Field Measurement of Fundamental Period of Buildings in Thailand by Using HVSR Method

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Abstract

Seismicity of Bangkok is different with other cities as it is situated on the low seismic zone but placed on the border of the Indo-Australian and Eurasian plates which can produce the large earthquake. Evaluation of a fundamental period by using ambient vibration data is the frequently used method. A group of existing reinforced concrete buildings, height range from 17 m to 124 m, situated in the Bangkok City; Thailand has performed the ambient vibration test and HVSR method was applied to calculate the fundamental frequencies and fundamental periods of the buildings in this paper. A numerical analysis developing the finite element technique (FEM) will be done to verify the accuracy of the measurement results. FEM has also been used to assess the impact of the stiffness of the infill wall and the opening's proportion of the infill wall on the fundamental period and higher modes of RC frame constructions.

Keywords: Fundamental Periods, Fundamental Frequencies, Ambient Vibration, HVSR, Infill wall.

1. Introduction

When designing for earthquake resistance and evaluating its effectiveness, the fundamental vibration period of structures is a critical component. The fundamental period of the structures mainly influenced by the mass, stiffness, and the ration of damping. There are others factors which affect the fundamental period of the structure are location (a type of seismic zone), a quality of soil, structural irregularities, a length of a structure, a height of the structure, etc. These factors make it challenging to establish a precise assessment of a building’s fundamental period for both a new building’s design and the appraisal of an existing building.

Simplified empirical formula, numerical simulations for various types of structure and experimental methods can be used to estimate the fundamental period of the structure. The present codes basically give the empirical formulas or numerous estimations for the fundamental period of the structure with or without the effects of infill walls. The expression offered by seismic codes around the world have been created using regression analysis of values predicted using both numerical and empirical methods. Based on vibration data collected after previous earthquakes, the most widely used expressions are now available worldwide. The simplified empirical formula for the fundamental period of the structure is mostly a relationship between the height of the building and a unique coefficient for each typology. In addition, current research has focused on RC buildings and has used both numerical and analytical methods.

Now, for the same structural system and building height, the available codes, experimental expressions, and numerical expressions give varying answers for the vibration period of investigated buildings. This gap becomes more noticeable when values from code relationships contrast with those derived from numerical analyses and, even more so, when they are contrasted with values provided by in-situ experimental measurements. Many researchers have previously investigated the causes of these variations.

Not all the components capable of influencing mass and stiffness are typically taken into account in the model when performing structural analysis on RC buildings, such as the stiffness of non-structural materials. A relationship based on in-situ experimental measurements might then be a good alternative strategy to estimate the fundamental vibration frequency of buildings based on a single measure appropriate to encompass the contributions of all structural parameters on the shaking of RC buildings. To establish an empirical formula to measure the basic period of RC buildings, many researchers are collecting data on building vibrations caused by earthquakes and other sources of trembling.

HVSR (horizontal vertical spectral ratio), also known as the Nakamura method, is the most popular method to estimate the natural period of the building. It is a very popular tool to approximate the natural period of the structures as its ease in field acquisition and data processing. Serval research paper present that the result from HVSR is nearly same with other techniques such as weak-motion measurements or numerical simulations Mucciarelli and Gallipoli [1]. In this paper, the researcher will perform an ambient vibration test on existing buildings in Bangkok for the investigation of the relationship with the natural period and the height of the building in Thailand by using HVSR method. The finite element model has been evaluated to know the performance of infilled wall on fundamental period of the building but also to check the accuracy of experimental results. The empirical formula for between 7 to 26 storeys buildings will be evaluated by using a regression method based on measure data.

2. Literature Review

2.1 Dynamics Characteristics of the Buildings by Numerical Analysis

Beskhyroun et al [2] studies the dynamic behavior of 13 stories reinforced-concrete building with both experimental and numerical models. The results from the experiment produced good agreement with the numerical model. To analyze the dynamic behavior of the buildings, [3] carried out the experimental method using OROS-OR36 Multichannel Noise and Vibration Analyzer. The outcome of comparing these two methods was seen to be similar. The analytical models can be corrected regarding the results of the experimental methods.

