

# DYNAMIC CHARACTERISTICS OF NON-SEISMICALLY DESIGNED REINFORCED CONCRETE BUILDINGS WITH SOFT SOIL CONDITION IN BANGKOK

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# SUMMARY

In this study, the investigation of the dynamic properties of reinforced concrete buildings in Bangkok, which are mostly non-seismically designed, is conducted by the measurement approach to perceive their seismic hazard. The natural periods and mode shapes in the translational and torsional motions of fifty buildings, varying in height from 20 to 210 meters and number of stories from 5 to 54 were identified from ambient vibrations by a technique in frequency domain. The fundamental periods of the buildings with 15 to 25 stories are found to be in the vicinity of the predominant period of the amplified ground motion of Bangkok soft soil layers, which is about 1 second. This concurrence illustrates potential of the subsequent resonance phenomena, which are the near-periodic amplified ground motion and the discrepancies with the data from buildings under earthquake resistant design practices in other countries are presented herein. From the results of mode shape analysis, the vertical profile plots of mode shape indicate that there is significant effect of foundation flexibility resulting from soft soil condition. The calculated effective modal mass ratios characterize the deformation behaviors and represent the meaningful information to justify the seismic risk of these buildings.

#### **INTRODUCTION**

Thailand has long been considered by most people as a low seismicity country because there has never been any evident record of the devastating earthquake in history. The metropolis with a population about ten million has been urbanized rapidly from the regional economic growth during the past few decades. Therefore, a large scale of building construction has been taken place whereas the seismic consideration has not been specifically required in the national building code because of the seismic-free confidence of the city. However, recent preliminary investigations reveal that there are some seismic risks from several

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active faults located in the northern and western parts of the country. Moreover, there are highly active earthquake belts, in the Thailand-Burma-Indochina region and the Sumatra fault system and subduction zone, located at about 400 to 1000 km. from the capital city, Bangkok. From the progressive understanding of seismic risk due to long distance earthquake, a seismic hazard assessment of Bangkok was comprehensively investigated (Warnitchai [1]). It was found that, the surficial deposits in Bangkok have the ability to amplify earthquake ground motions about 3 to 4 times, and the amplified ground motions can be described as narrowband random motions with a long predominant period of about 1 second. The seismic hazard characteristics of Bangkok are comparable to those of Mexico City, in which the well-known 1985 devastated event occurred where long natural period structures, and founded upon thick soft soil deposits, responded strongly to about 400 km distant earthquake. The problem of soil amplification of ground motions of Bangkok is, therefore, appears to be susceptible to the same type of Mexico City, by somewhat analogy. In fact, occasional events of tremors generated from remote earthquake were felt and caused chaos to Bangkok residents who are unfamiliar with the quakes. The most recent incidents in 2003 are the effect of the earthquake on January, 22, size 5.7 on Richter scale and centered 1000 km. away in Sumatra, Indonesia and the earthquake in Meiktila, Myanmar on September, 22, size 6.5 on Richter scale and centered 850 km. away. Although there was no report of collapse of building or casualties, long period effects were felt in many buildings where a large number of occupants rushed down to the ground level and some cracks in non-structural members were observed in few buildings. Local newspaper and medias promptly reported the event as the headline sensations. It was noticeable information that buildings with 15 to 25 stories were most susceptible to the quake.

The above mentioned facts well serve as a strong reason for an urgent need to develop the Bangkokspecific seismic design criteria from the available sources of data, possible methodologies and practical for engineering applications. One of the important tasks of the work is an extensive study of dynamic properties of the existing building in Bangkok. These properties include the natural periods and mode shapes of a building. In most cases, natural period of a building plays an important role in the determination of the seismic lateral force. Its influence becomes increasingly significant for a problem of the near-periodic amplified with a long predominant period and being within a range of building natural periods. The natural periods gain a great deal of interest for the investigation of seismic hazard of building, for example, Goel [2], Hong [3], Trifunac [4]. In normal practice, only the fundamental period of a building is used to evaluate the seismic force. Many empirical formulas in simple form for an estimation of this value are specified in different building design codes. The basis of the establishment of each code may be different due to some reasons such as the construction practices or the required level of design forces. It is therefore necessary to acquire accurate data of natural periods of the non-seismically designed buildings in Bangkok in order to develop more appropriate empirical formula. The mode shape of vibration can be used as essential information to characterize the deformation behaviors of the building and justify its seismic performance. The mode shapes of buildings founded upon soft soil are essentially required to investigate.

