# **Inventory Development for Natural and Built Environments:** Use of Seismic Motion and Microtremor for Vulnerability Assessment

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# Abstract

This study aims to establish and spread the damage assessment system for both ground and structures. In Mexico City, repeatedly attacked by big earthquakes, microtremor measurement was conducted at many points of ground and buildings, in collaboration with CIRES, Centro de Instrumentación y Registro Sísmico. While having grasped the present earthquake response characteristic of the ground and structures using measured data, the ability of assessment methods for earthquake resistance was examined. Consequently, the following results were obtained:

- (1) It was conformed that the earthquake response characteristics of the ground and structures can be exactly grasped by microtremor. And also, measured microtremor data is useful as basic data to predict future earthquake damages of the measured object.
- (2) The evaluating methods of vulnerability indices for ground and structures based on investigated data were proposed. Moreover, the validity of this method was verified by comparing with actual earthquake damages.

Our research aim at the next stage is to improve the accuracy of the proposed method and to spread its use in many economies.

Key Words: vulnerability index, dynamic characteristics, ground and structures, microtremor

## **Background, Goal and Objective**

Earthquake disaster is caused by the relation among the earthquake load and the vulnerability of ground and structures, which receive it. Earthquake load includes static load such as fault movement and dynamic load by earthquake motions. Although earthquake damage caused by fault movement is actively discussed recently, earthquake disasters are overwhelmingly caused by the dynamic load. Thus it is urgently needed to establish methods to predict the vulnerability of the ground and structures against the dynamic load and to evaluate the damage level caused by the dynamic load. The aim of this research is to establish a simplified accurate method to evaluate the vulnerability of the ground and structures using microtremor.

## Methodology: Concept of Vulnerability Indices

In this paper the vulnerability indices are defined as an index concerning the presumed value of shear strain for surface ground or drift angle for structures, which is derived from the product of the index and maximum acceleration of the expected earthquake motion. It is expected that these vulnerability indices can rationally estimate the risk of the ground and structures for assumption earthquakes. Furthermore, the validity of these vulnerability indices is expected to be generalized as compared with actual earthquake damage.

## In Case of Ground

When shear deformation at ground surface at the time of earthquake is set to  $\delta_g$ , the strain of surface ground  $\gamma_g$  is expressed as follows in approximation: (see Figure 1).

$$\gamma_{g} = \delta_{g} / h$$

$$= e \times a / (2\pi F_{g})^{2} \times 4F_{g} / V_{s}$$

$$= e \times A_{g} \times a / (\pi^{2} F_{g} V_{b}) \times V_{b} / V_{s}$$

$$= \frac{A_{g}^{2}}{F_{g}} \times \frac{e \times a}{\pi^{2} \times V_{b}}$$

$$= K_{g} \times C \times a$$
(1)

Where,

$$K_g = A_g^2 / F_g$$

$$C = e/(^2 \cdot V_b)$$
(2)
(3)





 $\gamma_g$ : Shear strain (in powers of 10<sup>-6</sup>)  $A_g$ : Amplification factor of the surface ground  $(=V_b/V_s)$   $F_g$ : Natural frequency of the surface ground (Hz)  $(=V_s/4h)$  a: Maximum acceleration of the basement(Gal) e: Efficiency of the maximum acceleration  $V_b$ : S-wave velocity of the basement (m/sec)  $V_s$ : S wave velocity of surface ground (m/sec) h: thickness of surface ground

Here, if it is assumed that it is  $V_b = 600$  m/s and e = 0.6, it is come to C = 1.0. Effective strain can be presumed as a value which multiplied by  $K_g$  value and the maximum acceleration in case of an earthquake.  $K_g$  value is an index peculiar to the measured ground, and it is possible to express the vulnerability of the ground. As shown in equation (2),  $K_g$  value can be easily derived from natural frequency  $F_g$  and amplification factor  $A_g$  which were presumed in each measurement point.

