# Seismic Behaviour of Tunnel Form Concrete Building Structures

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## ABSTRACT :

Multi-story reinforced concrete (RC) tunnel form buildings have been increasingly employed for mass construction industry in many countries. This system is very attractive for the medium to high-rise buildings with repetitive plans due to satisfactory performance during past earthquake, industrialized modular construction technique, low cast and also saving in construction time. Recent studies show that the current seismic codes and guidelines do not provide sufficient requirements for seismic design of these structures. The designers ought to adopt the traditional force based design methodology of framed structures for tunnel form. In this methodology, the fundamental period and the proposed behaviour factor (R factor) are used to compute the design base shear of a structure. Most seismic codes specify empirical formula to estimate the fundamental vibration period of building. Prior studies have shown that the empirical equations for predication of fundamental periods of this specified type of structures, may yield to inaccurate results. Some of new equations were suggested and a varied rang of parameters were considered to achieve a certain formulas. In this study, the fundamental period and mode shapes of tunnel form buildings, one of the basic parameters of seismic behaviour in linear response was investigated. Previous suggested formulas were studied and compared with each other. Some finite elements analysis carried out to show the influence of each parameter on the fundamental period. The results showed that the IBC 2006 formula for estimating the period of this type of structures, is still more reliable than other formulas which derived by different authors in recent studies.

**KEYWORDS:** Tunnel Form Buildings, Fundamental Period, Seismic Behaviour, Concrete

## 1. INTRODUCTION

Tunnel form buildings are built in many countries such Chile, Japan, Italy, Iran, Turkey and other countries. Due to their industrialized modular construction technique, they have been increasingly employed for mass construction industry in different countries.

The main components of this system are walls and flat plate slabs, where in-situ concrete is poured into two half-tunnel forms to shape load-bearing walls (shear-walls) and floor slabs simultaneously. Generally in a 24-hour, residential units can be rapidly built up. For this reason, tunnel form buildings are an attractive system for medium to high-rise buildings having repetitive plans. There is no precast elements in the structural elements. The walls and the slabs have almost the same thickness and cast in a single operation. This reduces the number of joists and results the monolithic structures provide high seismic resistance.

All of shear walls and slabs constructed with this method and also sliding form unit generally used to construct the corners of tunnel form buildings and the interior shafts (Elevator shafts or stair cases). Non-structural components such as facade walls, stairs and partition walls are used as prefabricated elements in the construction process.

The main components of this system are walls and flat plate slabs. Walls in tunnel form buildings have two functions: resisting lateral loads as well as carrying vertical loads. Tunnel form buildings diverge from other conventional reinforced concrete (RC) structures due to lack of beams and columns in their structural components. In these buildings, all of the vertical load carrying members, are made of shear walls and floor system. In addition, in tunnel form buildings, walls and slabs are made of thin concrete plates and rebars should be placed in one layer. So the confinements of concrete and ductility level can not be defined like other conventional structures.

The conventional seismic codes usually apply the traditional force based design methodology. In this methodology the fundamental period of structure, mode shapes and behaviour factor (R factor) are used to compute the design base shear of conventional building structures. But, recent studies showed that the current seismic codes and guidelines do not provide sufficient requirements for this type of building systems. Lee *et al*., Balkaya and Kalkan, Ghrib and Mamedov showed that current seismic codes and design provisions (e.g., IBC 2001, UBC 1997) inaccurately estimate the period and response-modification-factor for tunnel form buildings despite the fact that these parameters were directly used to compute the design base shear. Different simple expressions are used by various seismic codes to calculate the fundamental periods of structures. However, it has long been realized that significant errors have been occurred when the code-given formulas such as those in the UBC (1997) or other codes are utilized for shear-wall dominant systems or tunnel form buildings. To solve this problem for tunnel form buildings, some sets of formulas with different parameters were proposed based on the experimental or analytical studies. Researches on the accurate evaluation of fundamental period and response modification factor are going on. But, in this study, we focus on the influence of each parameter on fundamental vibration period and mode shapes of this type of the buildings. Some of these formulas are introduced and then a sensitivity analysis of parameters will carry out.

