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RAPID SEISMIC EVALUATION OF EXISTING DND BUILDINGS

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ABSTRACT

Several thousand of the Department of National Defense (DND) buildings are located in active seismic regions. Many of them are decades old and do not satisfy the current code requirements. Therefore, some of these buildings may be vulnerable to earthquake effects. In 1999, DND introduced a strategy for seismic assessment of existing buildings. Scores are assigned to each building to represent its seismic risk under the design seismic loads in the 1990 NBCC. However, the NBCC was revised in 1995 and again in 2005, and the seismic design loads have been changed significantly since then. In this study, revision of the DND seismic strategy and screening methodology is proposed. In addition, a computer software is developed to implement required calculations.

Introduction

Earthquakes cause devastating disasters to our built environment as evident in the recent earthquakes in the U.S., Japan, Turkey, Taiwan and Pakistan. Post-earthquake investigations have shown that older buildings, which were designed in accordance with codes that are now known to provide inadequate seismic protection, suffered the most damage. Newer buildings with improved design requirements and methods sustained relatively minor damage. Collapse of older and potentially vulnerable buildings have cost thousands of casualties and millions of dollars in economic losses.

A large number of the Department of National Defense (DND) buildings are located in active seismic regions. Consequently, some existing buildings built to earlier codes do not satisfy the current code requirements and may be vulnerable to earthquake effects. The provisions of the new code are primarily intended for the design of new buildings and it is up to the owner to decide if retrofitting is required.

Custodian government departments, such as the DND, have large inventories of older buildings. Many of these older buildings could be vulnerable to strong or even moderate earthquakes. In 1999, DND introduced a strategy for seismic assessment of existing buildings (Kulkarni 1999). This strategy requires that preliminary risk assessment be undertaken on existing buildings using the “Manual for Screening of Buildings for Seismic Investigation” (NRCC 1993) to determine the relative risk levels of buildings. This screening document was published by the National Research Council in December of 1993 and based on the 1990 National Building Code of Canada (NBCC 1990). The National Building Code of Canada was revised in 1995 (NBCC 1995) and again in 2005 (NBCC 2005). While in general terms the difference

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between the 1990 NBCC and 1995 NBCC is minimum, the 2005 version contains very significant changes in seismic requirements.

In this study, the major changes in seismic provisions of the 2005 NBCC from the previous version are reviewed. A plan to update DND seismic strategy, including the revision of the screening methodology, is proposed. Thus, the revised scores assigned to each building will represent its seismic risk under design loads specified in the currently effective NBCC. In addition, a computer software is developed to implement required calculations. Details are described in the following sections, and several examples are presented.

1999 DND Strategy

Several thousand DND buildings are located in seismic active regions. These buildings are of varied age and constructions, and at different levels of risk. A DND strategy was introduced in 1999 for seismic assessment of the buildings in moderate to high seismic zones and designed according to 1990 NBCC or earlier editions, as well as the buildings in low seismic zones and designed in accordance with 1970 NBCC or earlier editions (Kulkarni 1999). A rapid screening of these buildings was planned using the "Manual for Screening of Buildings for Seismic Investigation (NRCC 1993)" to determine the relative risk levels of the buildings. Then, the high risk buildings were subjected to detailed evaluation, and the measures to eliminate or mitigate seismic deficiencies of these buildings were explored in order to ensure their structural and nonstructural seismic safety.

The screening procedure is based on a rapid inspection of each building or its drawings. Information for each building is collected on a standard Seismic Screening Form (see p H-26 and H-27 in Kulkarni 1999 or p 88 and 89 in NRCC 1993), which is used to obtain a score for a Seismic Priority Index *SPI* for each building as

$$SPI = SI + NSI$$

where *SI* and *NSI* are respectively referred to as the Structural Index and Non-Structural Index, which respectively represent the deviation of the structural and non-structural seismic behaviours required by NBCC at time of design from those of 1990 NBCC. *SI* and *NSI* are determined from related key factors as below (see p H-5 to H-6 of Kulkarni 1999 or p 72 to 74 of NRCC 1993):

$$SI = A \cdot B \cdot C \cdot D \cdot E$$
$$NSI = B \cdot E \cdot F$$

A is the seismicity factor, originally based on the review of seismic data included in the 1990 and previous editions of NBCC. The range is from 1.0 (for effective seismic zone 2) to 4.0 (for zone 6).

B is the soil condition factor, based on the foundation factor in the 1990 and previous editions of NBCC. The value of *B* ranges from 1.0 for rock or stiff soil to 2.0 for very soft or liquefiable soil.