## In Case of Structures

It is considered that the vulnerability of structures against earthquake disasters can be estimated by the drift angle, related to the input earthquake acceleration  $\alpha$  in cm/s<sup>2</sup>. Here,  $\alpha$  is a portion which affects this structure among whole earthquake motion *a*, namely,

$$\alpha = e \times a \tag{4}$$

where *e* shows the efficiency of earthquake motion working for this structure. A deformation performance and the earthquake motion amplification can be estimated from the dynamic characteristics of structures. Here, the primary natural frequency of the structure that seems to have influence on earthquake damage is considered. Displacement  $\delta_i$  of *i*-th floor is estimated from this primary natural frequency *F* and amplification factor  $A_i$  of *i*-th floor as followings (see Figure 2).

$$i = A_i \times /(2 F)^2 \tag{5}$$

So, the drift angle  $\gamma_i$  of *i*-th floor is shown as,



Figure 2. Schematic model of n-th floor structures and its mode shape.

$$\gamma_i = (\delta_{i+1} - \delta_i) / h_i \tag{6}$$

$$=\Delta A_i \times \alpha / (2\pi F)^2 / h_i \tag{7}$$

$$= e \times Kbi \times a \tag{8}$$

where,

$$K_{bi} = \Delta A_i / (2\pi F)^2 / h_i \times 10000 \tag{9}$$

 $\Delta A_i$ : difference of amplification of the *i*-th floor, (=  $A_{i+1} - A_i$ ), and  $h_i$ : the height of *i*-th floor in m.

Thus, the drift angle  $\gamma_i$  for each floor is estimated by multiplying the vulnerability index  $K_{bi}$  the maximum acceleration on the basement ground *a* in cm/s<sup>2</sup> and the efficiency *e* of earthquake motion. Here,  $_{av}K_b$  value is the average of  $K_{bi}$  for each structure.

$$_{av}K_{b} = A/(2\pi F)^{2}/H \times 10000$$
(10)

where,

*A* : amplitude of the top floor, and *H* : height of the structure in m.

In addition, when  $_{av}K_b$  is substituted for  $K_{bi}$  of equation (8), the average drift angle  $\gamma_{av}$  will be calculated.  $K_{bi}$  and  $_{av}K_b$  are expressed in powers of 10<sup>-6</sup>, 10000 in equations (9) and (10) is used to multiply for adjustment.

#### Verification Method of the Vulnerability Indices

Microtremor measurement has been conducted for many ground and structures in Mexico City affected by earthquakes frequently. For ground, the vulnerability index Kg value is

calculated and verified to estimate the validity by comparing it with the past earthquake damages of 1957, 1979 and 1985. For structures, many types of structures, including both few stories and high rise buildings, were measured to obtain their dynamic characteristics. Many buildings have been measured for microtremor and their natural frequency has been obtained after the 1985 Michoacan Earthquake. In 1995, one relatively strong earthquake attacked Mexico City and some of these buildings were affected. In this study, microtremor measurement was conducted for some of these buildings to evaluate the effect of earthquake motions in the change of natural frequencies. As a result, the validity of vulnerability index obtained from the microtremor was checked by comparing it with the change of natural frequency as a quantitatively determined damage.



Figure 3. Measurement points in Mexico City

#### **Research Output of Phase I**

For Mexico City, measurement lines across the area with different ground condition or damage situation were set up around the affected area of the 1985 Michoacan Earthquake. Microtremor measurement for ground was conducted along these lines every 200 m approximately, as a result, natural frequencies and amplification factors were analyzed (see Figure 3).



Figure 4. Comparison between Microtremor and Strong Motion on Spectral Ratio H/V in Mexico

Figure 4 shows the result of comparing H/V spectrum ratio of both strong motion and microtremor. These strong motion records were observed at some stations in Mexico City. The H/V spectrum ratio is supposed to approximate the dynamic characteristics of surface ground. The shape of the ratio as the peak value or predominant frequency can be well in agreement both strong motion and microtremor. It shows that it is possible to estimate the dynamic characteristics from microtremor. It is aimed at from now on that H/V spectrum will be compared with dynamic characteristics of surface ground using larger strong motion records and the validity of the application technique will be verified to improve the accuracy.



Figure 5 - 7 show the distribution of natural frequency Fg, amplification factor Ag and vulnerability index Kg derived from Fg and Ag, for the ground of Mexico City. Each index shows a difference of the ground characteristics for hill zone, transition zone and deposit zone, and it is harmonic to the earthquake damage situations of 1957, 1979 and 1985.

