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Empirical formulas and Artificial Neural Networks to estimate the fundamental periods of existing and instrumented RC buildings in Thailand

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ABSTRACT

Even though Bangkok is situated away from known active faults (about 150 km), due to the soft alluvial basin in and around the capital city of Thailand, several of these high-rise buildings experienced noticeable structural and non-structural responses caused by recent long-distance and moderate earthquakes from $M_w > 7.5$ in the Sumatra subduction zone and $M_w > 6$ in Myanmar, Northern Thailand, and Laos. This raises the awareness to assess the dynamic characteristics of buildings in Bangkok and other provinces in Thailand. In the current study, ambient vibration measurements have been performed on 98 reinforced concrete (RC) buildings to determine relationships between the building fundamental period and height of existing structures built prior and after seismic design code issued in 2009. The measured buildings' height ranges of 7–142 m (2–35 stories) e.g., hospitals, condominiums, offices, etc. Different techniques are adopted to determine the two main translational fundamental periods in orthogonal directions of considered structures including Horizontal-to-vertical spectral ratio, Fourier spectrum analysis, and Half-power bandwidth method, and all considered methods show comparable results, and the empirical formulas are proposed. In order to validate this finding, the estimated fundamental periods of two instrumented hospitals from local and regional earthquakes give similar results to the proposed empirical formulas. In addition, artificial neural networks (ANNs) have been adopted to train and predict the fundamental period using the newly compiled database. For the same RC structures, the soil-structure interaction in Bangkok leading to a longer fundamental period than those reported in published literatures.

1. Introduction

The fundamental vibration period of structures is one of the key engineering parameters in assessing earthquake lateral forces for retrofitting existing structures and designing new construction. In several countries, most seismic design codes provide different formulas to estimate the fundamental natural periods of buildings mostly depend on the construction material, the structural systems,

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and the building height. These formulas are derived from different approaches such as empirical measurement from past earthquakes, ambient vibration, and finite element methods [1–4]. Among different methods, ambient vibration measurement is considered as a non-destructive investigation and budget solution to identify dynamic characteristics of interested structures [5,6]. It is imperative that the formula adopted in national seismic design code should accurately represents the expecting levels of seismic demand experienced by the structures during the future strong shaking causing damage and losses due to major earthquakes [7,8].

The seismic lateral load is calculated from a design spectrum depending on the fundamental period of vibration of the structure. ASCE7 [9] provide two ways to estimate the nature period of the building. If the total number of stories not exceeded than 12 stories with average story height is at least 3 m, the natural period of the building can be estimated as:

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

where N is the number of stories above the base. Moreover, the approximate fundamental period of building can be evaluated based on the structural height from the following equation:

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

where $C_{t=}$0.0466 for concrete moment-resisting frame and 0.0488 for all other structural systems, H is the height of the building in meters and x is 0.9 for concrete moment-resisting frame and 0.75 for all other structural systems. Similar units are going to be used throughout the current manuscript.

Bangkok's seismic hazard had long been considered relatively low, and most of the built environments were designed and constructed without seismic design consideration. The Thai seismic design was first issued in 1997 based on the Uniform Building Code (UBC) 1985 edition limited only to northern and western parts of Thailand (classified as the UBC zone 2) without considering the Bangkok Metropolitan Area (BMA). Subsequently in 2007, the revision had been issued with the requirement for equivalent lateral force for public buildings including BMA without seismic detailing provision. In 2009, the DPT 1302-09 standard was issued with detailed descriptions of beam and column seismic detailings and modern design procedures according to the ASCE7-05 edition. Consequently, several structures built prior 2009 were designed and constructed without compliance with the seismic requirement.

Due to fast economic growth and dense urbanization, several important infrastructure and high-rise buildings have been constructed in the capital city of Thailand, and the recent major urban development are located in Chao Phraya River Delta. The Chao Phraya basin covers thirty percents of the country area, and is home to fourty percents of the country's population. Several previous microzonation studies in Bangkok basin have been performed and these earlier works indicating very low shear wave velocity profile within 30 m (Vs30) (between 60 and 180 m/s) [10–14]. This deep alluvial deposits could amplify long-period ground motions for tall structures. Until recently, several moderate to large earthquakes (Mw $\geq$ 6.0) occurring in Andaman Island, Mynamar, Laos, and Northern Thailand always create noticeable structural and nonstructural vibration for tall structures in Bangkok causing alarm and anxiouness for inhabitants of tall buildings. People rushed out of highrise structures always reported if these earthquakes were occurred during the working hours. In addition, several seismic hazard studies reveal that Bangkok could be subject to long distances and large earthquake from the Three Pagoda Fault with Mw 7.5 at 150 km and from the Sagaing fault with Mw 8.0 at 400 km distance from the most densely populate and capital city of Thailand [15,16].

The above information indicating the important requirement to estimate the natural vibration periods to approximate the level of seismic design force for retrofiting of exisitng structures and designing new constructions. In current study, literature reviews in determining natural vibration period of buildings in different countries have been provided. Moreover, the relationships between fundamental vibration period and height of reinforced concrete (RC) buildings in Thailand are analysed base on ambient vibration measurement of 98 buildings and comparing with the earthquake response data from instrumented buildings. For the same structural type, the soil-structure interaction in Bangkok leading to a longer fundamental period than those reported in published literatures. Note that the current building database is distinctive to previous study by Poovarodom et al. [17] with about 50 structures were considered. In addition, artifical neural networks (ANNs) has been adopted to trained and tested the current dataset revealing that it

Table 1
Empirical and code-based to approximate building periods in different countries.

