Evaluation of Natural Frequency Through Measurement of Ambient Vibration for Wall-type RC Structures

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Abstract

Presently, apartment structure plans tend to depart from the standard pattern based on owners' requests and frame structures are becoming popular instead of wall-type structures and typical structure systems. Moreover, traditional concepts concerning effective land use in addition to importance of view lead to building high-rise buildings with heights of more than 100 m. According to UBC97, the seismic design of such buildings is gaining more attention, specifically, calculations of exact period are very important for equivalent static analysis. The purpose of this study was to consider the safety factors for the natural period of wall-type and high-rise apartments by comparing the natural period obtained by ambient vibration tests and period simplified formulae recommended by UBC97.

Target structures followed by a building's height, structural system and plan type were selected. The reinforced concrete structure apartment's natural periods were measured using the ambient vibration method. An approximately 30% error between the eigenvalue analysis and test data obtained by the ambient vibration method has been reported.

Keywords: Wall-type structure; fundamental vibration period; ambient vibration; period formula

1. Introduction

The basic aim of seismic design currently used in structures is to obtain the lateral force to weight ratio using the unique dynamic property and applying it as the seismic load to a structure. Most seismic designs are made to prepare for earthquakes only after incurring earthquake damage and then recognizing its severity. In the US, seismic designs were established following the 1971 San Francisco Earthquake and in Korea, seismic design was first introduced in 1988. So, from 1988, to the early 1990's, seismic design was difficult to apply in actual work, since the concept was not fully understood. As a result, many structures were constructed with poor seismic design. Moreover, since the late 1990's, occupants started to demand greater variety in the shapes of buildings. At this time, the earthquake-vulnerable piloti-type apartment or flat plate and flat slab structure, where the shear wall core of the center of the building is connected to an external column, was adopted to reduce the story height. As a result, apartment buildings having various floor plans were introduced in new towns in Gyeonggi Province in Korea. With such diverse shapes, structural engineers doubted the validity of the various coefficients applied in structural design. They experienced particular trouble calculating the natural period reflecting the dynamic property during the seismic design of buildings. The equation for the vibration period presented in the structural design standard in Korea is based on the earthquake data from other countries, and existing studies have reported a significant difference between the actual measurements and the calculations¹. Therefore, many equations in Korea must be reviewed further.

The purpose of this study is to measure the natural period as the basis of seismic design of an apartment building and to evaluate the actual natural period of the building according to the floor plans and structural type of an apartment building in Korea in order to present economic measures for seismic design.

2. Natural Period Calculation

2.1 Equation for Period Calculation in US and Korea

The standard in the US is based on the ATC3-06² of 1975, which is the value determined by the structural period value actually measured during the San Fernando Earthquake in 1971. In Korea, the same equation is used as that given in UBC97³ and

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ATC3-06 in the US. These provide the equation for period calculation for steel moment frames, reinforced concrete moment frames, and other structures.

The approximate basic vibration period $T$ (sec.) is calculated using the following equation:

$$T_a = C_T h^{3/4}_n$$  \hspace{1cm} (1)

Here,

- $C_T$ = 0.085: Steel moment frame,
- 0.073: Reinforced concrete moment frame and steel eccentrically braced frame,
- 0.049: All other buildings

$h_n$: Height from the bottom of the building to the top (m)

In the case of a steel reinforced concrete shear wall structure, Equation (1) or (2) can be used.

$$T_a = 0.0743 h_n^{3/4} / \sqrt{A_c}$$  \hspace{1cm} (2)

Here,

- $A_c = A_e [0.2 + (D_e / h_n)^2]$
- $A_e$: Cross sectional area of shear of the shear wall parallel to the direction of the seismic load on the first floor (m²),
- $D_e$: Length of the shear wall parallel to the direction of the seismic load on the first floor (m)

### 2.2 Other Equations for Period Calculation

In Japan and other countries, equations such as Equations (3) ~ (5) are used for period calculation. These equations consider only the height ratio and the number of floors as a variable (i.e. these variables are only related to the height component) for steel reinforced buildings.