# DYNAMIC PROPERTIES OF BUILDINGS

#### Empirical formulas for the fundamental periods of RC buildings

The techniques for determining of the dynamic properties of buildings can be classified into three main categories; empirical formula, numerical calculation from model and measurement of the actual system. The empirical formula in codes is currently available for the fundamental period where it is a simple relation between the periods of buildings and their geometry. Even though this approach is considered as a rough estimation, the predictions made using only a few of data of building configuration were shown to be as accurate as a more complex computer based methods (Ellis [5]). Some of the empirical formulas for natural period, T (second), recommend in building codes are shown as follows;

NEHRP-94 [6] provisions which is restricted to buildings not exceeding 12 stories in height and having a minimum story height of 3 meters is

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

In which N is the number of stories. ATC3-06 [7] and earlier versions of US codes recommend

$$T = \frac{0.09H}{\sqrt{D}} \tag{2}$$

Where *H* is the height of the building above the base (m.), and *D* is the dimension at base in the direction under consideration (m.). For Thailand, the formulas in Equation 1 and 2 were adapted to the current national building code. In the Uniform Building Code 1997 (UBC 1997 [8]), a simple formula is

$$T = C_{\star} H^{0.75}$$
(3)

For height in meter,  $C_t = 0.0853$ , 0.0731 and 0.0488 for steel MRF, RC MRF and all other buildings, respectively.

The period formulas above were developed, based largely on periods of buildings measured from their motions recoded during many earthquake events. To acquire these valuable data, array monitoring system of a large number of buildings has to be set up and natural periods of buildings can be extracted from their responses triggered by many earthquake events. The operating durations depend on the frequency of earthquake occurrences, which may vary from few years to decades. This technique is neither practical nor possible to apply in Bangkok. Therefore, the ambient vibration study is employed herein with full awareness of its limitations.

# Identification technique by ambient vibration tests

The measuring equipment comprises three uniaxial servo accelerometers (forces balance type) with  $\pm 2g$  full-scale range and a portable seismic data acquisition unit with a 22-bits analog-to-digital converter and 130 dB dynamic ranges. This system allows the lower limit on threshold level being well below the ambient responses of most of low and medium-rise RC buildings.

To identify the natural periods of building, measurements are taken place on the top floor with different sensor arrangement schemes so that translation modes in two orthogonal axes, i.e. north-south and east-west directions, and torsional modes could be detected (Petcharoen [9], Yinghan [10]). The natural vibrations from ambient disturbances of the building are recorded and analyzed further with an assumption that excitations are stationary random process with a board band spectrum. The natural periods are, then, estimated from peaks in the Fourier spectra. Besides a traditional identification by random vibration concepts (Trifunac [11]), resonant amplification of a building can be induced at particular modes by oscillating a human body in time at each building natural period. This technique can improve the accuracy of the identified natural periods and damping which were used successfully in steel or flexible structures (Glanville [12], Brownjohn [13]). The natural periods and damping ratios are identified straightforwardly from free vibration responses of building after the termination of human excitation. The better identified parameters can be achieved from the higher acceleration amplitudes which are about 3 to 8 times of those from ambient vibrations.

The measured signal is then divided into a number of segments and the statistical characteristics of each segment are compared so that the abnormal part of record, which may arise from some unforeseen circumstances, can be indicated and excluded from the analysis.