Country	Building Code/Authors	Structural System	No of Buildings	Height Range	Expression	Remark
USA	(ASCE07, 2016)	RC			$T = 0.1N$	For moment frame <12 stories
		RC MRF			$T = 0.0466H^{0.9}$	
		RC SW			$T = 0.0488H^{0.75}$	
Thailand	((DPT1302- 2009)[18]	RC			$T = 0.02H$	
Taiwan	[1]	RC	21	8–77 m	$T = 0.0294H^{0.804}$	
Thailand	Poovarodom et al., 2004	RC	50	20–210 m	$T = 0.019H$	
Europe	[19]	RC	244	1–20N	$T = 0.016H$	
Singapore	[4]	RC	116	4–30 N	$T = 0.0372H^{0.8325}$	Soft Soil
					$T = 0.0244H^{0.8840}$	Firm Soil
Jordan	[3]	RC	26	1–6N	$T = 0.367H_n^{0.57}$	Longitudinal
					$T = 0.0.267H_n^{0.71}$	Transverse

where RC = Reinforced Concrete Buildings, MRF = Moment Resisting Frame, SW= Shear Wall, T = Natural period of the building, H= Height of the building (in meters), N = No of Stories of the building.

can be used to analysis the dynamic characteristics of Thai buildings.

2. Ambient vibration measurement and artificial intelligence application in different countries

The fundamental period of the building typically plays a crucial role in designing safe and resilient structure due to its influences the dynamic behaviour of the structure during earthquake events. In addition, due to the dissimilarity in the necessary level of design load, material properties, and variance construction practice, the code formulas for different countries tend to be varying, Table 1. For code-based formula, it would provide a straightforward method for estimating the fundamental period without the need for complicated computation or detail modelling. These formulas are often derived from empirical data, but they might not account for the specific special architectural features of individual buildings.

Hong and Hwang [1] evaluated twenty-one reinforced concrete moment resisting frame structures in Taiwan under earthquake vibration to estimate the fundamental periods of buildings. The autoregressive exogeneous (ARX) model can be used to identify the frequency transfer functions of investigated structures, after which the fundamental vibration periods can be determined. It was found that, generally, fundamental periods of structures in Taiwan is lower than similar type of structures in California based on the UBC 97 formula due to the different design and construction practices between Taiwan and California buildings (Infilled masonry wall are mostly adopted in Taiwan while dry wall is used in California). The proposed fundamental period formula for Taiwan buildings is shown below

$$T = 0.0294H^{0.804} \tag{3}$$

Poovarodom et al. [17] determined the fundamental periods of fifty buildings ranging mostly from 5 to 40 stories located in Bangkok from ambient vibration measurement through Fourier spectrum analysis. Comparison between the fundamental periods of buildings in Bangkok and Taiwan indicating that the structure in Bangkok has longer fundamental periods which might be due to no seismic consideration for buildings constructed in Bangkok and different soil structure interactions. The formula for structural period in Bangkok is

$$T = 0.019H \tag{4}$$

and later adopted in the current Thai seismic design code (DPT 1302-09) is

$$T = 0.02H \tag{5}$$

Gallipoli et al. [19] conducted ambient vibration tests on two hundred forty-four buildings in four European countries with heights ranging from one to twenty stories. They used four different methods—HVSR, SSR, NonPaDAn, and HBW—to estimate the natural frequency, and NonPaDAn and HBW methods were adopted to estimate the building damping ratio. Then the proposed formula of building fundamental period for RC buildings is in the form

$$T = 0.016H \tag{6}$$

Al-Nimry et al. [3] performed the ambient vibration test for 29 masonry infill reinforced concrete buildings from one to six story structures through HVSR method in Jordan. Then, the researchers evaluated the linear model analysis of 15 buildings with the effect of infill wall to calculate the natural period of the building. The period of vibration measure with microtremor was much shorter than the current Jordan seismic design code. The new empirical formula of building natural period for masonry infill RC up to 6 stories' height for a typical infill RC frame in Jordan is proposed:

for longitudinal direction,

$$T = 0.0367h_n^{0.57} \tag{7}$$

for transverse direction,

$$T = 0.0284h_n^{0.71} \tag{8}$$

In addition, building dynamic properties might differ depending on the soil type in different area where the structures are situated. Since Singapore dense population living mostly in tall structures, and these high-rise buildings mostly subjected to long-distance and large Sumatra earthquakes, ambient vibration testing were carried out on 116 buildings ranging from 4 to 30 floors to determine the natural period of buildings using HVSR analysis [4]. Researchers used the regression method to generate empirical formulas for natural periods, and then analyse those models taking into account the influence of soil condition. The intended period-height relationships of buildings situated at soft-soil are about fourty percents longer than vibration periods valued for buildings situated on firm-soil. The following is the suggested empirical formula for the first mode of the natural period.