- **Japan**: $T = h_n (0.02 + 0.01 \sigma)$ \hspace{1cm} (3)
  - $h_n$: height of the whole structure
- **India and Bangladesh**: $T = 0.1N$ \hspace{1cm} (4)
  - $N$: Number of floors
- **Canada**: $T = 0.1 (N - 1)$ \hspace{1cm} (5)

### 2.3 Existing Research Investigation for the Natural Period

The natural period of a structure is dominated by the shape and height of the structure. During the 1990's in Korea, most apartment buildings were around 20 floors in height, while more recently apartment buildings of more than 30 stories have also been constructed. Therefore, the natural period is expected to vary according to the height. Moreover, the floor plan shape also ranges from a square shape to a Y or K shape; the natural period is therefore also expected to vary according to the shape. The actual measurement of the natural period and the equation for the period calculation therefore need to be reviewed. The study by Li-hung Lee\(^4\) of the period calculation of 20 apartment buildings in Korea shows a correlation to the equation using the height and effective area of the shear wall, as shown in Fig.1.

Moreover, the current standard equation used in Korea is judged to be a conservative equation. In particular, as the fundamental frequency of a structure is closely related to the stiffness of the structure, the evaluation of the tendency of stiffness change according to the measured natural period will greatly help the maintenance of the structure.

The study by Khan\(^5\) of the equation for the period calculation showed that the infill, which is the nonstructural material ignored in the structure modeling, significantly affects the period. Therefore, the infill wall needs to be considered in period calculation. Rakesh\(^6\) studied the vibration period according to the frame form and reported that the measured period was always greater than the period calculated by a simple equation in all cases of reinforced concrete moment frame because of the lowered stiffness due to the fracture of the RC structure when the ground acceleration was 0.15g or more. In other words, the current simple equation yields an excessively short period at the high ground acceleration and needs to be modified.

### 3. Measurement and Results

#### 3.1 Method of Measuring the Period

**3.1.1 Structure**

Various apartment buildings constructed in the capital region were studied. Four high-rise apartment buildings that have a tower type plane and 4 linear type apartment buildings were measured by applying the existing equation for period calculation. The representative structural plane of each apartment building type was collected and 8 buildings were selected in consideration of the representative plane, elevation shape, and building height as shown in Table 1.; the vibration period of each building was then measured. Whole buildings were completed after new construction prior to moving-in. Therefore cracks were ignored.
The tower type apartment buildings constructed in Korea are generally high-rise with more than 25 floors. Although high-rise apartment buildings are generally constructed of a steel frame and a steel framed reinforced concrete structure, reinforced concrete wall type or shear wall core and flat slab type apartment buildings with more than 25 floors have recently been constructed in the capital region; they were therefore selected for the study.

The linear type apartment buildings are generally 15-story buildings, which were mostly constructed between 1980 and the early 1990's, when the apartments were supplied on mass. In apartment buildings designed prior to 1988, seismic design was not considered and the period calculation equation was thus not applied. As such, many buildings are likely to have long periods. The buildings targeted for this study were newly constructed buildings in which seismic design was incorporated. These linear type buildings were included to compare with the tower type apartment buildings.

### 3.2.2 Measurement of Vibration Period

(A) Measurement of Ambient Vibration

Measurement of ambient vibration can be performed to obtain the dynamic characteristics of buildings. The fundamental period can be obtained by measuring the ambient vibration. This measurement method does not damage the building and a high volume of data can be obtained for the spectrum average through a long period of measurement. However, the spectrum of ambient vibration is smaller than one measured under an actual seismic event, because when an earthquake occurs the stiffness of a structure becomes lower than a structure without seismic damage. Therefore, a more conservative result in natural period than that for the actual behavior is likely to be obtained. Moreover, to measure the ambient vibration, a high-resolution sensor which can measure the amplitude of 10-5 g or larger is needed.

(B) Synchronized Human Excitation Method

When the repeated excitations conforming to the natural period of a building are applied to a building, the response amplitude of the building gradually increases due to the resonance. The type of resonance based excitation method using manpower as the excitation force is generally called the synchronized human excitation method. The advantage of this method is that it does not require additional equipment and is a simple measurement method applicable immediately before the completion of construction, or even after public use. However, this method requires the forcing frequency to induce the resonance. This forcing frequency can be obtained by measuring the ambient vibration. Moreover, this measurement method can only be carried out by persons who are familiar with it, in order to obtain an accurate measured value.

### 3.2.3 Measurement Methods Applied in this Study

(A) Ambient Vibration Test

As shown in Fig.2., the measurement system is installed first, and the preliminary data for setup are then acquired. The test data are then obtained. Upon the consent of construction site management, the test is conducted on the roof when no work is being performed. The test is conducted under the condition of minimum noise around the measuring system (accelerometer).

