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IMPACT OF CHANGES IN THE NBCC 2005 SEISMIC PROVISIONS ON THE DESIGN OF RESTRAINTS FOR OFCS AND ESSENTIAL RIGID COMPONENTS

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ABSTRACT

The seismic design provisions in the NBCC 2005 are based on an earthquake hazard level higher than that used for the NBCC 1995 provisions, which involves an increase in the seismic design accelerations. This paper presents the main results of a study of the impact of the increase in accelerations on the seismic design of rigid non-structural components such as transformer tanks, reservoirs, emergency power generators, etc., and their foundations or restraints. The provisions of the 1995 and 2005 editions of NBCC for equipment located above grade level and for the calculation of base shear forces of low-rise buildings or control units for essential equipment having different lateral load resisting systems of limited ductility are presented as well. In order to get a global conclusion about the behaviour of rigid components, the analysis has been made in relation with different earthquake records.

Introduction

The seismic provisions in the 2005 edition of the National Building Code of Canada NBCC (NRC/IRC 2005) are based on an earthquake hazard level corresponding to a probability of exceedance of 2% in 50 years, corresponding to a return period of 2500 years, while the provisions of the 1995 edition (NRC/IRC 1995) were based on a hazard level with probability of exceedance of 10% in 50 years, corresponding to a return period of 475 years. This significant increase in the design earthquake hazard level involves an increase in the seismic design accelerations. It is recognized that seismic accelerations are important factors for the design of rigid essential non-structural components such as High Voltage Direct Current components, transformer tanks, reservoirs, emergency power generators, etc., and their foundations or restraints, and for the design of low-rise rigid buildings or control units for essential equipment. We intuitively tend to conclude that higher accelerations directly imply higher forces on acceleration-sensitive components, which may translate in rehabilitation of existing equipment or higher direct costs for construction of new equipment. This paper presents the main results of a study of the impact of the increase in accelerations on the seismic design of rigid structural and non-structural components. Firstly, the input seismic forces are computed according to the approach currently used in industry for high natural frequency components taking into account their location in different seismic regions of Québec, their interchangeability and the uniformity design aspect. These forces are then compared to the predictions of

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the equation proposed in the NBCC 2005 and based on the spectral acceleration at fundamental period of 0.2 s and 5% damping, Sa(0.2), and those obtained from the NBCC 1995 provisions and based on the seismic zonal velocity, v. Secondly, a comparison is made between the 1995 and 2005 NBCC provisions for functional components located above grade level and for base shear forces of rigid buildings ($T \leq 0.2$ s) having different lateral load resisting systems of limited ductility. In order to get a global conclusion about the behaviour of rigid components, the whole analysis has been made in relation with different earthquake records.

Seismic shear force coefficient at the base of rigid or rigidly attached mechanical equipment located at grade level

The seismic shear force at the attachment point of a component is proportional to the weight of the component, W, and is equal to the product of a seismic force coefficient and W. This coefficient is equivalent to the product of either the input peak ground acceleration or the spectral acceleration and other force modification factors that can vary from one building code to another. The approaches commonly used in industry and proposed in NBCC 1995 and 2005 for the evaluation of this coefficient are presented and compared (in Table 1) for equipment located at grade level on firm soil in different regions of Québec and with different earthquake hazard levels.

Common industry method for acceleration-sensitive components

The seismic design base shear force, V, for equipment located in the province of Québec is currently evaluated as the product of the component weight (W) and a coefficient equal to 0.23 g (Equation 1). This coefficient is equivalent to the peak ground acceleration defined in NBCC 1995 for zone 4, with the exception of the Charlevoix region where the site-specific peak ground acceleration of 0.7 g is used. The coefficient of 0.23 g was adopted by industry to ensure interchangeability of equipment and design uniformity. It is also usual practice to increase the seismic base shear force of rigid industrial components by 50% to account for the variability of soil effects on the seismic force amplification at various regional sites.