For soft soil,

$$T = 0.0372H^{0.8325} \tag{9}$$

For firm soil,

$$T = 0.0244H^{0.8840} \tag{10}$$

In addition, machine learning has steadily been introducing in estimating the fundamental period of buildings. Asteris et al. [20]

used the ANNs with back propagation analysis to train and to predict the natural period of the buildings. For the input, their model the reinforced concrete building with different openings, different height, strength of infills and different span. Charalampakis et al. [21] adopting M5Rules and ANN to estimate the fundamental periods of buildings and found that the number of spans is insignificant to estimate building vibration. Mirrashid and Naderpour [22] presented two computational models (a neural network and a neuro fuzzy system (ANFIS) to estimate the fundamental period of infilled RC frames. Both methods seem to outperform the existing code based equations in estimating the fundamental periods. Inqiad et al. [23] used machine learning such as Multi Expression Programming (MEP), Extreme Gradient Boosting (XGB), and Gene Expression Programming (GEP) to predict the natural period of the buildings, and the opening ratio and the number of stories are the most significant factors influencing the building vibration period.

3. Methodologies

Ambient vibration technique is a common dynamic measurement method used to record the dynamic characteristics of a structure under normal conditions, without causing large excitation [3,4,19,24,25]. The purpose of ambient vibration measurement is to captures the natural vibrations of a structure caused by factors like wind, traffic, or operational use. By analysing this measurement, engineers can assess a structure's vibration periods, identify modes of vibration, and detect any anomalies or damage. The sensor is mostly placed on top of investigated structure and the ambient vibration measurement would be recorded. Furthermore, the signal will be analysed to determine fundamental natural periods in both orthogonal directions.

3.1. Instrumentation and data collection

In current study, ambient vibration measurement is taken by CUSP tri-axial MEMs accelerometer manufactured by Canterbury Seismic Instruments, New Zealand, Fig. 1a. The sensor has a dynamic range of 128 dB for 0.1–20 Hz with a sampling frequency of 200 Hz. To synchronize the vibration measurements, the accelerometer is equipped with an external GPS sensor, to guarantee accurate timing. During the measurement, Y axis was oriented longitudinal direction of structures, and the X axis was oriented transverse direction of structures. The sensor has been placed either at the topmost or nearest to the top of the building to get the strongest vibration of the buildings. The sensor is usually placed towards the centre of the building to obtain the translation mode of the building and to avoid obtaining torsion mode. The measurement is continuously recorded for at least 30–50 min, and before processing data, the anomaly in ambient record was investigated to remove any high frequency noise for further analysis. The signal data has been separated to several segments (about 5 min) in order to get the statistical characteristic of record data for further analysis.

3.2. HVSR method

The HVSR method is a widely used technique for analysing ambient vibrations. The HVSR approach is proposed on the basis that the vertical component of motion's spectral amplitude is mostly unaffected by the site effects and consists primarily of attenuation along the source-station line. Attenuation and source effects will therefore eventually be removed from the findings of the ratio between the horizontal and vertical spectrum [26–31]. Castro et al. [32] using HVSR technique to determine the dynamic characteristic of two dams from earthquake ground motion by calculating the ratio of the amplitude of the Fourier spectra of horizontal and vertical components. Gallipoli et al. [33] determine the fundamental translational periods of 80 Italian building using ambient measurement with four different analyses including HVSR, standard spectral ratio, non-parametric damping analysis, and half bandwidth method, and it show comparable.

In this study, the vibration frequency of fundamental mode of monitored buildings corresponds to the frequency at the maximum amplitude of HVSR curve. The HVSR values have been calculated by the following equations

$$\frac{H}{V} = \frac{\sqrt{EW^2}}{V} \text{ or } \frac{H}{V} = \frac{\sqrt{NS^2}}{V} \tag{11}$$

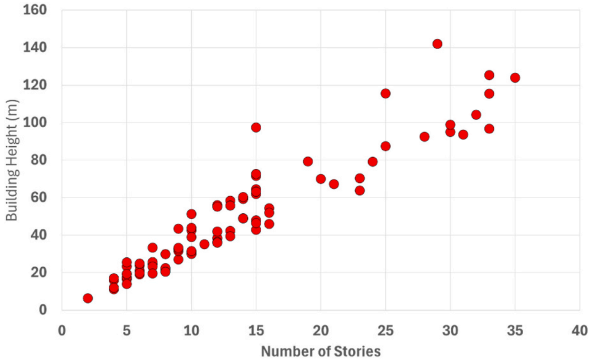

Fig. 1. The relationship of building height and number of stories in current database.

where $\frac{H}{V}$ is the horizontal-vertical spectral ratio, EW = transverse component (x-direction) of a Fourier spectrum recording, NS = longitudinal component (y-direction) of a Fourier spectrum recording, and V = vertical component (z-direction) of a Fourier spectrum recording. The lower frequency (or longer period) between both components has been considered as the first fundamental period (T_1), and the other has been adopted as the second fundamental period (T_2).

3.3. Fast Fourier Transform (FFT)

The other way to determine fundamental periods are through the Fast Fourier Transform (FFT) in the assumption that the measurement is stationary random process with a broad band spectrum, Trifunac [34]. The FFT could be used to analyse the structural responses in the frequency domain, revealing the natural frequencies, mode shapes, and damping characteristics of structures. In current study, the lowest frequency (or longest period) between both directions corresponding to the dominant vibration period of the building.