(B) Synchronized Human Excitation Method

When the repeated excitations conforming to the natural period of a building are applied to a building, the response amplitude of the building gradually increases due to the resonance. The type of resonance based excitation method using manpower as the excitation force is generally called the synchronized human excitation method. The advantage of this method is that it does not require additional equipment and is a simple measurement method applicable immediately before the completion of construction, or even after public use. However, this method requires the forcing frequency to induce the resonance. This forcing frequency can be obtained by measuring the ambient vibration. Moreover, this measurement method can only be carried out by persons who are familiar with it, in order to obtain an accurate measured value.

### Table 1. Target Buildings for Actual Measurement of Vibration Period

| Building* | Feature | Height (m) | General** |
|-----------|---------|------------|-----------|
| T-1       | Y type  | 104.3      | 2.9 m/210 mm |
| T-2       | Intermediate height | 75.3 | 2.9 m/210 mm |
| T-3       | Y type, Clearance between stories | 104.3 | 2.9 m/180 mm |
| T-4       | K type, 4 households on each floor | 104.3 | 2.9 m/210 mm |
| I-1       | 2 households on each floor | 44.8 | 2.8 m/18 mm |
| I-2       | Hallway type, Clearance between stories | 50.4 | 2.8 m/18 mm (Partial pilotis) |
| I-3       | 35.2 | 2.7 m/18 mm |
| I-4       | 47.6 | 2.8 m/15 mm (Partial pilotis) |

*Model Definition (Type): T-Tower type, I-Straight line type ** Story Height/Slab Thickness

### Fig.2. Sequence of Ambient Vibration Data Measurement

### Fig.3. Sequence Synchronized Human Excitation Data Measurement
(B) Synchronized Human Excitation Test
To improve the reliability of ambient vibration data, the synchronized human excitation test only checks if the resonance is generated in the first fundamental period. Therefore, the ambient vibration test was conducted first before the synchronized human excitation. Since the purpose of the synchronized human excitation test is to check the natural period measured in the ambient vibration, the synchronized human excitation test was performed with 3~5 people.

3.2.4 Measurement System Installation and Data Measurement
(A) Measurement System
Fig. 4. shows the measurement system installed on the rooftop of a building. A sensor channel of the accelerometer was installed in the short side direction and in the long side direction. Another channel was installed at the symmetrical point of the measurement position toward the measurement direction in order to monitor the effect of building torsion.

(B) Data Acquisition
- Positions of Measurement Sensors
Three accelerometer sensors were used for measurement. As shown in Fig. 5., sensor ① measured the effect of torsion while sensors ② and ③ measured the acceleration in each direction. The sensors were installed based on the directions set in the structural analysis of the building to be measured.
- Measurement Position in Each Building
The data were obtained at the top floor, and only the dominant 1st mode was measured. Since the largest amplitude occurs at the top floor in the 1st mode, a sensor was placed on the top floor of each building. Vibration waveforms were obtained from 3 measurements for 20 minutes each. Fig. 6. shows the measurement positions in each building.

3.3 Measurement Result
3.3.1 Ambient Vibration Test
The fundamental frequencies generated by the ambient vibration applied to the building listed in Table 3. were measured, and the reciprocally related fundamental periods were then measured. For each test, the sensors were installed in each building, and a set included 3 measurements for 20 minutes each. As the buildings were still under construction, the tests were conducted on public holidays and 1 set was measured for all buildings. At the beginning of the test, while the data showed some errors due to the surrounding noise, no problem occurred with the frequency. Table 2. shows the fundamental frequency and natural period measured in each building.
3.3.3 Synchronized Human Excitation Test

The synchronized human excitation test was conducted to verify that the measured ambient vibration data were actually the fundamental frequency of the building. Since the ambient vibration data can be assumed to be reliable when the synchronized human excitation test generates the resonance, the synchronized human excitation test was conducted on the T-1 and I-3 buildings for verification. For the test, 3 persons exerted excitation on the building as shown in Fig. 7. (a) based on the 1st natural period presented in the ambient vibration test result in Table 3.

When the building is excited with 0.6Hz (Fig. 7. (c)), which is the natural frequency generated by the ambient vibration, resonance occurs and the amplitude then decreases when the synchronized human excitation is stopped with proper damping as shown in Fig. 7. (d). This means that the resonance occurred even when a small force such as manpower was applied in the same fundamental frequency of the building, and thus the result of the ambient vibration test can be considered to be reliable. Moreover, the fact that the vibration was generated even by a small load such as ambient vibration means that the excited frequency was the natural period of the weak axis. Using the resonance data, the damping of the structure can be estimated, and this will be useful for measuring the deterioration of buildings.

