Bulletin of the Seismological Society of America, Vol. 99, No. 2B, pp. 1483–1485, May 2009, doi: 10.1785/0120080252

Short Note

Rotational Seismic Load Definition in Eurocode 8, Part 6, for Slender Tower-Shaped Structures

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Abstract This note describes the rotational seismic load definition as included in Part 6 of Eurocode 8 (EC8.6, 2005). The Eurocode 8, Part 6 (EC8.6, 2005), definition of the rotational ground-motion component depends upon the structural subsoil compliance, which is controlled by the shear-wave velocity in the top 30 m of ground. A comparison of the effects of the rocking ground motion and the horizontal ground motion on the response of a 160 m reinforced concrete chimney shows that for the Eurocode 8, Part 6 (EC8.6, 2005), definition of the rotational seismic ground motion, the rocking excitations contribute significantly to the overall response of the structure. The engineering code formulas for the rocking component of ground motion, however, should be calibrated and reconciled with the results of the latest empirical research.

Introduction

For some structures such as slender towers, the rocking excitations can contribute substantial additional seismic response. In spite of the lack of recorded data on the rotational strong ground motion, the problem has been studied, and it has been shown that the classic response spectrum method can be formulated to also include the rotational excitations (Castellani and Boffi, 1986, 1989).

On 22 February 2005, Eurocode 8, Part 1 (EC8.1, 2005), was formally approved for use in 28 European countries. Part 6 of Eurocode 8 (EC8.6, 2005), which was approved on 25 September 2005 proposed to include (in addition to traditional horizontal seismic actions) three rotational excitations. This is probably one of the first codified rotational seismic loads ever proposed. The purpose of this note is to briefly describe the load definitions of Eurocode 8, Part 6 (EC8.6, 2005), that apply to rotational excitation.

Formal Seismic Load Definition for Slender Towers

Eurocode 8, Part 6, deals with the design rules for tower-shaped structures, including bell towers, intake towers, radio and TV towers, masts, chimneys (including free-standing industrial chimneys), and lighthouses, with additional special provisions for reinforced concrete and steel chimneys. Point 3.6 of Eurocode 8, Part 6 (EC8.6, 2005), proposes to take into account one vertical and two horizontal components of seismic ground motion acting simultaneously. It also proposes to take into account the corresponding simultaneous action of rotational components of seismic load for the tall structures designed in regions of high seismicity. The formal decision to eventually include rotational components of seismic ground motion is left to the national authorities of the countries implementing the codes. Eurocode 8, Part 6, recommends including the rotational seismic excitations for structures higher than 80 m and for cases in which seismic design acceleration defined by product $a_g S$ is not less than $0.25g$; a_g is design acceleration for type A ground and S represents the soil factor (g is the acceleration of gravity). Eurocode 8, Part 6 (EC8.6, 2005), recommends either the time history or the response spectrum method for analysis. In the first case one should apply simultaneous action of six records of seismic ground motion (three translations and three rotations). In the second case for the translational loads, the response spectrum defined by Eurocode 8, Part 1 (EC8.1, 2005), should be applied. To account for the three rotations Eurocode 8, Part 6 (EC8.6, 2005), recommends the response spectrum method, in which the rotational response spectra about two horizontal axes (x and y) and the vertical z are defined by

$$\mathrm{R}_{\mathrm{x}}^{\theta}(T) = \frac{1.7\pi S_e(T)}{V_S T}, \quad (1)$$

$$\mathrm{R}_{\mathrm{y}}^{\theta}(T) = \frac{1.7\pi S_e(T)}{V_S T}, \quad (2)$$

$$\mathrm{R}_{\mathrm{z}}^{\theta}(T) = \frac{2.0\pi S_e(T)}{V_S T}, \quad (3)$$

where $S_e(T)$ (m/sec^2) is the elastic horizontal response spectrum defined for the site, T is the natural period (sec), and V_S is the average S-wave velocity (m/sec) in the top 30 m of the ground profile (Eurocode 8, Part 6 [EC8.6, 2005] recommends applying the value corresponding to low-amplitude soil vibrations, i.e., to shear deformations on the order of 10^{-6}). When the top 30 m shear-wave velocity is not known from experiments, the values corresponding to ground types A, B, C, and D as proposed by Eurocode 8, Part 1 (EC8.1, 2005), may be used ($V_S = 800$, 580, 270, and 150 m/sec, respectively).