$$\mathbf{V = PGA \cdot W} \tag{1}$$

NBCC 1995 and 2005 provisions for equipment and non-structural components

It is noteworthy that the 1995 edition of NBCC (NRC/IRC 1995 a, b) is still currently in use as several municipalities have not yet approved the recent 2005 edition (NRC/IRC 2005). The seismic design force provisions for mechanical/electrical equipment are given in Article 4.1.9.1 (15 to 22) of NBCC 1995 and in Article 4.1.8.17 of NBCC 2005. According to these provisions, the mechanical/electrical components of a building and their anchorage should be designed for a minimum lateral seismic force, V, given in Equations 2 and 3.

$$V_{1995} = v\ I\ C_p\ A_r\ A_x\ W_p = v \cdot I \cdot W_p = \text{coefficient} \cdot I \cdot W_p \tag{2}$$

$$V_{2005} = 0.3\ F_a\ S_a(0.2)\ I_E\ C_p\ A_r\ A_x / R_p\ W_p = 0.24\ S_a(0.2) \cdot I_E \cdot W_p = \text{coefficient} \cdot I_E \cdot W_p \tag{3}$$

Where v is the zonal velocity ratio, I (or I_E) is the seismic importance factor of the structure, C_p is the seismic coefficient for mechanical/electrical equipment, A_r is the response amplification factor to account for the type of attachment of the component, A_x is the height factor to account for variation of response of the component with elevation, and W_p is the weight of the component. For rigid and rigidly connected components, $C_p = 1$ and $A_r = 1$. The height factor A_x is equal to $1.0 + (h_x/h_n)$ and $1.0 + 2(h_x/h_n)$ in NBCC 1995 and 2005 respectively, where h_x is the height from the base of the structure to the point where the equipment is attached and h_n is the total height of the structure; for equipment at grade level, $A_x = 1$. R_p is the component force modification factor introduced in NBCC 2005 and is taken as 1.25 for rigid or rigidly attached equipment.

Table 1. Seismic base shear force coefficient for rigid equipment at grade level and assumed to be located in different seismic regions in Québec

Building Location	**Industry V/W**	**NBCC 1995** $V_{1995}/I \cdot W_p = v$	**NBCC 2005** $V_{2005}/I_E \cdot W_p = 0.24\ S_a(0.2)$
Chicoutimi	0.23	0.15	0.15
Lévis	0.23	0.15	0.14
Montréal	0.23	0.10	0.16
Québec City	0.23	0.15	0.14
Tadoussac	-	0.30	0.20
La Malbaie*	0.70	0.40	0.55

* 0.7 g is the peak ground acceleration at La Malbaie

The results presented in Table 1 indicate that the method used in industry with an equivalent acceleration of 0.23g for the evaluation of the seismic shear force coefficient for mechanical/electrical equipment is compatible with the NBCC 2005 provisions; in addition it is slightly conservative in the cases studied here. Also, except for Montréal and La Malbaie, the NBCC 2005 provisions yield lower forces than those of the NBCC 1995 provisions.

Seismic shear force coefficient at the base of rigid or rigidly attached mechanical equipment located above grade level: NBCC 1995 versus NBCC 2005

The amplification of peak ground accelerations along the height of a building is accounted for in NBCC through the height amplification factor A_x that is equal to $1 + h_x/h_n$ in NBCC 1995 (NRC/IRC 1995 a, b) with a maximum amplification of 2 at the rooftop level, and $1+ 2\ h_x/h_n$ in NBCC 2005 (NRC/IRC 2005), with a maximum amplification of 3 at rooftop. The seismic force coefficient for rigid or rigidly attached equipment located at the mid height and at the rooftop of a 2-story building assumed to be located in various seismic regions of Québec was evaluated according to the NBCC 1995 and 2005 provisions. The results are presented in Tables 2 and 3.

Table 2. Seismic shear force coefficient for rigid equipment located at the mid height of a 2-story building assumed to be located in different seismic regions of Québec

Building Location	**NBCC 1995** $VA_x/I \cdot W_p$	**NBCC 2005** $VA_x/I_E \cdot W_p$	V_{2005}/V_{1995}
Chicoutimi	0.23	0.30	1.32
Lévis	0.23	0.28	1.24
Montréal	0.15	0.33	2.21
Québec City	0.23	0.28	1.26
Tadoussac	0.45	0.40	0.90
La Malbaie	0.60	1.10	1.84