In the I-3 building, the 1st natural period by ambient vibration was measured to be 1.80Hz; the metronome was thus set to 1.80Hz and the sound generated by the metronome was used for the synchronized human excitation. Using the preliminary test result, two people performed excitation on the building to generate the accelerated vibration waveform. The FFT shows the measurement of frequency at 1.83Hz. Resonance similar to the T-1 building was confirmed.

### Table 2. Fundamental Frequency Measurement

| Measured Building | Measured Frequency (Hz) | Fundamental Vibration Period (s) |
|-------------------|-------------------------|---------------------------------|
|                   | Weak axis | Strong axis | Weak axis | Strong axis |
| Tower Type        |           |             |           |             |
| T-1               | 0.62      | 0.76        | 1.61      | 1.32        |
| T-2               | 0.91      | 1.11        | 1.10      | 0.90        |
| T-3               | 0.57      | 0.66        | 1.76      | 1.52        |
| T-4               | 0.53      | 0.59        | 1.89      | 1.69        |
| Straight Line Type|           |             |           |             |
| I-1               | 1.51      | 1.71        | 0.66      | 0.58        |
| I-2               | 1.21      | 1.93        | 0.83      | 0.52        |
| I-3               | 1.8       | 2.59        | 0.49      | 0.39        |
| I-4               | 1.18      | 1.76        | 0.85      | 0.57        |

### Table 3. Fundamental Frequency Measurement

| Measured Building | Ambient Vibration Frequency (Hz) | Synchronized human excitation Frequency |
|-------------------|---------------------------------|----------------------------------------|
| Tower Type        |                                 |                                        |
| T-1               | 0.62                            | 0.65                                  |
| Line Type         |                                 |                                        |
| I-3               | 1.8                             | 1.83                                  |

3.4 Comparison of Vibration Period Criteria for Verification

3.4.1 Existing Cycle

(A) Other Frame Type Structures

The measured data were compared to the period calculation equation presented in UBC97 and introduced in Chapter 2. Fig. 8. shows a comparison with the equation for other frame type structures.

The circular points are the measurements of vibration mode to the longitudinal direction, while the X points are the measurement of vibration mode to the transverse direction. Although the measurements generally show the shape of the equation in the design standard, measurements for buildings taller than 100 m have a larger error range and tend to be conservative. Therefore, if the simple equation in UBC97 was used to calculate the period for the design of high-rise apartment buildings of 25 or more floors, the design is likely to be rather conservative.

3.4.2 Inter-Relationship between Ambient Vibration and Earthquake

The natural period of a structure shows the unique features according to the mass and rigidity of a structure. In the building standards of many countries, including those for seismic design, basic vibration periods are included for the equation to calculate the design and shearing force. This is because the basic vibration period acts as an important variable that represents the
Measuring such basic vibration periods is very difficult because vibration must be forced by a vibration source for the structure. Furthermore, the target structures are to be sold and the data must therefore be acquired without any loss since they must be intact when handed over to their future owners. However, for the data in the range of this research, the period must be calculated by measuring the vibration response of the structures when earthquakes occur; it is therefore necessary to use existing studies to examine the relationship of the behavior of the building during actual earthquakes and during regular times where no vibrations occur.

James L. Beck et al. reported approximately 30% error between the eigenvalue analysis and test data using the actual Northridge earthquake data for 4 story and 11 story steel structures. This difference is because the analytical result is from the simulations only considering the framework of the building; the data acquired during a seismic event includes different load cases and nonstructural members. Moreover the structure can be damaged under service environment.

R.D. Marshall et al. conducted a study on the relationship of a building's earthquake response according to the LOMA PRIETA earthquake with normal non-vibration states. This study demonstrated that the natural period measured during actual earthquakes increased by 20% - 30% compared to the natural period of normal non-vibration states.

The buildings considered in this study are of the Reinforced Concrete Shear Wall-Moment Frame System similar to the CSUH Administration building (61 m) and Pacific Park Plaza building (94 m). Thus, approximately 25% higher period than ones measured from ambient vibrations is appropriate for use in comparison with other research results. It can be found in R.K.L Su's report similar results.