The extension of the response spectrum method to include rotational excitations is formulated in terms of the discrete mathematical representation of the structural model. For the simultaneous action of horizontal translation excitations along axis x and rocking excitations about horizontal, orthogonal axis y (vibrations in plane x-z), the equation of motion of the discrete system is given by

$$[\mathrm{M}]\{\ddot{\mathrm{u}}\} + [C]\{\dot{\mathrm{u}}\} + [K]\{\mathrm{u}\} = -(\{\mathrm{m}\}\ddot{x} + \{mh\}\ddot{\theta}), \tag{4}$$

in which

$\{\ddot{\mathrm{u}}\}$ is the vector representing the accelerations of the degrees of freedom of the structure relative to the base;

$\{\dot{\mathrm{u}}\}$ is the vector representing the velocities of the degrees of freedom of the structure;

$\{\mathrm{u}\}$ is the vector representing the displacements of the degrees of freedom of the structure;

$\{\mathrm{m}\}$ is the vector comprising the translational masses in the horizontal direction of the translational excitation; it coincides with the main diagonal of the mass matrix [M], if the vector $\{\mathrm{u}\}$ includes only the translational displacements in the horizontal direction of the excitation;

$\ddot{x}(t)$ is the translational ground acceleration, represented by S_e;

$\ddot{\theta}(t)$ is the rotational acceleration of the base, represented by R^{Θ};

and the participation factor in the modal analysis of mode k is defined as

$$a_{ku} = \frac{\{\Phi^{\mathrm{Tr}}\}\{\mathrm{m}\}}{\{\Phi^{\mathrm{Tr}}\}[\mathrm{M}]\{\Phi\}}. \tag{5}$$

For the term $\{mh\}\ddot{\theta}$ the participation factor is

$$a_{k\Theta} = \frac{\{(\Phi h)^{\mathrm{Tr}}\}\{\mathrm{m}\}}{\{\Phi^{\mathrm{Tr}}\}[\mathrm{M}]\{\Phi\}}, \tag{6}$$

where

$\{\Phi\}$ is the kth modal vector;

$\{\Phi h\}$ is the vector of the products of the modal amplitude Φ_i at the ith degree of freedom and its elevation h_i;

and Tr stands for transposition.

The effects of the rotational ground excitations may be combined with those of the translational excitation via the square root of the sum of the squares rule.

Eurocode 8, Part 6 (EC8.6, 2005), emphasizes the need to properly account for soil structure interaction effects as well as for the second-order effects, which for slender towers on compliant soil under rotational (rocking) excitations can play an important role. Eurocode 8, Part 6 (EC8.6, 2005), recommends neglecting the second-order effects if the overturning moment due to inclusion of second-order effects does not exceed the basic overturning moment by 10%. It should also be noted that the definition of torsional seismic response spectrum in Eurocode 8, Part 6 (EC8.6, 2005, equation 3, rotation around the vertical axis) is of less importance for slender towers, but it has been included in Eurocode 8, Part 6 (EC8.6, 2005), for the completeness of the formal definition of the rotational components of seismic ground motion.

Numerical Example

In the article by Zembaty and Boffi (1994) the seismic response of a 160 m reinforced concrete chimney, based on the horizontal response spectrum defined by Eurocode 8, Part 1, and the rotational (rocking) response spectrum defined by Eurocode 8, Part 6 (EC8.6, 2005, equation 1), were calculated for the damping ratio $\xi = 0.05$. The analyzed chimney and its basic dimensions are shown in Figure 1, and the Young modulus of the concrete used in the dynamic calculations is 1.776×10^{10} N/m^2. Neither the shaft of the

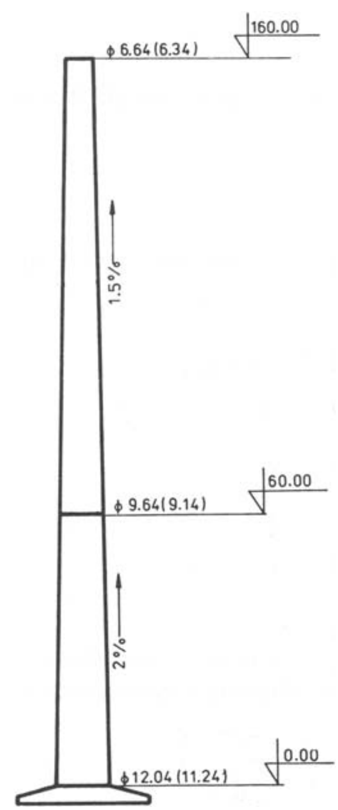

Figure 1. Sketch showing the 160 m reinforced concrete chimney analyzed in the numerical example. All dimensions are shown in meters (the internal diameters are shown in parentheses). The diameter of the foundation equals 20 m.