Mode shapes of building, as the vertical profile of translation modes, can be obtained by comparing the magnitudes and phases of the Fourier spectral of each story. However, due to a limit number of sensors, simultaneous measurement of all stories is not possible, thus one accelerometer is set at the top of building and the others are moved step by step to lower levels. In addition, top floor vibration patterns, which characterize the coupling motion in each direction, are obtained from the kinemetic relationships between rotational and translational motions based on the assumption of rigid floor diaphragm.

# **IDENTIFICATION RESULTS AND DISCUSSIONS**

In this study, 50 reinforced concrete buildings in Bangkok, varying in height from 20 to 210 meters and number of stories from 5 to 54 were investigated by the afore mentioned technique. The distribution of building heights is presented in Figure 1, along with the corresponding number of stories.



Figure 1. Distribution of number of stories and height of buildings

#### Periods of the tested buildings

In some discussions (Trifunac [14], Trifunac [15]), the measured period of building, which includes the effects of soil-structure interaction, is referred as the apparent period, and the fundamental period refers to the period of the first mode of vibration of a fixed-base model. In this paper, where the measurements were taken place under very low amplitude ranges, a plain word of period is used throughout the discussion in order to avoid confusion.

The empirical formula of period for buildings in Bangkok can be constructed from these data and compared to the period formula in the UBC 1997 and the improved formula proposed by Goel [2] based

on periods of buildings measured from their motions recorded during many earthquakes. It is noted that the database contains a large portion of building with ground motion acceleration smaller than 0.15 g., and all records are from structures shaken strongly but not deformed into the inelastic range. The discrepancy between periods of buildings measured from the ambient vibrations and earthquake excitation can be investigated from the research done in the same group of buildings. For example, 21 RC buildings in Taiwan were monitored for their response under seismic excitation, with peak accelerations ranged from several gals to few hundred gals, by Hong [3], and 45 RC buildings were studied for their ambient vibration responses by Leu [16]. Empirical formulas of buildings periods were proposed and the comparison is presented in Figure 2. There is no significant different observed from the results form two approaches. Hence, the measured periods from ambient vibration in this study may supersede the unavailable strong motion records, provided that structures behave linearly.



Figure 2. Comparison of periods identified from ambient vibration and earthquake excitations: example case in Taiwan

The empirical formula of UBC 1997, as shown in Equation 3, can be derived by Rayleigh's method under the following assumption: (1) Lateral forces are distributed linearly over building height; (2) base shear is proportional to  $1/T^{\frac{2}{3}}$ ; (3) weight of the building is distributed uniformly over its height; and (4) deflected shape of the building, under application of the lateral forces, is linear over its height. (Goel [2])

In US seismic codes, the second assumption applies in the velocity-controlled region of the design spectrum. An investigation in detail on this assumption is necessary before adapting into Bangkok-specific recommendation. At present, a simple linear regression analysis is, therefore, adequate to establish the empirical period formula because the differences involved in regression analysis may be less significant than the effects of the uncertain seismic conditions of Bangkok.

In addition, using Rayleigh's method, the fundamental of a shear building with uniform lateral stiffness over height can be estimated in a different form as (Goel [2]):

$$T = C_1 N \tag{4}$$

in which the coefficient  $C_1$  depends on the unit mass and stiffness properties of the building. For buildings in this study, height and number of stories are quite linearly correlated, as shown in Figure 1, therefore Equation (5) may be rewritten in terms of the total building height, H, as:

$$T = C_1^* H \tag{5}$$

The regression formulas for buildings in this study are obtained by the first order constrained regression analysis. The formula for building period and number of stories is

$$T = 0.067N\tag{6}$$

and the formula for building period and height is

$$T = 0.019H$$
 (7)

The measured periods in two orthogonal lateral directions shown by circles connected by a vertical line are plotted against N and H, and the associated regression formulas are presented in Figure 3 and 4 respectively.