Bui, Hans [4] used a finite element model to verify the unusual mode shape and to compare with in-situ measurement of the asymmetric building and the effects of its soil. The results of natural frequencies and the mode shapes of the model from in-situ measurement show a respectable agreement of the numerical model’s results.

2.2 Dynamics Characteristics of Building by Site Measurement

The natural frequency of the building from the experimental result gives the most exact result as the measurements are performed after the construction. It means field measurement already take into account all the parameters that influence on the dynamics’ characteristics of the buildings. Chiauzzi, Masi [5] measured the ambient vibration of 12 RC buildings with the height range from 12 to 70 meters at 3 locations.The result of emprical measurement of the natural period from ambient vibration is lower than building code or numerical estimation as building code value are evaluated from stronger shaking level and numerical model cannot model for all influence components to mass and stiffness.

According to Hong and Hwang [6], the structural array monitoring system was operated in 21 building around in Taiwan with Central recording system to predict the natural period (T) of the buildings. The identified T in Taiwan is lower than UBC 97 due to the design and construction practices of such buildings (dry wall are used in California while Taiwan used masonry wall) are significantly different between Taiwan and California

Al-Nimry, Resheidat [7] tested the ambient vibration at the roof of 29 selected infill wall buildings with one to six stories tall to measure the natural period of the houses in Jordan. The period of vibration measure with microtremor was much shorter than code value.

2.3 Various Natural Period Code from Various Countries

ASCE07-16 showed two ways to estimate the nature period of the building. If the total number of stories in building is not exceeded than 12 stories with average story height is at least 3m, the natural period of the building can be estimated as

$$T = 0.1N \tag{1}$$

where N = number of stories above the base.

Moreover, the approximate fundamental period of the building can be evaluated with height-depend on formula,

$$T = C_t h_n^x \tag{2}$$

where C_t =0.0466 for concrete moment-resisting frame and 0.0488 for all other structures, h = the height of the building and x is 0.9 for moment-resisting frame of reinforced concrete buildings and 0.75 for all the other structural systems.

In UBC 1997, the natural period of the building can be determined as

$$T = C_t h_n^{3/4} \tag{3}$$

All other structural systems for UBC 1997 and ASCE-07 16 are same for coefficient C_t, but for the moment resistance frame, a C_t is 0.0731 in UBC 1997.

By using regression method, Thailand, Taiwan, and turkey evaluate their own empirical formula of the natural period which are shown in Table -1.

Table 1, Equations of natural period by the regression Method from Various Country.

Reference	Region	Equation
Poovarodom, Warnitchai [8]	Thailand	$T = 0.02H$
Guler, Yuksel [9]	Turkey	$T = 0.026H^{0.9}$
Hong and Hwang [6]	Taiwan	$T = 0.0297H^{0.804}$
Gallipoli, Mucciarelli [10]	European	$T = 0.016H$

Where T = the natural period of the building and H is the height of the buildings.

For the purpose of determining the fundamental period of vibration, a comparison of the abovementioned height-related experiments is explained in figure-1. It makes sense that the fundamental period computed by such expressions is produced, emphasizing the requirement for additional research and improvement of the idea.

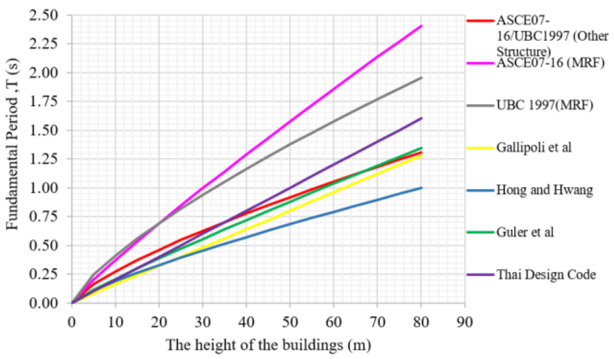

Fig. 1 The Correlation between Derived Height Depended on Expressions.

3. Methodology

3.1 Building Measurement Done in the Study

In this paper, field measurement of the ambient vibration test was mostly performed on the 16 reinforced concrete buildings, storeys range from 5 to 26 floors in the Siriraj. There are 2 buildings, storeys range from 6 to 9 floors in Mahidol University, Salaya Campus will perform the ambient vibration test. Data collection started in November,2022 last week and finished in February 2023. Table-2 described the list of buildings that performed the ambient vibration test.