Velani and Ramancharla [35] proposed the new empirical formula for the fundamental natural period of tall buildings of shear wall frame and reinforced concrete frame in India. Twenty-one RC buildings of these two building systems were carried out ambient vibration test and used the Fourier spectrum method to evaluate the natural period of the buildings. Velani and Kumar [36] tested 28 tall buildings in India and evaluate the natural periods by using Fourier spectrum analysis to compared with existing Indian and international code. Trifunac [37] employed Fourier spectrum analysis to compare ambient vibration and forced vibration tests on buildings in order to establish different mode forms and frequencies of vibration, as well as the related damping values, with sufficient precision for most practices.

3.4. Half-power bandwidth method

The half-power bandwidth (HBW) method is the classical method to estimate the natural frequency and damping ratio of the buildings. The classical application of the half-power bandwidth approach may result in severe inaccuracies. Several past studies revealed that the HBW gave the accurate estimation of fundamental period and damping ratio but still have limitation for higher mode for multi degree of freedom system [38,39].

This method, which is based on the frequency-response curve, involves finding the two frequencies that have response amplitudes that are equal to the maximum split by the square root of two. The response curve typically exhibits a peak at the natural period of the building between these two frequencies. To determine the first fundamental period (T_1) of building, the longer period of peak amplitude of response curve between two components is selected. A horizontal line with the necessary amplitude will intersect the response curve at two spots according to the approach, which assumes the existence of these two frequencies.

4. Results

In total, 98 reinforced concrete buildings varying height from 7 to 142 m (i.e. from 2 to 35 storey) in Bangkok and Northern

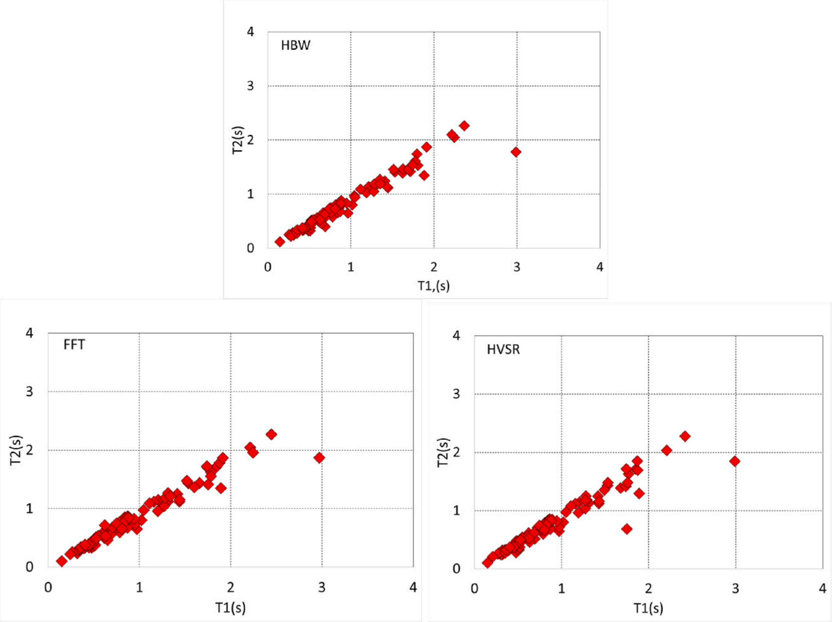

Fig 2. Comparison of orthogonal fundamental periods derived using 3 different approaches from ambient measurement.

Thailand were measured and processed using previous mention analysis. The building age of construction in the current database extent from 1950 to 2020. Out of 74 buildings measured in Bangkok, 25 buildings were constructed before the introduction of DPT 1302-09 seismic design code. For buildings situated in Chiang Mai and Chiang Rai, whose soil property is classified as stiff soil, NEHRP site class D [40,41], additional 24 structures were investigated. Only eight buildings were built before the implementation of recent seismic design code. Fig. 1 shows the distribution of building heights and the related number of stories, and it could be noticed that there is a linear relationship between the number of stories and the height of buildings.

4.1. *The measured translation periods from ambient vibration*

All three methods previously mentioned were used to analyse the measurements. Both major translational periods were determined by HVSR, Fourier spectrum analysis, and HBW techniques. In Fig. 2, the comparison of the two translational periods for each technique was shown. The y-axis displays the second translational period in contrast to the x-axis, which displays the first fundamental period. Overall, there is good agreement between all considered techniques, which for the most part fall between 0.5 and 3 s. The fact that both orthogonal translational periods are comparable indicates that the structures are similarly stiff in both directions. In Fig. 3, the comparison of the first translation fundamental period determined from three different techniques seems to show similar results. The fundamental periods used for further investigation will be used those determined from the FFT analysis.