Figure 3. Relationship between measured periods of first translational modes and number of stories

In order to understand the characteristics of the periods of Bangkok buildings, Equation 1 is included in Figure 3, and Equation 3 and the following regression formulas from previous researches are included in Figure 4



Figure 4. Relationship between measured periods of first translational modes and height

The best-fit regression formula from the measured periods of RC MRF buildings in California, is (Goel [2])

$$T = 0.0507 H^{0.92} \tag{8}$$

and their recommendation, by constrained regression at the exponent = 0.90 and lowering the best-fit line in order to intentionally underestimate the period which results in a conservative base shear, is

$$T = 0.0466H^{0.90} \tag{9}$$

The regression formula from the measured periods of RC MRF building in Taiwan (Hong [3]), is

$$T = 0.0294 H^{0.804} \tag{10}$$

In Figure 3, it is clear that periods of these building are not well suited to the code recommendation for all ranges of number stories. In Figure 4, periods of building measured in Bangkok and Taiwan indicates that the building systems in Taiwan possess higher lateral stiffness than those in Bangkok. This may result from two main reasons, the construction practices in Bangkok in which the seismic considerations are mostly ignored, and the geotechnical properties of soil beneath their foundations. For periods obtain from strong motions as Equations 8 of 9, the significant period elongation due to concrete cracking and soil-structure interaction is very prominent. It is observed that the regression this study is bounded by the UBC 1997 for RC SW formula at the upper side and the UBC 1997 for RC SW formula at the lower side. However, this observation is not rational enough to specify the recommendation in a seismic code. Further

investigations on the effect of period elongation and considerations for the conservative base shear for the specific characteristics of earthquake ground motion are necessary for a sound establishment of recommendation.

It should be noted that the fundamental periods of the buildings with 15 to 25 stories are in the range of 1 second which is in the vicinity of the predominant period of the amplified ground motion of Bangkok soft soil layers. This observation illustrates potential of the subsequent resonance phenomena, which are the near-periodic amplified ground motion and the amplification of building responses at this predominant period. It also well explains the recent resonance effects of these buildings due to the long distance earthquake.

In this study, the identified periods of higher modes in 30 buildings were achieved. The ratios between the periods of the first mode,  $T_1$ , and the second mode,  $T_2$ , in the same translational direction can be used to characterize the deformation behaviors of buildings. From the theoretical models of a uniform shape building with fixed support, the ratio of  $T_1$  to  $T_2$  is 6.28 for a cantilever flexural building and 3.0 for a cantilever shear building (Chopra [17]). Then, the frame action or shear wall action influenced in the lateral stiffness of buildings in this study behave nearly in shear deformation type. In some buildings, intermediate behaviors resulting from the combination effects of frames and walls, shear wall and masonry wall, can be observed. This is common for RC buildings as previously reported by Li [18] but contrasting with the behavior of steel buildings where the actions of frames are remarkably stronger than those from walls (Satake [19]).



Figure 5. Ratio of periods of the first mode and the second mode in the same translation direction

# Identified vibration mode shapes

The vertical profiles for each of the translational modes are obtained from the relative magnitude of peaks in the Fourier spectra. The smooth lines fit by the low-order polynomial function are used to approximately represent the discrete points from measurement in order to eliminate order from this measuring technique. Generally, mode shape of buildings can be used to transform the equation of motion from the spatial coordinate system into the normal coordinate system. Moreover, vibration mode shapes of buildings can be used to characterize their deflection behaviors, as the flexural deflected shape, the shear deflected shape and the intermediate deflected shape, by considering the effective modal mass ratio  $M_n^*$ ,

calculated from the mode shape (Chopra [17]).  $M_n^*$  is defined as the portion of the mass of a multistory building which is effective in producing the base shear due to the n-th mode.  $M_n^*$  depends on the distribution of the mass of the building over its height and on the shape of the mode, and the expression of the calculation of fixed base building is

$$M_{n}^{*} = \frac{(L_{n}^{h})^{2}}{M_{n}}$$
(11)