Table 3. Seismic shear force coefficient for rigid equipment at the rooftop of a 2-story building assumed to be located in different seismic regions of Québec

Building Location	**NBCC 1995** **$VA_x/I\cdot W_p$**	**NBCC 2005** **$VA_x/I_E\cdot W_p$**	**V_{2005}/V_{1995}**
Chicoutimi	0.30	0.45	1.49
Lévis	0.30	0.42	1.39
Montréal	0.20	0.50	2.48
Québec City	0.30	0.42	1.42
Tadoussac	0.60	0.60	1.01
La Malbaie	0.80	1.66	2.07

Results presented in Tables 2 and 3 indicate that equipment located above grade level and designed according to NBCC 2005 is subjected to higher seismic forces than those according to NBCC 1995. Therefore, in Québec, the NBCC 2005 requirements for the seismic design of rigid components and their restraints located above grade level are more stringent than those of NBCC 1995, especially at the rooftop level. The only exception is for Tadoussac where the two sets of requirements are practically equivalent.

Seismic force coefficient for rigid equipment: PGA vs 0.24 $S_a(0.2)$

As previously discussed, the seismic force coefficient to compute the shear force for rigid equipment can be expressed in terms of either the peak ground acceleration (Eq.1 used by industry) or the spectral acceleration at fundamental period of 0.2s and 5% damping, $S_a(0.2)$ (Eq.3 used in NBCC 2005). In a comparative study of the two approaches, we have used 10 synthetic accelerograms compatible with the target uniform spectra for Montréal and corresponding to a probability of exceedance of 2% in 50 years. Two accelerograms (Nos. 1 and 2 in Table 4) were used for each M-R (earthquake magnitude and epicentral distance) scenario to account for the randomness of the records (Atkinson and Beresnev 1998) and the PGA and 0.24 $S_a(0.2)$ were obtained for each accelerogram. In addition, these same indicators were obtained for seven recorded accelerograms, including five from the 1988 Saguenay earthquake with epicentral distances varying between 40 and 150 km, one from the 2005 Grand-Portage earthquake (Rivière-du-Loup), and one from the 1985 Nahanni earthquake (Table 5).

Table 4. Seismic force coefficients for equipment based on $S_a(0.2)$ and PGA using synthetic accelerograms for Montréal

Magnitude M	Epicentral Distance (km)	Accelerogram 1		Accelerogram 2	
		PGA (g)	0.24 $S_a(0.2)$ (g)	PGA (g)	0.24 $S_a(0.2)$ (g)
6.0	30	0.43	0.14	0.52	0.20
6.0	50	0.24	0.15	0.19	0.11
7.0	50	0.51	0.16	0.63	0.16
7.0	70	0.30	0.14	0.29	0.16
7.0	100	0.24	0.13	0.26	0.12

Table 5. Seismic force coefficients for equipment based on $S_a(0.2)$ and PGA using recorded accelerograms

Earthquake	Station	Epicentral Distance (km)	PGA (g)	0.24 $S_a(0.2)$ (g)
Saguenay (1988)	Chicoutimi	43	0.13	0.036
	St-André	64	0.16	0.017
	La Malbaie	92	0.027	0.063
	Tadoussac	109	0.051	0.009
	Québec City	150	0.12	0.035
Grand Portage (2005)	Kamouraska*	32.3	0.066	0.018
Nahanni (1985)	Site 1, Iverson	7.5	1.10	0.62

- Network of accelerographs of Hydro-Québec (TransÉnergie)

The results shown in Tables 4 and 5 indicate that the peak ground acceleration is not a good indicator of the seismic base shear demand. While any two ground accelerograms can have different peak values, their spectral accelerations can be very close - it is the mean value of the spectral accelerations that defines the target uniform hazard spectra for a site. Also, the seismic force coefficient expressed in terms of PGA is much higher than the one evaluated in terms of $S_a(0.2)$. Therefore, the industry approach based on the equivalent peak ground acceleration yields seismic force coefficients higher than those calculated using the NBCC 2005 provisions that are based on the spectral acceleration at 0.2s. However, it should be emphasized that the NBCC provisions represent minimum requirements. High frequency rigid components are known to be very sensitive to peak ground accelerations and the equivalent PGA approach helps to take into account the regional hazard.