Table 2, The list of research buildings

Building Name	Number of Stories	Height (m)	Age (years)
Siriraj Hospital Compound			
Nurse Dormitory	9	32.77	32
Nawamindrapobitr	26	124.25	5
Adulyadejvikrom Building	13	42.3	>10
84 anniversary Building	10	51.3	>10
Syanmindra	15	48	>10
72 anniversay building	10	42.58	52
Her Majesty Cardiac	15	64.5	29
Kosol	5	17.5	>10
Princess Mahachakri Building	13	42.9	65
Anandamahidol	10	39	34
100th Year Somdech PhraSrinagarindra Building	15	62	13
Chalermphrakiet	16	54.4	>10
Srisavarindira Building	15	63.26	12
Female Dormitory	13	39.5	>10
His Majesty the King's 80th building	15	71.65	16
Piyamaharajkarun building	12	56.02	16
Mahidol University, Salaya Campus			
Adiyathorn building	6	24	5
Medical Technology	9	27	>10

3.2 Natural period by HVSR Method

The HVSR method is unlike other methods as it needs one location to record the motion (ambient vibration due to wind, swell, traffic and etc) to get the directions of both horizontal and vertical. Then each component has been averaging to get Fourier transform of both components. Then Horizontal and vertical ratio can be computed. The result gives a peak at frequency of maximum amplification because of the change in the polarization of Rayleigh waves at the frequency of maximum amplification is non-destructive and low-cost method.

The Horizontal to Vertical Spectral Ratio (HVSR) technique has been used to estimate fundamental period values from ambient vibration signals captured close to the highest level of buildings. In this paper, Castro et al.[11] claim that the HVSR approach can offer an estimation of the determining a structure's fundamental frequency by comparing amplitudes of the Fourier spectra on the highest level of constructions, the total recorded amount of horizontal and vertical elements. With this method, the fundamental mode of a building's vibration frequency corresponds to the frequency at the HVSR shape's maximum amplitude.

The recorded data will be input to CUSP view which can write a vibration into various software. The researcher will use Seismosignal to filter the vibration from 0.1 Hz to 25 Hz with filter type Butterworth and time step 0.005s. A baseline will be corrected as linear and filter configuration will be bandpass. The filtered data X, Y and Z will run through a standard HVSR method which generated by python programming software. The estimated natural period will be plotted.

The researcher used CUSP-Ms as a seismometer which is the digital triaxial accelerometer. During the vibration recording time, Y axis was placed at the North-south direction. This seismometer collected the ambient vibration of buildings from X, Y and Z direction. It takes 5 minutes to collect one set of data and 6 sets of data will collect for one building. The measurement was carried out at the top-most and center of the buildings. Based on a longitudinal and a transverse spectrum over vertical one, the two HVSR curves are determined. Among them, the longer fundamental period values are taken and the following equations are applied in this study

$$\frac{H}{V} = \sqrt{\frac{EW^2+EW^2}{2V^2}} \quad or \quad \frac{H}{V} = \sqrt{\frac{NS^2+NS^2}{2V^2}} \qquad (4)$$

Where $\frac{H}{V}$ = Horizontal-Vertical spectral ratio from x direction or y direction, EW=horizontal component (x-direction) of Fourier spectrum recording at research building, NS= horizontal component (y-direction) of Fourier spectrum recording at research building, and V= vertical component (z-direction) of Fourier spectrum recording at research building.

3.3 Natural Period by Numerical Analysis

Analyzing the natural period of the building by Numerical Analysis is one of the objectives of this paper, but also the alternative way to check the accuracy of the natural period from the site measurement.

In this study, a chosen building's numerical analysis was done using ETBAS-20. In order to understand how the infill wall (masonry wall) functioned in the natural period of the building, it was taken into account as a structural element in the numerical simulation. The masonry wall was modelled as a wall in ETABS for the stiffness of the building. The location of the infill was placed in the same area as the existing condition, but also without the infill wall, and the infill wall without any door or window openings (a fully infill wall) was modelled to examine the outcome of the natural period of the buildings.