With the followings definition;

$$M_n$$
 = the effective modal mass in the *n*-th mode =  $\sum_{j=1}^{N} m_j \phi_{jn}^2$ 

 $L_n^h$  = the modal force in the n – th mode due to inertia mass of the building =  $\sum_{j=1}^{n} m_j \phi_{jn}$  $m_j$  = the mass in the j – th story

$$\phi_{in}$$
 = the vibration mode shape at the *j*-th story in the *n*-th mode

For a given geometrical configuration and the distribution of mass and stiffness of a building, mode shape and hence  $M_n^*$  can be computed. By changing the relative stiffness between beam and column, two extreme bounds of value of  $M_n^*$  for flexural and shear deflected shape of a uniform building can be computed. The estimated  $M_n^*$  from the measured mode shapes obtained in this study are then use to locate the deflection type of building between the two extreme bounds. In Figure 6, the calculated effective modal mass ratios of the first mode, defined as the ratio of  $M_1^*$  to the total mass of the building, for fixed base models of 5 bays, uniform building with the inter-story height of 3.0 m. are shown as the upper line for the shear deflected type and the lower line for the flexural deflected type. The data from the measured buildings indicate that most buildings perform vibration in the intermediate deflected type with the majority lines in the vicinity of the shear deflected type.



Figure 6. Effective modal mass ratios for the identified buildings

The vertical plots of the measured vibration mode reveal movement at base to a certain degree. The illustrated examples of mode shapes of a 35-story building are shown in Figure 7 and 8, in which the normalized movement at base reaches about 8% for the first mode, and 24% for the second mode, relative to the maximum motion at the top floor. These effects result from soil-structure interaction which is not only lengthening the periods but also shifting the mode shapes at ground level from those of a similar structure on a rigid foundation. It was stated (Ellis [5] and Meli [20]) that soil-structure interaction effects are more pronounced in smaller buildings where the relative stiffness of the building with respect to the soil is higher. However, there was no example of strong evidence in those reports. In this study, Figure 9 shows the normalized mode shape of the first modes in translation direction at ground level plotted against building height. The results show that the movements at base of low rise buildings founded on soft soils obviously confirm the above hypothesis, and emphasize the critical roles of the soil-structure interaction effects that should be incorporated in further seismic considerations.



Figure 7. Vibration mode shape (First mode) of the example building



Figure 8. Vibration mode shape (Second mode) of the example building



Figure 9. Movement at base from mode shape of the first translational modes

## CONCLUSIONS

Based on the ambient measurement data of the dynamic properties of 50 reinforced concrete buildings in Bangkok, the following conclusions are drawn from this study:

- (1) The measured periods of buildings in this study, which are mostly non-seismically designed, are comparable longer than the periods of the earthquake resistant designed buildings, derived from low amplitude motion of buildings. However, the measured periods are significantly shorter than those obtained from strong motion records of buildings.
- (2) The simple regression formulas of the first translation periods are presented. It was found that the periods of buildings with 15 to 25 stories are in the vicinity of the predominant periods of the amplified ground motion of Bangkok soils and this observation well explains the recent resonance effects of these buildings due to the long distance earthquake.
- (3) From the comparison between the identified vibration mode shape and the theoretical fixed base model of building, the effective modal mass ratios classify buildings in this study as the intermediate defected shape with the majority lies in the vicinity of the shear defected shape. The results indicated from the ratios of the periods of the first mode and the second mode in the same translational direction also support this statement.
- (4) The identified vibration mode shapes reveal significant movement at base. The movements are more pronounced when the relative stiffness of the building with respect to the soil is higher. This is the cause of soil-structure interaction effect which is obvious in this case of buildings founded on soft soils.