### 3.4.3 Comparison Analysis Results

A preceding study reported that the vibration period obtained from structural analysis did not consider the role of nonstructural materials, such as finishing materials, and thus differed significantly from the actual vibration period of the building. Although not all of the nonstructural materials could be considered in this study, the role of the slab needs to be considered for better accuracy of the dynamic analysis of a structure. Thus, the cases of a slab stiffness of 100%, 50%, and 30% were compared with the diaphragm behavior modeling of the slab for conventional analysis. The commercial structural analysis program, MIDAS, was used for analysis. The program uses the Rayleigh-Ritz Method based eigenvalue analysis of the fundamental frequency of a structure.

The analysis showed that the 100% slab stiffness yielded an approximately 50% lower measurement of the fundamental vibration period of the building, as shown in Fig.9. This is because the structure modeling did not reflect the nonstructural factors and the
measurement of the building reflected the fact that no damage had occurred to the building.

Table 5. Error of Measured and Calculated Periods with Consideration of Slab Rigidity

| Measured Building | Measured Period | Measured Period×2 | Calculated Period (A) | Calculated Period (B) | Error Rate (B/A) |
|-------------------|-----------------|-------------------|-----------------------|-----------------------|------------------|
| T-1               | X 1.61          | 3.22              | 2.52                  | 2.77                  | 1.05             |
|                   | Y 1.32          | 2.64              | 1.75                  | 1.48                  | 0.82             |
| T-2               | X 1.10          | 2.2               | 1.8                   | 1.48                  | 0.82             |
|                   | Y 0.90          | 1.8               | 1.48                  | 1.48                  | 1.05             |
| T-3               | X 1.76          | 3.52              | 3.66                  | 3.18                  | 0.97             |
|                   | Y 1.52          | 3.04              | 1.17                  | 1.17                  | 1.01             |
| T-4               | X 1.89          | 3.78              | 3.66                  | 3.19                  | 0.94             |
|                   | Y 1.69          | 3.38              | 1.17                  | 1.17                  | 1.01             |
| I-1               | X 0.66          | 1.32              | 1.37                  | 1.17                  | 1.04             |
|                   | Y 0.58          | 1.16              | 1.17                  | 1.17                  | 1.01             |
| I-2               | X 0.83          | 1.66              | 1.82                  | 1.21                  | 1.16             |
|                   | Y 0.52          | 1.04              | 1.21                  | 1.21                  | 1.01             |
| I-3               | X 0.49          | 0.98              | 0.83                  | 0.64                  | 0.82             |
|                   | Y 0.39          | 0.78              | 0.64                  | 0.64                  | 1.01             |
| I-4               | X 0.85          | 1.7               | 1.56                  | 0.90                  | 0.79             |
|                   | Y 0.57          | 1.14              | 0.90                  | 0.90                  | 1.01             |

As shown in Table 5., the differences between the measured values times 2 and the calculated values of the I-shape type (rectangular shaped building and intermediate height) were generally within 10%. Even when the building was taller than 70 m, the difference was around 20%, indicating a functional relationship occurring between the calculated value and measured period times 2 by ambient vibration. Therefore, a database of additional tests can be useful for the utilization of calculated values.

In future analysis, studies are needed on the role of nonstructural materials to verify the mass factor and functional relation. Moreover, the stiffness of the nonstructural object, which is not reflected in the modeling for structural analysis in structural design, should be considered. Since the stiffness is undervalued when the rigid and large partition walls are not considered, an error can occur in the calculation of the period, which is considerably affected by stiffness and mass, and can cause the excessive design of structures. When the impact of stiffness of the nonstructural object is clarified, the existing equation for period calculation can be improved.

4. Conclusion

As the size of cities increases, residents tend to prefer apartment living and the demands for architectural space are also diversifying as their lifestyle patterns change. Since the construction industry satisfies such demands for various plane shapes and high-rise buildings, different structural systems need to be incorporated, and structural engineers find it difficult to apply the design criteria, particularly the period calculation equation for seismic design. In response to this, this study reviewed the simple equation depending solely on height, and verified it with actual measurements. By using 8 measured sample data, the authors drew the following conclusions.

(1) When the existing period calculation equation was applied to the existing reinforced concrete wall type buildings, up to 4 times deviation was generated. The calculated seismic loads will therefore differ greatly according to which equation is applied.

(2) Verification of the calculation of the period using the ambient vibration method with the synchronized human excitation method indicated a relatively accurate natural period of a building. The natural period of a building to be applied for its design can thus be obtained through actual measurement.

(3) The value calculated using the Rayleigh-Ritz method was about twice the actual measurement. This is likely because the mass factor used for analysis differed from the mass condition at the time of usage and because the nonstructural material was not reflected in modeling. However, since a correlation occurred between the two values, further studies are recommended.

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