C is the factor for type of structure, and related to the ductility requirements in the 1990 and previous editions of NBCC. A low value for *C* (1.0) means that the structure has inherently good seismic properties or is specifically designed to resist earthquakes, whereas a high value (up to 3.5 for un-reinforced masonry buildings) indicates a lack of toughness of the system against ground shakings.

D is the factor for irregularities of structure, such as vertical or horizontal irregularities, weak storey, high sensitivity to torsion, modifications and deteriorations etc. If the NBCC at the time of design included requirements to an irregularity, then the related factor takes lower value (1.0). Otherwise, *D* may take higher value up to 4.0 if several irregularities exist simultaneously.

E is the building importance factor, ranging from 0.7 for buildings with low occupancy to 3.0 for buildings with special operational requirements and designed before 1970.

F is the factor taking into consideration the falling hazards to life and hazards to vital operations, which are respectively considered by factors F_1 and F_2, and $F = \max(F_1, F_2)$. If no specific hazards are identified, the values of F_1 and F_2 are both equal to 1.0. The values of F_1 and F_2 are respectively increased up to 3.0 and 6.0 for flexible (frame types, building with weak storey or torsion) or deteriorated buildings because of increased risk of non-structural damage for such buildings in a possible strong earthquake.

The score of Seismic Priority Index (*SPI*) is related to the seismic risk for the particular building subjected to 1990 design earthquake loads. All the buildings should be ranked in order of priority according to the score. The higher the score, the higher the priority. As a starting basis of the ranking, the priority can be considered as low if *SPI* is less than 10, medium if *SPI* is between 10 and 20, and high if *SPI* is 20 or larger. Buildings with *SPI* score over 30 can be considered as potentially hazardous (see p H-6 in Kulkarni 1999, also p 75 in NRCC 1993).

At the time of the DND strategy coming into effect, the 1995 NBCC was published already. However, the revision of the 1995 NBCC from the 1990 edition is minimum, and the corresponding changes in seismic design loads can be reasonably neglected in the screening process. Therefore, the DND strategy is still based on comparison of the 1990 NBCC with the previous editions of NBCC.

Major Changes in Seismic Provisions of 2005 NBCC

Based on new experiences and updated knowledge on earthquakes around the world during the recent two decades, significantly refined data and methods combined with substantially revised requirements for seismic design have been introduced in the 2005 NBCC. The changes of the 2005 NBCC from the 1995 edition are significant. The major aspects of the changes are summarized in Table 1.

Table 1. Major changes from 1995 NBCC to 2005 NBCC.

Aspects	1995 NBCC	2005 NBCC
1. Exceedance probability of seismic hazard	10% probability of exceedance in 50 years, which is equivalent to a return period of 475 years (see p. 481 in NBCC 1995) .	2% probability of exceedance in 50 years, which is equivalent to a return period of approximately 2500 years. This probability is exactly equal to the target probability of failure in seismic design, so that the seismic reliability of structures can be evaluated more accurately. Thus, a uniform safety margin in seismic design within entire Canada can be obtained more easily than before (see Division B p C-10 in NBCC 2005, p 244 in Heidebrecht 2003, & p 258 in Adams and Atkinson 2003).