chimney nor its foundation were designed to withstand seismic effects. In the computations, in which equations (1) and (2) and (4)–(6) have been applied, the soil compliance effects were included for the shear-wave velocity of the soil $V_S = 200$ m/sec, density of the soil $\rho = 1800$ kg/m^3, and Poisson ratio $\nu = 0.25$. Only the rocking and horizontal flexibility of the subsoil have been taken into account (vibrations in the vertical plane).

In Figure 2 the plot of bending moments in the chimney shaft due to joint action of horizontal and rocking excitations is shown and denoted as total. The contribution of only rocking effects to the bending moments is also plotted and denoted as rotation. The response spectrum calculations were carried out for the design acceleration $a_g = 0.1g$.

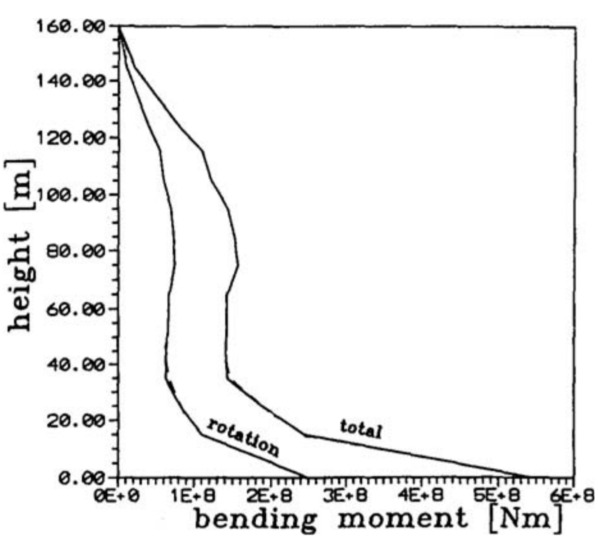

Figure 2. Plot of bending moment along the shaft of 160 m high reinforced concrete chimney and contribution of the rotational (rocking) effects according to Eurocode 8, Part 6.

Discussion and Conclusion

The definition of the rotational seismic load as proposed by Eurocode 8, Part 6 (EC8.6, 2005), for slender, tower-shaped structures has been presented. Example calculations of the seismic response of a tall industrial chimney show a substantial contribution of the rocking effects in the overall seismic response. The rotational seismic load around the horizontal and vertical axes is defined in Eurocode 8, Part 6 (EC8.6, 2005) as the multipliers of horizontal response spectra dependent upon the shear-wave velocity of the top 30 m of the ground. Such a definition means that the rotational seismic load as defined for slender towers is quite arbitrary and depends only upon the soil compliance and not on the seismological parameters of the expected earthquake and its detailed wave propagation characteristics.

In addition, as has been shown in the articles by Lee and Trifunac (1985, 1987, 2009), the ratio of rocking to horizontal spectra depends not only upon the shear-wave velocity in the top soil layer but also on the waves with higher phase velocities associated with the deeper ground layers. In figure 1 of the article by Lee and Trifunac (2009) an example of dispersion curves is shown for a ground profile at El Centro, California. It can be seen from this figure that the higher the period of the waves the more the wave velocities contribute to rocking ground motion. For the period of 1–10 sec, respective phase velocities reach maxima at about 3–4 km/sec, which means that the rocking excitations will depend also upon the high-velocity wave components. The actual Eurocode 8, Part 6 (EC8.6, 2005), proposal given in equations (1)–(3) suggests just the opposite relation and may lead to erroneous results, which means that further development and empirical scaling of these formulas should follow. The problem is not easy to resolve because typical code formulas have to cover various load and structural scenarios and usually represent a conservative compromise between the actual state of the art in the research and engineering simplicity.

Data and Resources

All data used in this article came from published sources listed in the references.

Acknowledgments

The author wishes to thank the reviewers for important, incisive suggestions on improving the manuscript.

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Manuscript received 27 August 2008