On the other hand, microtremor measurement was conducted precisely for 24 buildings including both few stories and high-rise buildings and their foundations. Figure 8 shows the relationship between the natural frequency Fs and the number of stories N. This natural frequency was estimated from the microtremor at both the top and bottom of the building. In this figure, following equation is also attached as a reference.

$$\frac{1}{F_b} = 0.06N \sim 0.1N \tag{11}$$

Many results of the measurement shows smaller values than the estimated value obtained with the equation above. These structures were the most affected by past earthquakes. Also the mid-to-high-rise buildings with more than eight stories were affected by past earthquakes, except two, which were built in recent years. In addition, it is supposed that the mid-to-high-rise buildings that suffered a damage, resonated with soft deposit ground from their natural frequencies. Although the natural frequency of few stories building is higher than the value presumed from a standard  $F_b$ -N relation, the natural frequency of a mid-to-high-rise building having suffered damage in 1995 shows a lower value than a standard value. One building reinforced after suffering damage, 21 stories buildings under new constructing standards and other high-rise buildings conform to a standard  $F_b$ -N relation in general. From the above mentioned, it is thought that the vulnerability of buildings can be estimated roughly from the  $F_b$ -N relation of Figure 8.



Figure 8. Relationship between number of stories and natural frequency on buildings

# **Any Other Relevant Information**

The practicality of the proposed vulnerability index for structures was verified with the buildings in Istanbul before and after the 1999 Kocaeli Earthquake in Turkey (Mw=7.6, maximum PGA for rock site in Istanbul was 41 Gal), as an example. Microtremor measurements have been

conducted for several types of structures including historical Suleymanive monuments such as Hagia museum, mosque, Sophia Sehzade mosque, and a newly constructed 14-story office building, % before the August 17, 1999 Kocaeli .⊆ dF/F Earthquake. In order to investigate the impact of this earthquake on the measured structures in Istanbul, microtremor measurement was again conducted. These measurements were performed by in cooperation with Bogazici University and Istanbul Technical University.

Consequently, even if not visible, the influence of the earthquake could be



confirmed. Moreover, the influence of an earthquake which appears as the vulnerability index and the change of natural frequencies was able to be checked quantitatively. The shift rate of natural frequency were 2.8 % for Suleymaniye mosque built approximately 500 years ago, 8.9 % for the Hagia Sophia museum built approximately 1500 years ago, 4.8 % for Sehzade mosque built approximately 500 years ago and 8.5% for an office building newly built. It seems that the impact of the earthquake is small; thus the change of the natural frequency is also small. For the measured structures, the rigidity was lowered 7 - 16 % by the Kocaeli Earthquake. As said before, natural frequency shifts, dF, can be considered as an expression of the degree of damage.

Figure 9 shows the relationship between  $_{av}K_b$  value and the rate of natural frequency shift, dF/F. The relation between  $_{av}K_b$  and the frequency shift rate suggests that  $_{av}K_b$  can be given as damage degree before the earthquake. Figure 9 shows that the larger  $_{av}K_b$ , the larger damage in general. Both Suleymaniye and Sehzade mosque have the same type of structure the structure of the Hagia Sophia museum is similar to them. On the other hand, the office building has different characteristics a RC structure. The change of natural frequency also corresponds well to the vulnerability index against earthquake disasters for structures. This suggests that the proposed index  $_{av}K_b$  value is appropriate. Thus, it is expected that the danger of a structure can be assessed by  $_{av}K_b$  before sustaining earthquake damage.

# **Concluding Remarks**

The target of this study in the Research Stage I is to propose a simple and exact vulnerability index based on the result of microtremor measurements for ground and structures. As a result of this study, it was confirmed that the seismic response characteristics of ground and structures could be exactly obtained from the result of measurements. And also, a widely applicable vulnerability index was proposed from the viewpoint of the strain corresponding to typical deformation of ground and structures. The validity of the proposed vulnerability index was verified by comparing its results with the damage and/or influence of actual earthquakes.

According to the proposed vulnerability index, it is expected that the exact area and extent of damage will be able to be predicted by using the investigation data before the earthquake. The earthquake damage situation will be obtained exactly by comparing the investigation results before and after the earthquake. After this, it is expected that the rational countermeasure before earthquakes and quick response after earthquakes will be more exactly and efficient. In this way, limited resources will be utilized effectively during disasters.

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