## 2. CODE FORMULAS

The empirical formulas for the fundamental vibration period of concrete shear wall buildings specified in current building codes (UBC 97, IBC 2006) is of the form:

$$T = C_t H^{\frac{3}{4}} \tag{2.1}$$

Where $H$ is the height of the building in meters above the base and the numerical coefficient $C_t$ is taken as 0.049. UBC and SEAOC 96 permit an alternative value for $C_t$ to be calculated from:

$$C_t = 0.0743 / \sqrt{A_c} \tag{2.2}$$

Where $A_c$, the combined effective area (in square meters) of the shear walls is defined as:

$$A_c = \sum A_i (0.2 + (D_i / H_i)^2) \tag{2.3}$$

In which $A_i$ is the horizontal cross sectional area (in square meters), $D_i$ is the dimension in direction under consideration (in meters) of the *i*th shear wall in the first story of the structure. The current Korean Building Code (KBC) specifies that the fundamental period of multi story shear wall dominated system to determine the design base shear can be estimated by:

$$T = 0.09H / \sqrt{B} \tag{2.4}$$

Where $H$ is the height of the building in meters, $B$ is the full plan dimension of the building in meters in direction parallel to the applied forces. The empirical formulas in the Canadian Building Code (NBCC 95) is of the form:

$$T = 0.09H/\sqrt{D_S} \tag{2.5}$$

Where $D_S$ is the length of wall or braced frame in meters that constitutes the main lateral resisting system in direction under consideration.

## 3. FORMULAS DEVELOPMENTS IN THE PAST

Goel and Chopra (1998) have suggested a formula. They had studied the available data on the fundamental vibration period of buildings measured from their motion recorded during several California earthquakes (Goel and Chopra 1997a). This database contained data for 106 buildings, including 21 buildings that experienced peak ground acceleration $\ddot{u}_{go} \geq 0.15g$ during 1994 Northridge earthquake. The remaining data come from motion of buildings recorded during the 1971 San Fernando earthquake and subsequent earthquake. They compared the database information with the code formulation and showed that code formulas were grossly inadequate. In figure 1, the variation of the measured and the code calculated period are shown. The comparison leads to these observations: For majority of buildings, the code formula gives a period longer than the measured value. The longer period from the code formula leads to smaller seismic coefficient.

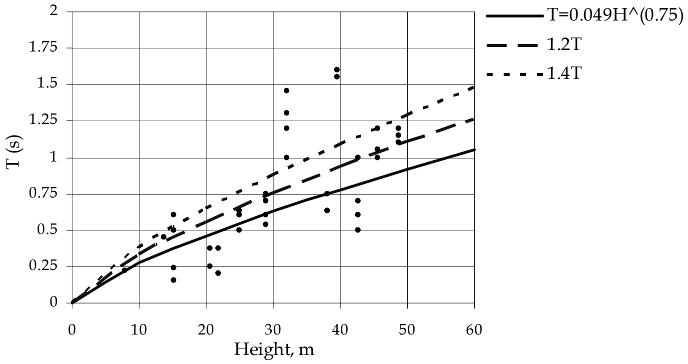


Figure 1 The measured and the code (UBC) calculated periods (Goel and Chopra 1998)

Based on the database, Goel and Chopra have suggested the formula in the form of

$$T = C(0.0019 \sim 0.0026)H/\sqrt{A_C} \tag{3.1}$$

and

$$A_e = \sum (H/H_i)^2 \frac{A_i}{1+0.83(\frac{H_i}{D_i})^2} \tag{3.2}$$

Where $A_i, H_i, D_i$ are the area, height and dimension in the direction under consideration of the *i*th shear wall.

