# Optimization Study on Building Height Based on the Predominant Site Period and Structural Natural Period

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DOI: 10.32629/aes.v5i3.2796

**Abstract:** Through a case study analysis of the Mexico earthquake, this research reveals the hazards of period resonance. The study explores the optimal heights for steel structures and reinforced concrete frame-shear wall structures on different types of sites to optimize seismic design. By comprehensively considering the advantages and disadvantages of the building heights of steel structures and reinforced concrete frame-shear wall structures, the safety and durability of buildings during earthquakes can be significantly improved.

***Keywords*****:** predominant site period, structural natural period, disaster prevention and mitigation, resonance

## 1. Introduction

Earthquakes pose the greatest natural threat to urban safety, causing enormous losses to human life, property, and cultural heritage. The severity of earthquake damage is not only related to the tectonic environment of the city but also significantly influenced by site conditions. In 1985, an 8.1 magnitude earthquake struck the Pacific Ocean floor off Mexico. This earthquake had a focal depth of 33 km, resulting in over ten thousand deaths and displacing more than 300,000 people, with over 8,000 buildings damaged. The extensive damage in Mexico was mainly attributed to its geological conditions, as the foundation consisted largely of weak, artificially compacted soil. In the city center, situated on soft soil foundations, seismic wave recorder analysis indicated a predominant site period of 2 seconds. The most severely damaged buildings in this area were concentrated in the 5 to 15-story range. The fundamental structural period of these buildings was approximately 1.0 to 1.5 seconds. Initial seismic activity caused the separation of walls from the main building structure, increasing the fundamental structural period and bringing it closer to the predominant site period, thus inducing stronger resonance than in other buildings [1]. Therefore, in building design, it is crucial to avoid the coincidence of the structural natural period with the site's predominant period to prevent resonance and mitigate earthquake-induced damage. To ensure the safety of human life and building property during earthquakes, it is necessary to propose optimization recommendations for different building structures and stories based on the resonance relationship between site period and structural fundamental period for each site type.

**Figure 1: Mexico Earthquake Site**

## 2. Selection of Site Parameters Based on Resonance

In some site research applications, commonly used parameters include the predominant site period, site characteristic period, and fundamental site period. These terms are often confused and incorrectly used in research. The site period includes the predominant site period and the fundamental site period, which differ significantly from the site characteristic period, although they influence each other. According to the “Code for Seismic Design of Buildings,” the site characteristic period is the period value corresponding to the starting point of the descending segment of the earthquake influence coefficient curve used in seismic design, reflecting factors such as earthquake magnitude, epicentral distance, and site type [2]. The site characteristic period can be calculated based on recorded strong ground motion data and used for seismic design according to site safety evaluation results. The site period is an inherent property of the site [3], representing the vibration period generated by seismic waves acting on different types of sites. It results from the interaction between the site and the seismic activity and is influenced by various media such as soil and foundation. The “Handbook of Earthquake Engineering Site Selection” stipulates that the characteristic period can be used to determine the site category in seismic design, as shown in Table 1[4].

**Table 1: Classification of Site Categories Based on Site Characteristic Periods**

| Site Characteristic Period (Tg/s) | Site Categories |
|---|---|
| <0.1 | I |
| 0.1~0.4 | II |
| 0.4~0.8 | III |
| >0.8 | IV |

The fundamental site period is the natural period of the site. Assuming the site is a horizontally layered half-space and each soil layer is an isotropic linear elastic body, the period of the first mode of vibration in the absence of damping effects in this site system is called the fundamental site period [5]. According to the “Engineering Geology Handbook,” the predominant site period is described as follows: “When seismic waves propagate through soil layers, multiple reflections occur at interfaces of different properties, generating seismic waves with different periods. If a seismic wave period coincides with the natural period of the surface soil layer, the resonance effect will amplify the seismic wave’s amplitude. This period is called the predominant site period.” [6] Its value varies with the geotechnical characteristics of the site. When the site soil is harder, the predominant period shortens, and the seismic wave amplitude is smaller. Conversely, when the site soil is softer, the predominant period lengthens, and the seismic wave amplitude is larger. This variation is because different geotechnical characteristics affect the propagation speed and reflection properties of seismic waves, leading to changes in the predominant period. Through real earthquake observation records [7], Hou Rubin [8] compared and analyzed the evaluation effects of seismic site effects using two site periods as site parameters. Using the predominant site period as a parameter more significantly reflects the site’s amplification resonance effect. Therefore, this paper adopts the predominant site period as a reference. Wei-Qiang Jiang and others[9], through the seismic safety evaluation of 380 projects in the Pearl River Delta and Chauhan regions of Guangdong Province, found a certain correlation between the predominant site period and the structural characteristic period and proposed a relationship formula between the predominant site period and the structural characteristic period in the Pearl River Delta region.