4. Result and Discussion

4.1 Experimental Result

Table No-3 shows that HVSR method is used to estimate the fundamental period (Tn), fundamental frequency (Fn) and total height (H) of the reinforced concrete structure and the fundamental period.

Table 3. The fundamental periods and frequencies by HVSR

Building Name	H (m)	Tn (s)	Fn (Hz)
Siriraj Hospital Compound			
Nurse Dormitory	32.77	0.5686	1.7578
Nawamindrapobitr	124.25	2.2001	0.4547
Adulyadejvikrom Building	42.3	0.8425	1.1841
84 anniversary Building	51.3	0.7872	1.2726
Syanmindra	48	0.8193	1.2207
72 anniversay building	42.58	0.6276	1.6143
Her Majesty Cardic	64.5	1.0177	0.9827
Kosol	17.5	0.3213	3.1402
Princess Mahachakri Building	42.9	0.8186	1.2268
Anandamahidol	42.9	0.8464	1.1780
100th Year Somdech PhraSrinagarindra Building	62	1.2078	0.8270
Chalermphrakiet	54.4	1.5266	0.6561
Srisavarindira Building	63.26	1.1580	0.8667
Female Dormitory	39.5	0.9705	1.0315
His Majesty the King's 80th building	71.65	1.3140	0.7599
Piyamaharajkarun building	56.02	1.4187	0.7080
Mahidol University, Salaya Campus			
Adiyathorn building	24	0.5631	1.7790
Medical Technology	27	0.7652	1.2935

The data visualization implement for time series graph is defined as data points at subsequent time gaps. Each point on the graph in this study refers to a time and an acceleration that was observed, and acceleration was measured in all three directions at the same time. The time series graphs above were all taken from two separate heights (the highest and shortest on the list of buildings). For collecting data, the sensor has been put at the highest level of the structure (levels 5 and 26, respectively). The highest acceleration for both horizontal directions are around 1.5*10-4g for Kosol (5 storeys) and 4*10-4g for Nawamindrapobitr (26 storeys). The highest acceleration for vertical direction are around 2*10-4g for Kosol and 2*10-3 g for Nawamindrapobitr (26 storeys). Figure 2 showed the horizontal and vertical direction of the acceleration for Kosol building and figure 3 represented the acceleration of Nawamindrapobitr for both vertical and horizontal directions.

