectral ratio obtained from microtremor measurement.

(2) Using the Inverse Distance Weighting method, a distribution map of predominant period of ground can be numerically estimated under the limited microtremor observation values.

(3) Seismic fragility function with a base shear coefficient can be obtained from the maximum drift angle of old Japanese-style wooden house, which is evaluated by the predominant period of ground. Also, the collapse rate of old Japanese-style wooden house for each base shear coefficient can be predicted by the seismic fragility func-
The challenge of the future is to make an accurate evaluation of seismic damage prediction of old Japanese-style wooden house against a string earthquake ground motion with the Japan Meteorological Agency seismic intensity of “6 upper” level. In addition to the evaluation of seismic damage prediction of old Japanese-style wooden house, it is very important to accurately evaluate a predominant period of ground surface layer under the limited microtremor measurements. Predominant period distribution greatly depends on the seismic fragility function for a base shear coefficient as well as $H/V$ spectral ratio obtained from microtremor measurement.

Therefore, further investigation on seismic damage prediction of old Japanese-style wooden house against a string earthquake ground motion may be needed to accurately evaluate the effect of seismic fragility function with a base shear coefficient on the seismic damage prediction of old Japanese-style wooden house and make some concrete conclusions.

REFERENCES