$$T_g = T\left(1 + 0.0038 I^{2.25964}\right) \tag{1}$$

In this equation, $T_g$ represents the characteristic period of the site, T denotes the predominant period of the site, and I signifies the seismic intensity.

This paper derives the range of predominant periods for different sites in the Pearl River Delta by using the relationship formula between the characteristic period and the predominant period of the site. The characteristic period values for different site types are shown in Table 1, and the resulting ranges of predominant periods for various sites in the Pearl River Delta are presented in Table 2.

**Table 2: Classification of Site Categories Based on Site Dominant Periods**

| Site Dominant Period (Tg/s) | Site Categories |
|---|---|
| 0.1 | I |
| 0.049~0.398 | II |
| 0.196~0.797 | III |
| >0.392 | IV |

## 3. The Optimization Analysis of Natural Vibration Period of Building Structures

Morales[10], based on the theoretical assumption of a purely bent cantilever beam and the measured dynamic performance data of 18 buildings in California under moderate earthquake conditions, proposed a formula for calculating the fundamental period of reinforced concrete shear wall structures.

$$T_1 = 0.13\frac{h}{l^{0.25}} - 0.4 \tag{2}$$

Qi Guifen et al[11]., based on vibration measurements of 32 existing reinforced concrete high-rise and multi-story buildings and using regression analysis, proposed a formula for calculating the fundamental period of such buildings.

$$\begin{aligned} T_{CW} &= 0.0159\left(H-2.88\right) \\ T_{LW} &= 0.017\left(H-11.65\right) \end{aligned} \tag{3}$$

Fang Ehua[12] collected measured and calculated fundamental periods of 37 high-rise building structures and used the least squares method to obtain a regression formula for the measured and calculated values of the fundamental period.

$$\begin{aligned} T_1 &= 0.25H \\ T_1 &= 0.10N \end{aligned} \tag{4}$$

Based on the research of Shen Pusheng and others[13], data from 302 constructed or under-construction high-rise and super high-rise buildings were collected. Through fitting analysis, a formula for calculating the fundamental period of high-rise buildings, using structural height as the independent variable, was derived.

$$T_1 = \begin{cases} -1.36\times10^{-5}H^2 + 0.0282H - 0.0958 & H \leqslant 201\text{m} \\ -8.2\times10^{-6}H^2 + 0.0164H + 2.12 & H > 210\text{m} \end{cases} \tag{5}$$

According to the "Load Code for the Design of Building Structures" (GB50009-2012, Appendix E: Empirical Formula for the Fundamental Natural Period of Structures)[14], the fundamental natural period of high-rise buildings can be estimated using the following general formula.

**Table 3: Structural Empirical Formulas**

| Structural Type | Calculation Formula |
|---|---|
| Steel Structure | $T_1 = \left(0.10-0.15\right)n$ |
| Reinforced Concrete Structure | $T_1 = \left(0.05-0.10\right)n$ |
| Frame-Shear Wall Structure / Frame-Tube Structure | $T_1 = \left(0.06-0.12\right)n$ |

Gong Maosheng[15] believes that the correct approach to fitting structural empirical formulas is to first determine whether the structure is time-varying, nonlinear, or damaged. Based on the fundamental period data obtained from 40 flexural frame-shear wall structures and 36 steel structures under actual earthquake response conditions using modal frequency identification methods, nonlinear regression analysis was conducted using the obtained structural parameters and first modal frequencies. This resulted in regression outcomes of different formula forms.