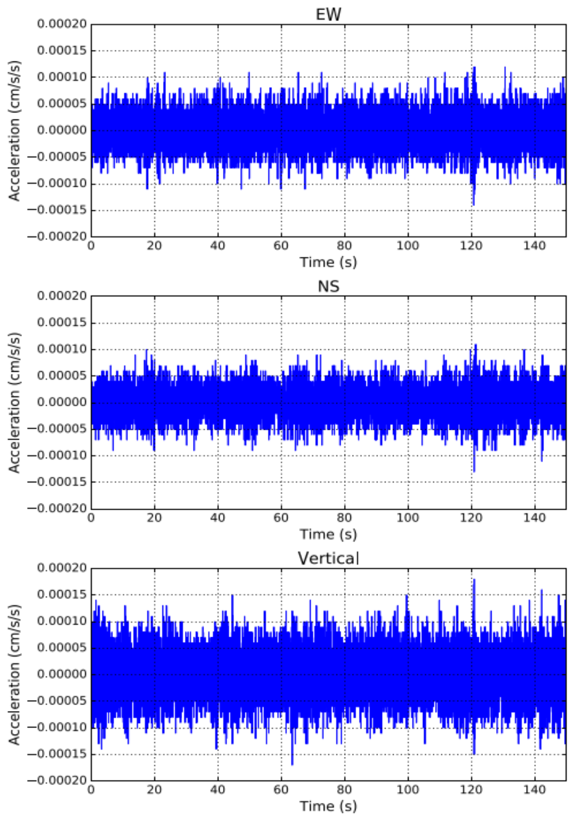

Fig. 2 The Time Series Graph of Each Direction for Kosol

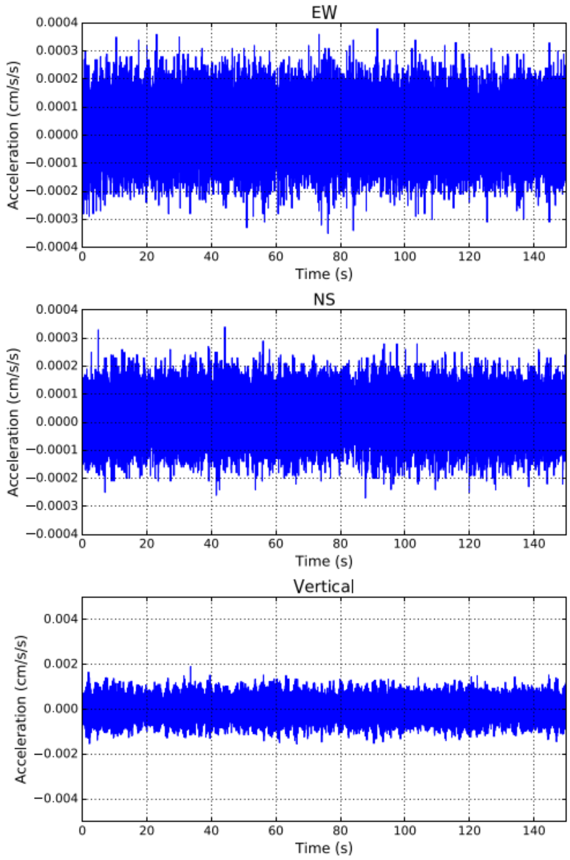

Fig. 3 The Time Series Graph of Each Direction for Nawamindrapobitr

Building vibration data gathered on the observed RC Thailand buildings are compared in Figure 4 with the standard provision code (ASCE-7-10 and DPT1302-09). Guler et al, [9] and previous studied, Ranaweera, J.K. and T. Ornthammarath ,[12]

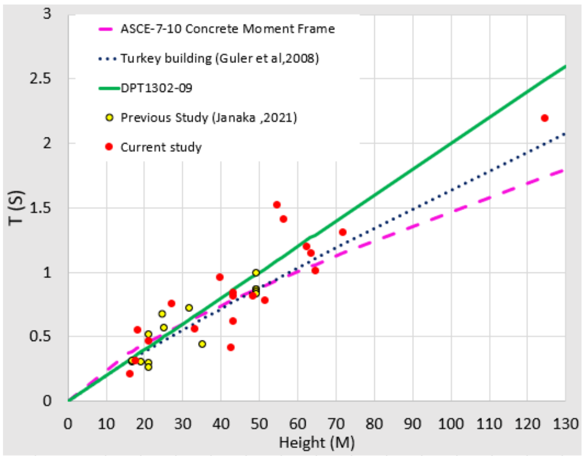

Fig. 4, The Correlation between Current Study and Various Provision Code.

To determine the relationship between the period and the height as a building parameter, linear regression analysis is used. As a result of heigh-depended on a relation of fundamental period for Thailand RC buildings in this study is 0.0191H with a regression coefficient R=0.98 which is very comparable to present Thailand's design code. Figure 5 describes the simple empirical expression calculated from measured data.

$$Tn = 0.0191H \quad (5)$$

where Tn= the fundamental period of the buildings and H= the height of the buildings (meter)

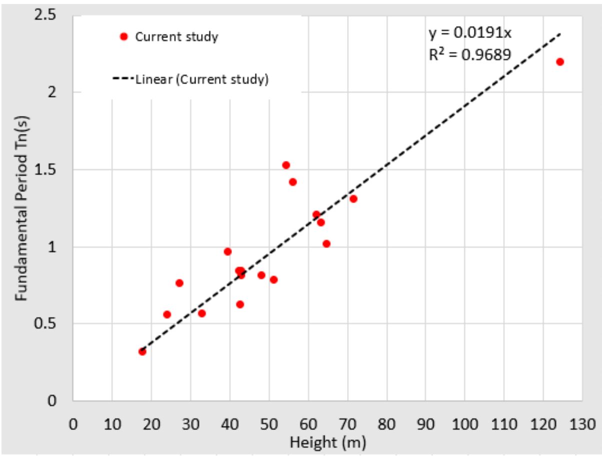

Fig. 5 The Empirical Formula of The Fundamental Periods of Monitored Buildings.

Figure 6 compare the results of the fundamental periods of the buildings from empirical expressions between experimental results of current study and Thai's Design code. Both of the expressions are height depended formulas.