Another research was done by Lee *et al* in 2000. They studied another database of fifty apartment buildings were recorded from March 1998 to April 1999. The studied buildings were completed and unoccupied during measurements. They have 10 to 25 stories of various sizes and plan shape. Based on the database, Lee *et al* have suggested the formula in the form of

$$T = CH^{t} / \sqrt{L_w} - 0.5 \tag{3.3}$$

Where $L_w$ is defined as the wall length per unit plan area, $H$ is the height of the building in meters, $C$ is a coefficient between 0.27 and 0,40 and $t$ is a parameter between 0.2 and 0.3. This model was derived from the fundamental period of a uniform cantilever beam, including flexural and shear deformations.

Balkaya and Kalkan have other suggestions for estimation of fundamental period of tunnel form building structures. They developed the formula in 2002 by an extensive three dimensional finite element analysis of 16 selected different plan for five different building heights (2, 5, 10, 12, 15 stories). The initial analysis results showed that the there was a clear difference in the fundamental period of those structures depending on their side ratio. So the database was categorized into two sets according to the plan dimensions ratio. If the ratio of long side to short side dimension was less than 1.5, these plans are accepted as square and those plans having the same ratio greater than 1.5 are accepted as rectangular. At the first, they suggested a formula in the form of:

$$T = Ch^{b1} \beta^{b2} \rho_{as}^{b5} \rho_{al}^{b5} \rho_{\min}^{b5} j^{b6} \tag{3.4}$$

Where the definitions of parameters are presented in Table 3.1.

Table 3.1 Parameters of Eqn. 3.4 for predicting fundamental period of tunnel forms (Balkaya, Kalkan 2002)

| Plan Type | $C$ | $b1$ | $b2$ | $b3$ | $b4$ | $b5$ | $b6$ | $\sigma_T$ | $R^2$ |
|---|---|---|---|---|---|---|---|---|---|
| Square | 0.158 | 1.400 | 0.972 | 0.812 | 1.165 | -0.719 | 0.130 | 0.025 | 0.982 |
| Rectangular | 0.001 | 1.455 | 0.170 | -0.485 | -0.195 | 0.170 | -0.094 | 0.025 | 0.982 |

$T$ : Period (s)
$h$ : Total building height (m)
$\beta$ : Ratio of long side to short side dimension
$\rho_{as}$ : Ratio of short side shear walls area to total floor plan
$\rho_{al}$ : Ratio of long side shear walls area to total floor plan
$\rho_{\min}$ : Ratio of minimum side shear walls area to total floor plan
$J$ : Plan Polar moment of inertia

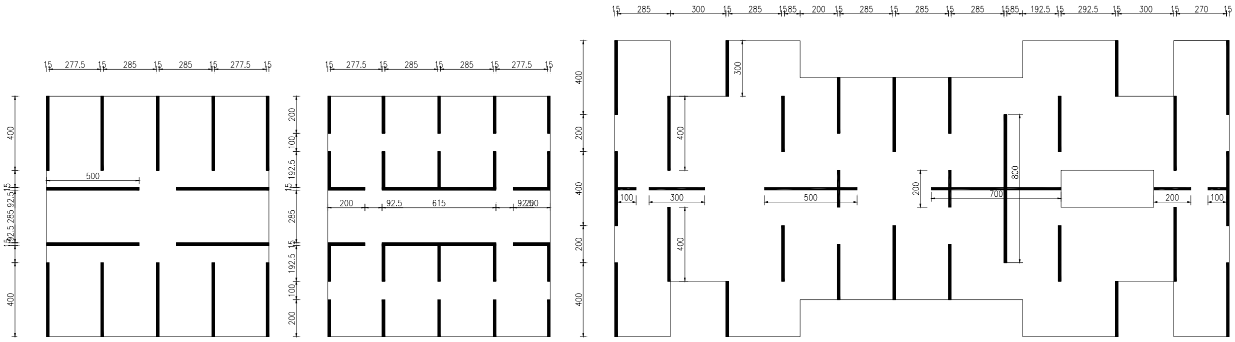
In recently research, they modified suggested formula by development in their database in 2004. New database was consisting of 20 different buildings with 7 different heights (5, 10, 12, 15, 18, 20 and 25 stories). Shear walls thickness was taken 12 cm for buildings up to 15 story, 15 cm for 18 story and 20 cm for 20 and 25 story buildings. The equation developed to predict the fundamental period of tunnel form buildings has the following form:

$$T = Ch \frac{\sqrt{R}}{R_{length}^{a} + R_{width}^{a}} \tag{3.5}$$

Where $h$ is the total height of building in m, $R$ is the ratio of long side dimension to short side dimension of building, $R_{length}^{a}$ is the ratio of shear walls area oriented along the length to a typical story area and $R_{width}^{a}$ is the ratio of shear walls area oriented along the width to typical story area. In this equation, $C$ and $a$ are the estimator parameters obtained from regression analysis, and are equal to 0.138 and -0.4, respectively.

## 4. SENSITIVITY ANALYSIS OF THE PARAMETERS

Pervious researches show that the total height of building, dimensions of plan and ratio of shear walls area to floor area were the main parameter in empirical formula for estimating the fundamental periods in tunnel form building structures. In order to study the sensitivity of parameters, various three dimensional finite element analysis of different cases performed. This developed database is consisting of 10 different plans with different heights (from 5 to 25 stories). Three samples of plans were shown in figure 3. Fundamental period of long direction, short direction and torsional mode of buildings were calculated.

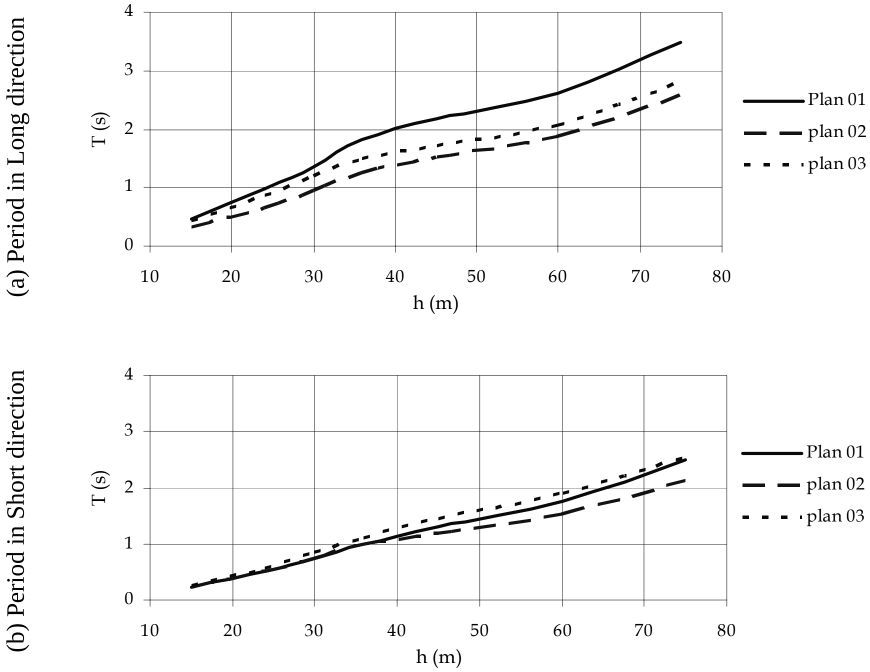


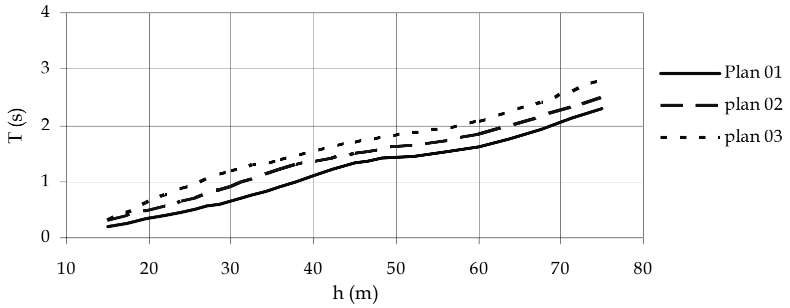
(a) (b) (c)

Figure 3 Some of typical plans of the database (dimension in cm)

### 4.1. Building height

Building height is the main parameter in the empirical formulas to estimate the fundamental period of all types of structures. To find out the influence of total building height on the fundamental periods in each direction and mode shapes, some of the results are presented in figure 4. As were shown in figure 4, the fundamental period in each direction is directly related to the total building height. Also, the order of the first three modes of structures is constant and does not depend on building height. It means that if the first mode of a structure is translation in X direction and torsional mode is the second mode shape, increasing or decreasing of the building height can not change this order.