4.2. *Regression analysis for Bangkok building database*

Regression analysis is the common technique used to derive the empirical correlations between the reinforced concrete building height and the fundamental periods from ambient vibration data. The standard equation for determining this relationship is

$$T_1 = \alpha N \tag{12}$$

$$T_2 = \alpha N \tag{13}$$

$$T_1 = \alpha H \tag{14}$$

$$T_2 = \alpha H \tag{15}$$

where T_1 *and* T_2 is the first and second translational fundamental periods, N is the number of stories, and H is the building height in meters, and α is the coefficient of the regression. In general, T_1 and T_2 are the longer and shorter periods between both building

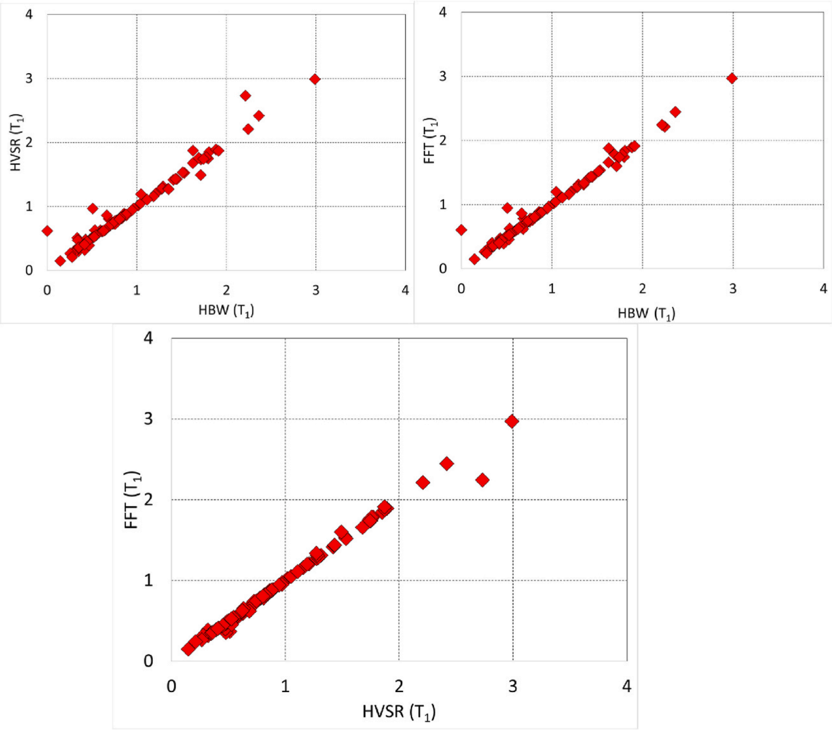

Fig. 3. Comparison of fundamental period of the first translational mode using 3 different methods.

directions, respectively. Moreover, to compare the soil-structure interaction effect, only Bangkok building database is considered in this section while the Chiang Mai and Chiang Rai building database is going to be separately discussed in the next section.

Fig. 4 display the comparison between estimated first and second fundamental period from ambient vibration measurement. The building fundamental vibration period is shown on the y-axis and building heights and stories is on the x-axis. The period heigh-relationship for T₁ and T_2 for reinforced concrete buildings located in Bangkok is.

For T₁ in Bangkok,

$$T1 = 0.069N \tag{16}$$

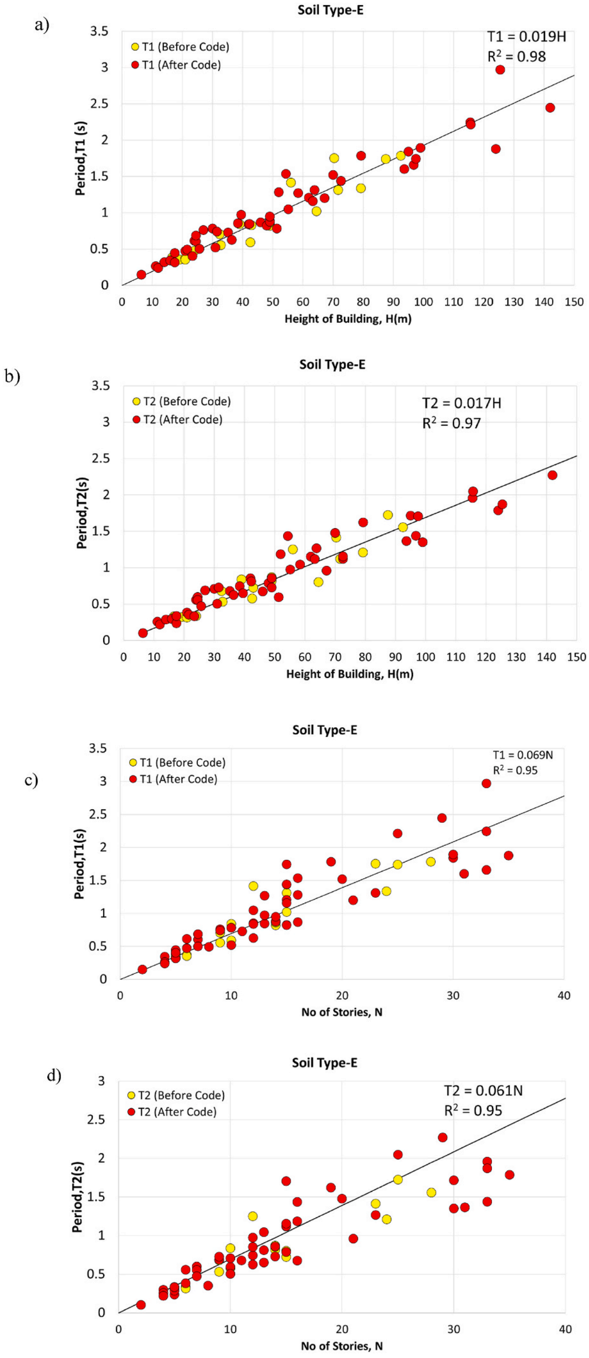

Fig. 4. Regression analysis for T_1 and T_2, and the summary of the ambient vibration test measurements uses the x- and y-axes to represent (a) (b) height and (c) (d) number of stories and natural period, respectively. Buildings built before and after the 2009 seismic design code is shown in yellow and red colors, respectively.