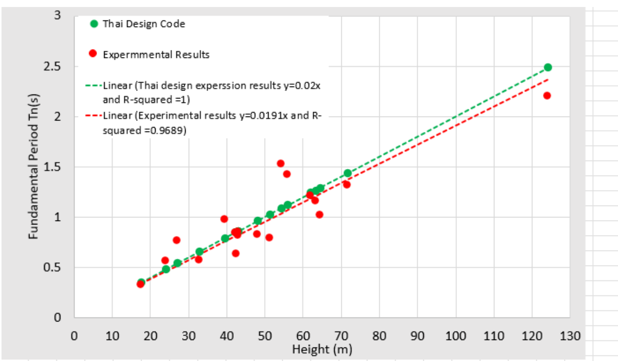

Fig. 6 The Comparison of Thai Design Code and Current Study, Height Depended Relation.

4.2 Numerical Analysis

84 Anniversary building had been modelled with ETABS-20 to check the fundamental period of building with measurement results. During modelling, infill wall was considered the parts of the structural element. The Tn from ETABS is 0.72s while experimental results give 0.78s. The results from both methods are almost the same. The material properties of 84 anniversary building are shown in table 4. The first period of the building from ETABS model is shown in figure 7. Modulus of Elasticity of concrete and masonry is taken as secant modulus. The stiffness of material is considered inelastic range due to remodeling over 20 years old buildings.

Table 4, The materials properties of 84 anniversary building for ETABS modelling.

Materials Properties	
Modulus elasticity of Concrete, Ec	13.3 Gpa
Concrete Strength	32 Mpa
Tensile Yield Strength, Steel	420 Mpa
Masonry Compressive Strength, Fm	10 MPa
Modulus elasticity of Masonry, Em	5 GPa
Thickness of infill wall panel	150mm thk

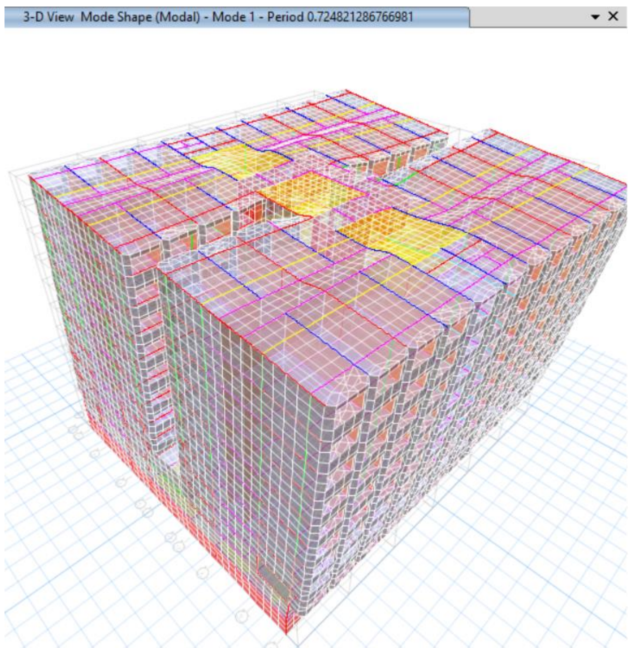

Fig. 7 The Model Analysis of 84 Anniversary Building as per Existing Conditions for Infill Wall.

4.3 The Role of the Infill Wall

The performance of infilled is affected on the fundamental period building. An 84-anniversary building was chosen to model with (infill wall frame) and without infill walls (bare frame). The bare frame model gave the Tn=2.4677s (shown in figure 8), however, the fully infill wall fundamental period is 0.6495s (shown in figure 9). The difference between the models is quite large, even though all the structural components and properties are the same and only infill wall played this difference. The layout plan of the 84-anniversary building is shown in figure-10.