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#### REFERENCES

- Warnitchai P, Sangarayakul C, Ashford SA, "Seismic Hazard in Bangkok due to Long-Distance Earthquake." Proceeding of the 12<sup>th</sup> World Conference on Earthquake Engineering, Auckland, New Zealand. Paper no. 2145. February, 2000.
- Goel RK, Chopra AK. "Vibration properties of building determine from recorded earthquake motions." Rep. No. UBC/EERC-97/14. Earthquake Engineering Research Center, Richmond, Calif, 1997.
- 3. Hong LL, Hwang WL. "Empirical formula for fundamental vibration period of reinforced concrete buildings in Taiwan." Earthquake Engineering and Structural Dynamics 2000; 29: 327-337.
- 4. Trifunac MD, Todorovska MI, Hao TY. "Full-scale experimental studies of soil-structure interaction-a review." Proceeding of the 2<sup>nd</sup> U.S.-Japan Workshop on Soil-Structure Interaction, Tsukuba City, Japan, March 6-8, 2001.
- 5. Ellis BR. "An assessment of the accuracy of predicting the fundamental natural frequencies of building and the implications concerning the dynamic analysis of structures." Proc. Instn Civ. Engrs 1980; 69(2): 763-776.
- 6. NEHRP Recommended Provision for the Development of Seismic Regulation for New Buildings. Building Seismic Safety Council, Washington, DC, 1994.
- 7. Tentative Provision for the Development of Seismic Regulation for Building. ATC3-06, Applied Technological Council, Palo Alto, CA, 1978.
- 8. International Conference of Building Officials. Uniform Building Code (UBC), Whittier, CA, 1997.
- 9. Petcharoen C. "Identification of dynamic properties of low and medium-rise buildings in Bangkok by an ambient vibration method." Master Thesis, Asian Institute of Technology, Bangkok, Thailand. 2002.
- 10. Yinghan P. "Identification of dynamic properties of reinforce concrete buildings from vibration measurement." Master Thesis, Thammasat University, Bangkok, Thailand. 2002.
- 11. Trifunac MD. "Ambient vibration test of a thirty-nine story steel frame building." Report no. EERL 70-02. Earthquake Engineering Research Lab. California Institute of Technology. Passadena, 1970.
- 12. Glanville MJ, Kwok KCS. "Dynamic characteristics and wind induced response of a steel frame tower." Journal of wind engineering and industrial Aerodynamics 1995; 54/55: 133-149.
- 13. Brownjohn JMW. "Ambient vibration studies for system identification of tall buildings." Earthquake Engineering and Structural Dynamics 2003; 32: 71-95.
- 14. Trifunac MD. discussion on paper "Period formulas for concrete shear wall buildings" and closure by Goel RK, Chopra AK. Journal of Structure Engineering ASCE 1999: 797-799.
- 15. Trifunac MD, Ivanović SS, Todorovska MI. "Apparent periods of a building Part I: Fourier analysis and Part II: Time-frequency analysis." Journal of Structural Engineering ASCE 2001; 127(5): 517-526.
- 16. Leu LJ, Liu CY, Huang CW, Chou JJ, Lee JH, Yeh SH. "Formulas for vibration period of RC buildings in Taiwan derived from ambient vibration data." The Eighth Asia-Pacific Conference on Structural Engineering and Construction, Singapore. Paper no. 1479, 2001.
- 17. Chopra A.K. "Dynamic of Structures: Theory and Applications to Earthquake Engineering (2<sup>nd</sup> Edition)." Prentice-Hall, Englewood Cliffs, NJ, 2000.
- 18. Li Y, Mau T. "Learning from recorded earthquake motion of building." Journal of Structure Engineering ASCE 1997; 123(1): 62-69.
- 19. Stake N, Yokota H. "Evaluation of vibration properties of high-rise steel building using data of vibration tests and earthquake observations." Journal of wind engineering and industrial Aerodynamics 1996; 59: 265-282.
- 20. Meli Ř, Faccioli E, Muria-Vila D, Quaas R, Paolucci R. "A study of site effects and seismic response of an instrumented building in Mexico city." Journal of Earthquake Engineering 1998; 2(1): 89-111.