Evaluation of seismic base shear forces for rigid low-rise buildings using NBCC 1995 and 2005

The minimum seismic base shear forces for rigid low-rise buildings (one or two stories) with lateral load resisting systems of limited ductility are calculated according to Equations 4 and 5 as proposed in the 1995 and 2005 editions of NBCC.

$$\mathbf{V_{1995} = [v\ S\ I\ F\ W]\ U/R} \tag{4}$$
$$\mathbf{V_{2005} = [2/3\ S(0.2)\ I_E/(R_d R_o)]\ W} \tag{5}$$

Where v is the zonal velocity ratio, S is the seismic response factor, F is the foundation factor and is equal to 1.5, U is the calibration factor equal to 0.6, I (or I_E) is the earthquake importance factor of the structure and is equal to 1.5 for post-disaster constructions, R and R_d reflect the energy dissipation capacity of the structure, R_o is the overstrength factor, S(0.2) is the spectral acceleration at a period of 0.2 s, W is the dead load of the structure plus 25% of the design snow load.

The base shear forces for low-rise buildings having different construction types (reinforced concrete, steel, masonry) and in different locations were computed according to Equations 4 and 5 and the results are shown in Tables 6 to 8.

Table 6. Base shear force coefficients for low-rise reinforced concrete buildings

Building Location	**Reinforced Concrete Buildings ($R = 2$, $R_d = 2$, $R_0 = 1.4$)**		
	V_{1995}/W	**V_{2005}/W**	**V_{2005}/V_{1995}**
Chicoutimi	0.43	0.22	0.52
Lévis	0.43	0.21	0.49
Montréal	0.28	0.25	0.87
Québec City	0.43	0.21	0.50
Tadoussac	0.85	0.30	0.35
La Malbaie	0.81	0.82	1.01

Table 7. Base shear force coefficients for low-rise steel buildings

Building Location	**Steel Buildings ($R = 2$, $R_d = 2$, $R_0 = 1.5$)**		
	V_{1995}/W	**V_{2005}/W**	**V_{2005}/V_{1995}**
Chicoutimi	0.43	0.21	0.49
Lévis	0.43	0.19	0.45
Montréal	0.28	0.23	0.81
Québec City	0.43	0.20	0.46
Tadoussac	0.85	0.28	0.33
La Malbaie	0.81	0.77	0.95

Table 8. Base shear force coefficients for low-rise masonry buildings

Building Location	**Masonry Buildings (R=2, R_d = 1.5, R_0 = 1.5)**		
	V_{1995}/W	V_{2005}/W	V_{2005}/V_{1995}
Chicoutimi	0.43	0.28	0.65
Lévis	0.43	0.26	0.61
Montréal	0.28	0.31	1.08
Québec City	0.43	0.26	0.62
Tadoussac	0.85	0.37	0.44
La Malbaie	0.81	1.02	1.26

The results shown in Tables 6 to 8 indicate that the minimum design base shear force evaluated according to NBCC 2005 and based on S(0.2) is generally smaller than the minimum requirement of NBCC 1995, except for masonry buildings located in Montréal and La Malbaie .

Conclusions

The first part of this study dealt with the calculation of the seismic base shear for rigid or rigidly attached essential functional components. The three main conclusions are:

- The NBCC 2005 method based on the spectral acceleration at 0.2s, S_a(02.), is more adequate than the peak ground acceleration method for the computation of seismic base shear force coefficient since the former accounts for the earthquake intensity, the epicentral distance and the site properties.
- The method used in industry (equivalent to peak ground acceleration used in NBCC 1995) yields slightly more conservative results than those of NBCC 2005. Consequently, reinforcement of essential rigid components based on these assumptions is not mandatory.
- The NBCC 2005 provisions are more stringent than those of NBCC 1995 for the calculation of seismic base shear force of equipment located above the ground level, especially at the rooftop.

The second part of the study dealt with the evaluation of the minimum seismic base shear for buildings with lateral load resisting systems of limited ductility (reinforced concrete, steel, and masonry) and assumed to be located in various regions of Québec. It is concluded that the provisions of NBCC 2005 are less stringent than those of NBCC 1995, except for masonry buildings in La Malbaie and Montréal.

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