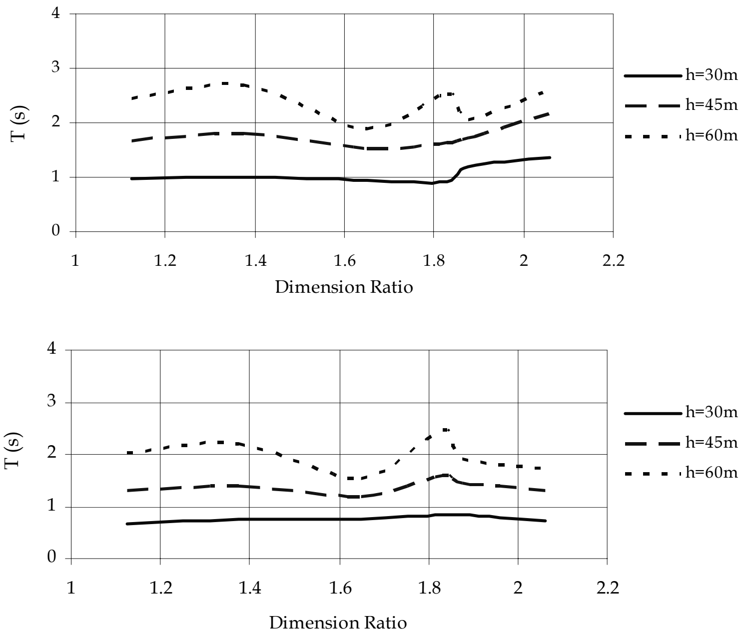


(c) Period in Torsional Mode

Figure 4 Relation of fundamental period and building height

### 4.2. Building Dimensions

Dimensions of building or dimensions ratio of building were concerned in some building code formulas or pervious researches. Some codes (KBC, ATC3-06) have suggested the formulas based on the building dimensions and Balkaya and Kalkan have suggested the different parameters based on dimensions ratio of building. To find out the influence of dimensions ratio of building on the fundamental periods in each direction and mode shapes, some of the results are presented in figure 5.



(a) Period in Long direction

(b) Period in Short direction

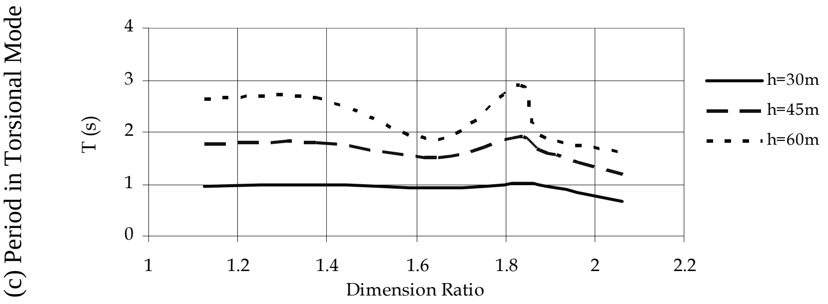


Figure 5 Relation of fundamental period and dimension ratio of building.

As were shown in figure 5, the fundamental period in each direction is not clearly related to the dimension ratio of building. Also the order of the first three modes of structures does not depend on building height. It means that by the same dimensions of building, the first mode shape, may be different in longitude direction, in short direction or torsional. For example plan (a) and plan (b) in figure 3 have the same dimensions. But the first three mode shapes of the plan (a) is torsional, in longitude direction and short direction respectively, and the first three mode shapes of the plan (b) is torsional, in short direction and longitude direction.