$$T1 = 0.019\,H \tag{17}$$

For T₂ in Bangkok,

$$T_2 = 0.061N \tag{18}$$

$$T_2 = 0.017\,H \tag{19}$$

It could be quickly noticed that the relationship between T_1 and building height is similar to those obtained by Poovarodom et al. [17] and the current Thai seismic design code (DPT 1302-09); however, in order to taking into account nonlinear phenomena during earthquake, slightly higher coefficient value has been adopted in the DPT1302-09. In addition, there is no significant difference between building built before and after the seismic design code in 2009. It is also noticeable that large variation could be observed for both fundamental periods estimated from the number of stories. Large variation could be observed for buildings greater than 15 story this is due to the fact that floor height for multi-story buildings can vary widely based on building regulations, functioning, and architectural designs.

4.3. The effect of soil-structure interaction

In previous section, only Bangkok building database is investigated; however, for building located at soft soil condition, the building period would tend to be longer than those structures located at stiffer soil, which is due to soil-structure interaction effect. Since the foundation of the structures situated on the soft soil are not fully attached at the ground level, but it would move together with the soft soil around the buildings. In current study, there are 24 buildings performed ambient vibration measurements in Chiang Mai and Chiang Rai whose soil property is classified as stiff soil (NEHRP site class D).

Fig. 5 display the comparison between the regression analysis from stiff soil for buildings built before and after the issue of DPT1302-09 seismic design code (yellow and red circles, respectively). The period heigh-relationship for T_1 for reinforced concrete buildings located in stiff soil in Northern Thailand is.

For soil type D,

$$T1 = 0.018H \tag{20}$$

It could be quickly noticed that the fundamental period for buildings located at soft soil is longer than those situated on stiffer soil about 10 %. It should be noted also that the current relationship is only applicable to building with story height until 60 m due to low number of high-rise buildings in Northern Thailand compared to Bangkok.

4.4. Comparison of data during earthquake events with ambien vibration data

The empirical period-height relationships derived in the previous section are based on microtremors measurements of 98 buildings. However, it is necessary for us to study the differences between the natural vibration periods of buildings obtained from microtremors and those obtained during earthquake events. As part of the effort to monitor the seismic performance of buildings in Thailand, two hospital buildings with 15 and 14 story in Chiang Mai and Chiang Rai, respectively, are instrumented with triaxial accelerometers to capture the responses of buildings subjected to tremors since 2022. The accelerometers are at the top and ground floor of these buildings and placed near the central position where shear wall is located, Fig. 2a and 3a.

From 2022 to 2023, four local and regional earthquakes between Mw 4.0 and Mw 5.7 with epicentral distance of 15 and 200 km, Table 2, Fig. 4a, had been detected on these instrumented structures. Table 3 illustrates the estimation of building first fundamental periods (T₁) caused by earthquakes comparing with the proposed equation (20). In general, the first fundamental period from both

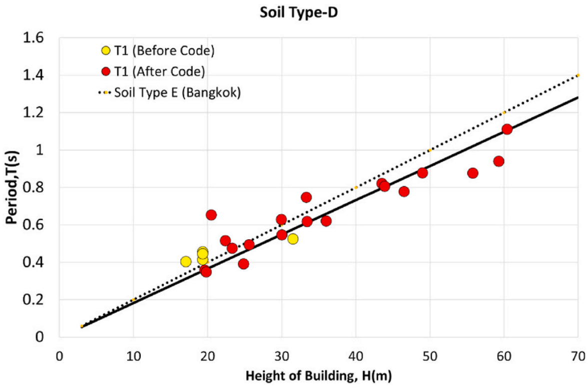

Fig. 5. Regression analysis is done for T_1, and the summary of the ambient vibration test measurements uses the x- and y-axes to represent height and natural period based on soil type D.

earthquake vibration and the proposed equation gives comparable results; however, there is a slight increase in fundamental periods for those with slightly larger ground shakings at the ground floor from EQ event 1 and 4 as previously reported in Gallipoli [33]. This might be because the soil structure interaction and the beginning of nonlinear characteristic of structural materials. However, the overall percentage difference is less than 12 % based on equation (20).

4.5. Comparison with other existing empirical formulas

It is interesting to compare existing empirical formulas with the proposed empirical formulas, Fig. 6. The other published empirical formulas with similar structural system used to compare including ([1,4,19]; ASCE 7–16) for buildings in Taiwan, Europe, Singapore, and USA, respectively. In general, the fundamental period of buildings situated in soft soil in Bangkok is longer than that predicted by other countries. For buildings in Northern Thailand lower than 60 m, the estimated fundamental period is comparable to the European natural period proposed by Gallipoli et al. [19] for similar structural types.