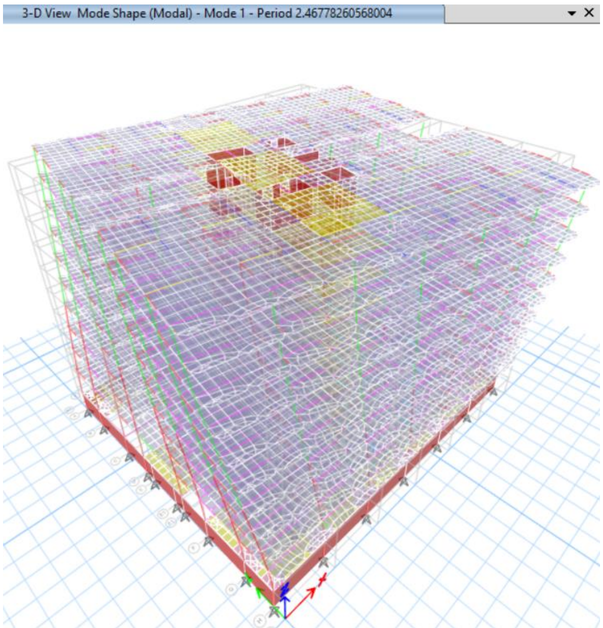

Fig. 8 The Model Analysis of 84 Anniversary Building (Bare Frame)

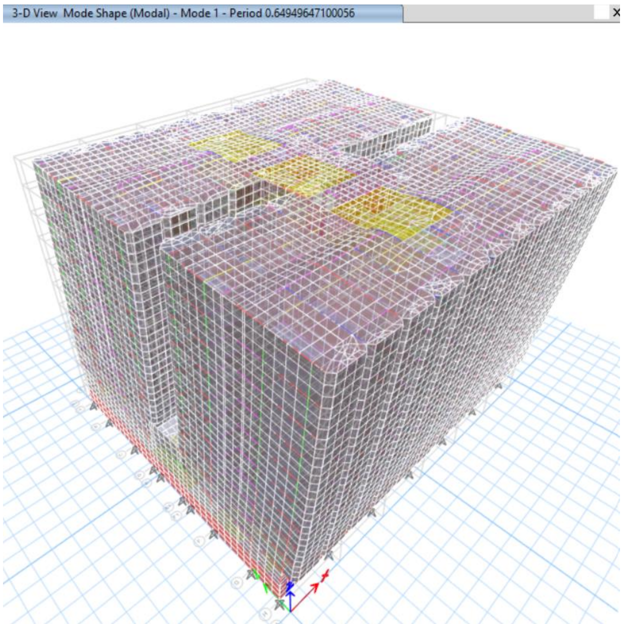

Fig. 9 The Model Analysis of 84 Anniversary Building (fully Infill Wall)

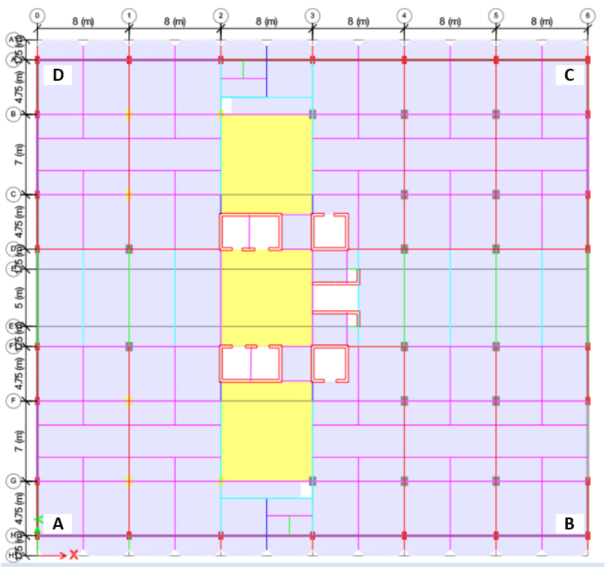

Fig. 10 The Layout of 84 Anniversary Building

For each vibration mode, the value of the modal participating mass ratio typically indicates the contribution of that mode to structural responses. This highlights the impact of the infill walls on the primary dynamic features, such as the building's mode shape. The displacement at the building's two opposite edges (A and C) at each of levels is considered for the X and Y directions.

In table 5, M is for the translation mode shape of modal participating mass rations and R is the rotational mode shape of modal participating mass rations. Figure 10 shows the mode shape patterns of bare frame and fully infill frame. Figure 11 illustrates the mode shape of the bare frame and fully infill frame from ETABS model.