### *4.3. Shear walls area*

Ratio of shear walls area to total floor area and/or dimensions of shear walls were considered in some building code formulas or pervious researches. Rx, Ry were defined as the ratio of shear walls area to total floor area in long and short direction respectively. To find out the influence of shear walls area on the fundamental periods in each direction and mode shapes, some of the results are presented in figure 6.

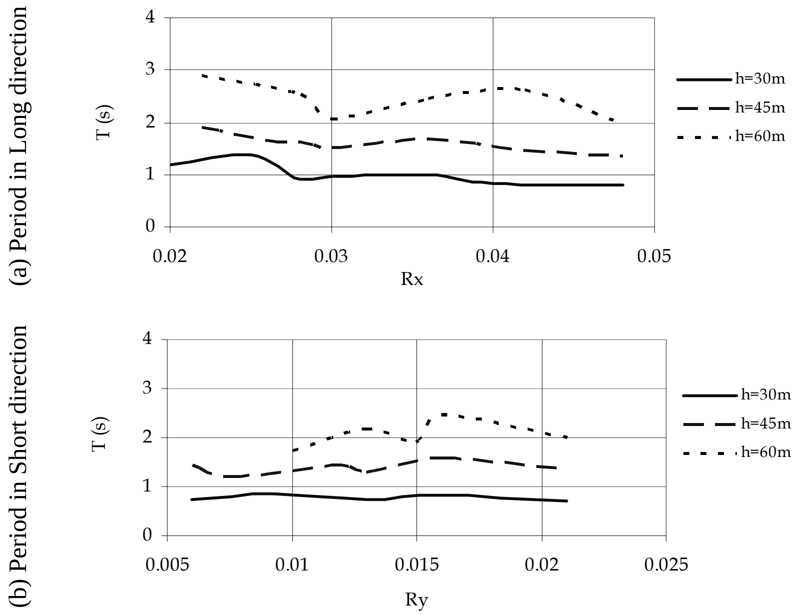


Figure 6 Relation of fundamental period and ratio of shear walls area to floor area.

As were shown in figure 6, the fundamental period in each direction is not clearly related to the ratio shear walls area to floor area of building. Also the orders of the first three modes of structures do not depend on this parameter. But as are shown in table 4.1 the summation of third power of shear walls lengths in each direction can be used to estimate the priority of longitude or short direction mode shapes.

Table 4.1 Shear walls lengths and priority of longitude or short direction mode shapes

| Plan No. | $\sum h_i^3$ in Longitude Direction( $m^3$ ) | $\sum h_i^3$ in Short Direction( $m^3$ ) | Period of First Longitude Direction Mode Shape (s) | Period of First Short Direction Mode Shape (s) |
|---|---|---|---|---|
| 1 | 2160 | 500 | 0.20 | 0.15 |
| 2 | 1250 | 500 | 0.21 | 0.17 |
| 3 | 640 | 500 | 0.32 | 0.28 |
| 4 | 270 | 500 | 0.32 | 0.43 |
| 5 | 1250 | 108 | 0.23 | 0.15 |
| 6 | 1250 | 432 | 0.20 | 0.18 |
| 7 | 1250 | 464 | 0.19 | 0.17 |
| 8 | 160 | 464 | 0.21 | 0.36 |

## 5. CONCLUSION

This study showed that the building height can be considered as the main parameter in estimating formulas for fundamental period of tunnel form buildings. The orders of the first three modes of structures remain unchanged for building with different heights. According to the developed data base, there is no close correlation between plan dimensions and/or shear walls area, and period and type of mode shapes (rotational and translational). But the summation of third power of shear walls lengths in each direction can be used to determine the priority of translational mode shape in each direction. The formulas based on building height (UBC, IBC) are simpler than the suggested formulas based on the other parameters. Also some of the suggested formulas are complicated to use. An attempt should be made to develop rational formulas to predicate period of this type of building and other parameters that affect on the seismic behaviour factor like R factor.

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