It is worthwhile to mention that several buildings in Northern Thailand built prior the announcement of DPT 1302-09 adopted the UBC 97 [42] formula (Equation (1)) to estimate the structure fundamental period. The formula is expressed as follow:

$$T = 0.1N \tag{21}$$

where T is fundamental period in second, and N is number of stories. However, the current study reveal that the estimated fundamental period is shorter than previously adopted. For example, a 10-story public structure in Chiang Mai with average height of 3.5 m would be measured the fundamental period of 0.6s; however, Equation (21) would give an estimate of 1.0s which might lower the appropriated seismic lateral forces.

5. Artificial neural network

Recently, Artificial Neural Networks (ANNs) have become adopted across various fields as computational modelling methods learning from observing complex data. Artificial Neural Networks (ANNs) structures are made up of highly connected, adaptive simple processing pieces (also known as artificial neurons or nodes) that can process and represent knowledge in large quantities in parallel. ANNs are extreme abstractions of their biological counterparts, but their purpose is not to mimic the workings of biological systems, but rather to apply our understanding of biological networks' functionality to the solution of challenging issues.

In this study, Multilayer Perceptron (MLP) neural networks with Back Propagation learning algorithm is used to estimate the fundamental period of the buildings. In order to calculate the value of a predetermined error, this method compares the output values with the correct result. The error is subsequently fed back throughout the network via a variety of techniques. With this data, the algorithm adjusts each link's weight to decrease the error function by a little amount. The network will typically converge to a state with a low computation error after an adequate number of training cycles. At this stage, the network has completed a particular objective function. As implied by the name, errors spread from the outer to the interior nodes. Therefore, the gradient of the network's error with respect to its variable weights is determined via back-propagation. Gradient descent is a general nonlinear optimization technique that is used to alter weights correctly. This training function is a straightforward first-order optimization technique that modifies the weights according to the gradient of the error relative to the weights. which has been used by Asteris et al. [20]. In order to minimize the error, one first finds the derivative of the error function with respect to the network weights, and then modifies the weights in order to lower the error (thus decreasing on the error function's surface). Consequently, networks with differentiable activation functions are the only ones where backpropagation can be used.

It was important to build the correct architecture for artificial neural networks to make predictions. The capable architecture of an ANN can be recognized with the identified number of parameters for input and output by assessing the ideal number of hidden layers and neurons. In this paper, several inputs have been considered as inputs to ANNs including soil types, structural shapes, the periods of design codes, the number of floors and building height. Due to considering its complexity, two hidden layers had been selected with different neurons in hidden layer 1 and 2 are going to be varied (Fig. 7). For transfer function, its role is to mapping input signals to output signals within the networks. Following Asteris et al. [20], the sigmoid function is commonly chosen due to their smoothness continuity and boundedness, and this activation function has been adopted in hidden layers of the current study.

The translational periods of 98 ambient vibration tested building are investigated as outputs. After several test, the best predicted input variables are the height of the building, the geometry of the buildings, soil types, the numbers of floor, and the periods of design codes. Each of these models was trained on 68 data sets (of a total of 98, or 70 % of the sets) and tested on 30 data sets (of a total of 98, or 30 % of the sets). The total number of epochs is set to 2000 in order to preventing overfitting data [43,44]. And the learning rate is varied between 0.01 and 0.05. The mean square error (SSE) was computed using the following equation, and the validity of the results

Table 2
Regional and local earthquakes detected by instrumental buildings in Chiang Mai and Chiang Rai.

No.	Date	Location	Magnitude
EQ 1	October 20, 2022	San Kamphaeng, Thailand (18.790°N, 99.106°E)	4.2
EQ 2	June 19, 2023	Pyapon, Myanmar (15.255°N 96.290°E)	5.6
EQ 3	November 9, 2023	Pai, Thailand (19.439°N 98.377°E)	4.2
EQ 4	November 17, 2023	Kēng Tung, Myanmar (21.217°N 99.330°E)	5.7

Table 3
Comparison of the first fundamental period for instrumented hospitals estimated from ambient vibration and earthquake recordings.

	NO	Recorded PGA at ground floor (m/s2)	T1(s) from Earthquake Data	T1 from Proposed Equation (20)	Percentage Difference (%)
Hospital 1	EQ 1	0.15	0.974	1.085	10 %
	EQ 2	0.02	0.968	1.085	11 %
	EQ 3	0.02	0.951	1.085	12 %
	EQ 4	0.04	0.970	1.085	11 %
Hospital 2	EQ 2	0.02	1.085	1.160	2 %
	EQ 3	0.03	1.085	1.160	2 %
	EQ 4	0.28	1.218	1.160	−10 %

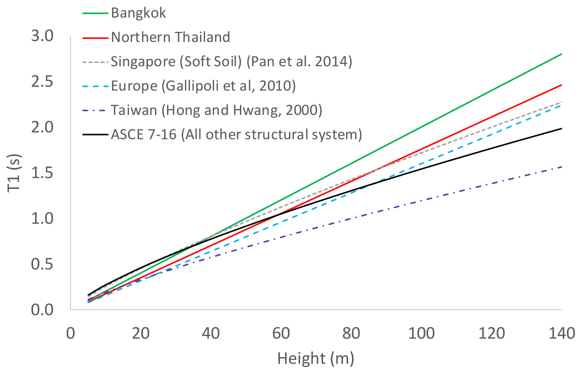

Fig. 6. Comparison of the proposed formulas for buildings in Bangkok and Northern Thailand with other published relationships.