Table-5, The fundamental period, and cumulative modal participation percentage mass for fully infill wall and bare frame.

	Bare Frame Model							Fully Infill Wall Model						
Mode	Tn (s)	Mx	My	Mx	Rx	Ry	Rz	Tn (s)	Mx	My	Mx	Rx	Ry	Rz
1	2.468	0.000	0.005	0.000	0.002	0.000	0.677	0.649	0.000	0.794	0.000	0.222	0.000	0.001
2	1.932	0.000	0.660	0.000	0.372	0.000	0.682	0.483	0.853	0.794	0.000	0.222	0.158	0.003
3	1.653	0.656	0.660	0.000	0.372	0.376	0.682	0.397	0.854	0.795	0.000	0.223	0.159	0.839
4	0.709	0.656	0.662	0.000	0.376	0.376	0.807	0.206	0.854	0.795	0.000	0.223	0.159	0.839
5	0.471	0.656	0.814	0.000	0.614	0.376	0.809	0.205	0.854	0.795	0.000	0.223	0.160	0.839

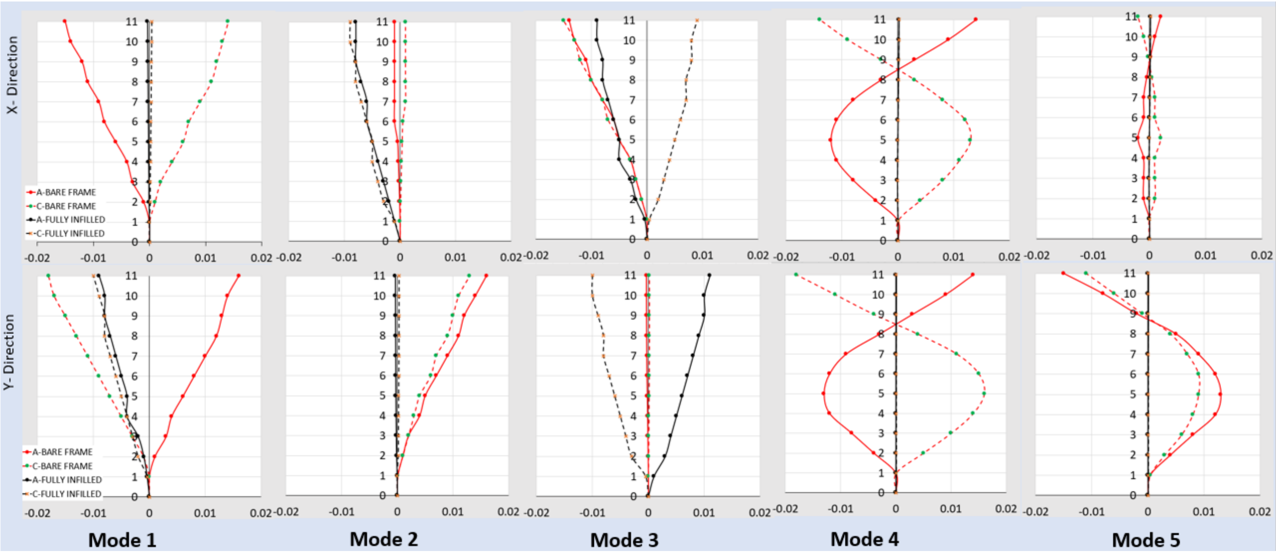

Fig. 11 The Mode Shape Extracted from the Fully Infill Wall and Bare Frame Mode

5. Conclusions

Many design codes offer straightforward formulas to calculate the fundamental period of structures starting with their primary attributes, such as material type, structural system, and building height. In this paper, 18 RC buildings in Bangkok were carried out ambient vibration measurements to estimate their fundamental periods. The obtained fundamental periods from ambient noise data are significantly lower than those obtained using Thai's building-code expressions. Based on the opening percentage of the infill wall, three different cases of numerical analyses for the 84th Anniversary building were conducted. To verify the correctness of the measurement result, numerical studies with infill walls whose location and opening perfectly match those of real buildings were used. The outcomes from the two various approaches were nearly identical. The numerical model showed that the infill wall significantly plays an important role in affecting the fundamental period of the buildings.

6. Acknowledgement

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