**Table 4: Regression Results for Different Formula Forms**

| ID | Formula Form | Regression Coefficient | | | | Variance |
|---|---|---|---|---|---|---|
| | | a | b | c | d | |
| 1 | $T_1 = a + bH / \sqrt[3]{B}$ | 0.1937 | 1.1431 | / | / | 0.0329 |
| 2 | $T_1 = a + bH^2 / \sqrt[3]{B}$ | 0.3533 | 7.44e-3 | / | / | 0.0340 |
| 3 | $T_1 = a + bH^C / \sqrt[d]{B}$ | 0.1075 | 0.0114 | 0.9454 | -1.1937 | 0.0244 |
| 4 | $T_1 = cH / \sqrt{B}$ | / | / | 0.1015 | / | 0.0505 |
| 5 | $T_1 = cH^{3/4}$ | / | / | 0.0511 | / | 0.0260 |
| 6 | $T_1 = cH^d$ | / | | 0.0543 | 0.7327 | 0.0260 |

| ID | Formula Form | Regression Coefficient |  |  |  | Variance |
|---|---|---|---|---|---|---|
|  |  | a | b | c | d |  |
| 7 | $T_1 = bH^c / \sqrt[d]{B}$ | / | 0.0304 | 0.7546 | -0.1529 | 0.0246 |
| 8 | $T_1 = aH$ | 0.0211 | / | / | / | 0.0305 |
| 9 | $T_1 = an$ | 0.0715 | / | / | / | 0.0562 |

From the table, it can be seen that Formula No. 5 is not only simple in form and convenient for computation but also has a small variance and good convergence. Therefore, based on relevant research, this paper adopts the following simplified method as the formula for the natural period of the structure.

**Table 5: Structural Empirical Formulas**

| Structural Type | Calculation Formula |
|---|---|
| Reinforced Concrete Frame-Shear Structure | $T_1 = 0.05H^{3/4}$ |
| Steel Structure | $T_1 = 0.065H^{3/4}$ |

Cai Yuanqi[16] proposed that the relationship between the fundamental period of a building and the predominant site period is not simply a matter of being as far apart as possible, but there is an optimal ratio. When $T_1 = \sqrt{3}T_g$, the relationship between the building structure and the site is most favorable. Based on the predominant period ranges of different sites and the empirical formula for the natural period of structures, and using the optimal ratio relationship obtained above, the most advantageous building heights for each type of building structure on different types of sites can be derived. The calculation results are as follows.

**Table 6: Optimal Building Height for Reinforced Concrete Frame-Shear Structures**

| Reinforced Concrete Frame-Shear Structure Building Height (m) | Site Categories |
|---|---|
| <5.241 | I |
| 2.025~33.06 | II |
| 12.857~83.445 | III |
| >32.397 | IV |

**Table 7: Optimal Building Height for Steel Structures**

| Structural Building Height (m) | Site Categories |
|---|---|
| <3.694 | I |
| 1.427~23.301 | II |
| 9.062~58.813 | III |
| >22.834 | IV |

Make the following analysis according to the above table:

(1) Overall Height Difference: The optimal building height for steel structures is generally lower than that for reinforced concrete frame-shear wall structures. Since steel structures are typically lighter than reinforced concrete frame-shear wall structures, their dynamic response to seismic waves differs. The lower mass of steel structures means they are more susceptible to resonance during an earthquake, necessitating a lower building height to optimize their seismic performance.

(2) Trend Development: The height trend for steel structures develops more rapidly compared to reinforced concrete frame-shear wall structures. As building height increases, the seismic performance of steel structures changes more noticeably. This is due to the excellent ductility of steel structures, which allows them to dissipate the energy from seismic waves through deformation. Consequently, the natural period of the structure is longer, and the relationship between the structural natural period and the predominant site period remains stable, leading to this phenomenon.

# 4. Conclusion

This study delves into the potential hazards of resonance phenomena, with a particular focus on the impact of the site period on building safety. Through an extensive literature review, we found that the predominant period of a site has the most significant effect on the safety of building structures. Using the relationship formula between the predominant period and the site characteristic period in the Pearl River Delta as proposed by Jiang Weiqiang, we derived the range of predominant periods for different site types in the Pearl River Delta. Additionally, as a secondary influencing factor, we adopted the empirical formula for building structures proposed by Gong Maosheng. Based on Yuanqi Cai's suggested optimal relationship between the structural natural period and the predominant site period, our research indicates that when $T_1 = \sqrt{3}T_g$, the relationship between the building structure and the site is most favorable. Consequently, we derived the optimal building heights for different types of buildings under various site predominant periods. This study provides a new perspective on seismic safety, demonstrating that selecting the appropriate building height can significantly reduce earthquake-induced risks.

## Acknowledgments

This paper was supported by the following funding project: National Key R&D Program of China (2023YFC3082100).

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