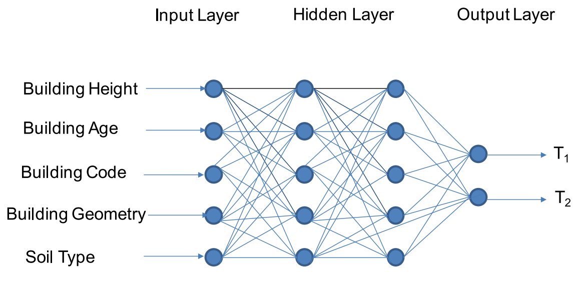

Fig. 7. Two hidden layer ANNs.

was verified by comparing them to the testing 32 data sets (30 % of the total).

$$SSE = \sum ni = 1 \sum mj = 1(yij - y\hat{}ij)2 SSE = \sum i = 1n \sum j = 1m(yij - y\hat{}ij)2 \quad (22)$$

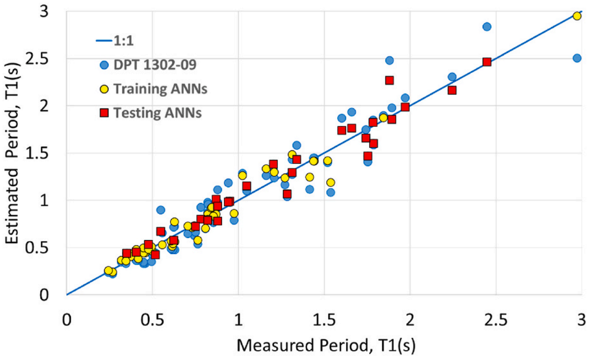

Fig. 8. The comparison of the estimated fundamental period using DPT, train, and test data from ANNs.

SSE is the sum of squares errors. y_{ij} represents the actual value of the jth output for the ith observation. $\hat{y_{ij}}$ represents the predicted value of the jth output for the ith observation. The training procedure is terminated when the SEE value reaches an acceptable range, e.g. SSE <0.5 or when the maximum number of training epoch reaches the pre-defined epochs. This prevents overfitting and ensures that the model generalizes well. The best ANN model, as determined by this process, and the number of neurons in 2 hidden layers are 40 and 40 respectively. The SSE values gave 0.39 and 0.25 in the training set and 0.54 and 0.32 in testing set. Fig. 8 showed the comparison between the measured periods with those computed from the DPT 1302-09 formula, the training and testing data predicted by using ANNs. It could be noticed that the trained ANNs give reliable values for the estimated first fundamental periods than those provided by the DPT1302-09 formula. The mean square error based on the DPT 1302-09 is about 0.05 while the MSE of test data is reduced to 0.02.

6. Conclusion

The current study measured and analysed ambient vibration of 98 reinforced concrete buildings in Bangkok and Northern Thailand built before and after the issue of DPT1302-09 seismic design code in order to determine the relationship between building height and fundamental period. In current study, different analysis including HVSR, FFT, and HBW methods have been adopted to obtain building first and second fundamental periods. Some major findings could be listed as follows.

- Different empirical formulas are computed with regression analysis for both translational fundamental periods and for soil type D and E. For Bangkok, the result reveal that the measured fundamental periods seem to correlate well with those estimates from the current seismic design code (DPT1302-09). This result has been reviewed by additional measurement for buildings built after the issue of the DPT1302-09.
- The results of this investigation reveal that, for the same structural type, the soil-structure interaction in Bangkok leading to a longer fundamental period than those reported in published literatures. However, for stiff soil in Northern Thailand, the proposed equation seems to give lower fundamental periods (about 10 %) than the ones in Bangkok (for soft soil).
- The estimated fundamental periods of two instrumented hospitals in Chiang Mai and Chiang Rai from four local and regional earthquakes have been used to compared with the ones estimated from the proposed formula. The maximum difference is found to be lower than 12 %.
- The ANNs was adopted to examine its applicability in estimating the building fundamental periods in the current database with building basic database, and it shows promising results as the MSE value is lower than those obtained from the one estimated by the code provision formula.
- The current database is developed only for reinforced concrete buildings, and the empirical formula might not be suitable to different structural types. The performance of ANNs observed in the existing work could be adopted for building height between 7 and 180 m. The empirical formula proposed in this study could be essential knowledge for engineers to consider appropriate seismic demand for structural strengthening or seismic design for new buildings in soft soil in the future.

CRediT authorship contribution statement

Teraphan Ornthammarath: Writing – review & editing, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Tun Tun Tha Toe:** Investigation, Data curation. **Rajesh Rupakhety:** Writing – review & editing, Validation, Supervision, Conceptualization. **Christian Malaga-Chuquitaype:** Writing – review & editing, Validation, Supervision, Conceptualization. **Janaka Ranaweera:** Writing – original draft, Investigation, Data curation. **Prem Pradittan:** Investigation, Data curation.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jobe.2024.111691.

Data availability

Data will be made available on request.

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