Aspects	1995 NBCC	2005 NBCC
2. Seismic data	Based on peak ground motion with above exceedance probability, The territory of entire Canada is divided into seven acceleration related seismic zones Z_a and seven velocity related seismic zones Z_v, ranging from 0 to 6 each (see p. 481 in NBCC 1995) A value v = zonal velocity ratio is given for each zone. The elastic response is determined by a function of structural fundamental period, $S(T)$, which has a same pattern for all zones with the same ratio of Z_a / Z_v in the entire country (see p 147 in NBCC 1995).	Seismic response acceleration $S_a(T)$ of 5% damped elastic vibrator with period T = 0.2, 0.5, 1.0 and 2.0s are respectively determined for the above exceedance probability (so-called uniform hazard spectra), and listed for each city. For a location between any two cities, linear interpolation and provided computer software can be used. New findings in the major earthquakes around the world within recent two decades are incorporated. New theories, methodology and technology are employed to generate data of seismic hazard with much improved accuracy (see Division B p C-10 in NBCC 2005, p 243 in Heidebrecht 2003, & p 255 in Adam and Atkinson 2003).
3. Soil conditions	All types of soil under building foundations are categorized to four categories from rock to very soft soils. Foundation factor F = 1.0, 1.3, 1.5 and 2.0 are respectively used to amplify seismic response of structures with relatively long fundamental period (T > 0.5). Cap is applied to $FS(T)$ for buildings with short period (T < 0.25). (see p 148-149 in NBCC 1995 & p 274 in Finn and Wightman)	Acceleration-based site coefficient F_a is used for short period building, while the velocity-based site coefficient F_v is used for long period buildings. Both are considered as functions of soil conditions, intensity of ground motion and period for refined expression of nonlinear soil behavior in earthquakes (see Division B, p 4-21 to 4-23 in NBCC 2005, & p 276 in Finn and Wightman 2003) Category 1 in 1995 NBCC is broken into three classes. Therefore, total six classes are specified. For the first five classes from hard rock (Class A) to soft soil (Class E), F_a ranges from 0.7 to 2.1, F_v from 0.5 to 2.1. Deamplification effect of hard rock is considered. For very soft soil (Class F), site specific geotechnical investigations are required
4. Importance factor I_E	I_{E95} = 1.0, 1.3 and 1.5 are used respectively for normal buildings, schools & post-disaster buildings (see p 148 in NBCC 1995)	I_{E05} = 0.8, 1.0, 1.3 and 1.5 are introduced respectively for buildings with low, normal and high occupancy, as well as for post-disaster buildings (see Division B p 4-23 in NBCC 2005)

Aspects	1995 NBCC	2005 NBCC
5. Effects of higher-order vibration modes on base shear	Included in the shape of response function $S(T)$ (see p 295 in Humar and Mahgoub 2003)	Factor M_v is introduced as the function of region, period and type of structure so that the effects of higher-order vibration modes can be considered more rationally (see Division B p 4-28 to 4-29 in NBCC 2005, & p 290-295 in Humar and Mahgoub 2003).
6. Load modifications due to ductility & overstrength	For load reduction due to ductility, $1.0 \le R \le 4.0$ is determined based on type of structure and detailing. For reduction due to structural overstrength, $U = 0.6$ is adopted (see p 149 in NBCC 1995)	$1.0 \le R_d \le 5.0$ for ductility, while $1.0 \le R_o \le 1.7$ for overstrength. Both are functions of type of structure and detailing (see Division B p 4-25 to 4-27 in NBCC 2005, & p 313 to 314 in Mitchell et al. 2003)
7. Structure irregularities	General statements are made about discontinuous vertical resisting elements and possible effects of setback, but no specific requirements are given (see p 151 & 152 in NBCC 1995, and p 245 in Heidebrecht 2003).	Eight structure irregularities are defined. Restrictions and analysis requirements are specified accordingly, such as no permission for week storey in the regions with $F_a S_a(0.2) I_E > 0.2$ (see Division B p 4-23 to 4-27 in NBCC 2005, p 245 in Heidebrecht 2003, & p 281 in DeVall 2003).
8. Analysis method	Equivalent static loads are used for design. Dynamic analysis is only permitted in few cases, e.g. estimating period and load distribution over the height, or assessing response of irregular buildings (see p 148 and 151 in NBCC 1995).	Dynamic analysis is preferred method, even though static method is applicable, if $F_a S_a(0.2) I_E < 0.35$, or $h < 60m$ and $T < 2s$ for regular buildings, or $h < 20m$ and $T < 0.5s$ for irregular buildings (if not torsion-sensitive). However, some limitations are applied to the results of dynamic analysis, such as period and seismic loads (see Division B p. 4-24, 4-28 in NBCC 2005, p 245-246 in Heidebrecht 2003, & p 288 in Humar and Mahgoub 2003, as well as Saatcioglu and Humar 2003)
9. Restrictions on structure type and height	Restrictions and height limits are imposed to some types of structure with limited ductility in seismic zones at certain level and higher (see p 152 in NBCC 1995)	Height limits and restrictions are applied based on structure types, ductility and design spectral accelerations (see Division B p 4-25 to 4-28 in NBCC 2005)

Aspects	1995 NBCC	2005 NBCC
10. Static base shear	$V_e = vFS(T)I_{E95}UW/R$ where *W* is the dead load (see p. 147 in NBCC 1995)	$V_e = F_{av}S_a(T)I_{E05}M_vW/R_dR_o$ but need not be greater than $\frac{2}{3}F_aS_a(0.2)I_EW/(R_dR_o)$ if $R_d \geq 1.5$ and shall not be less than $F_vS_a(2.0)I_EM_vW/(R_dR_o)$ where *W* is the dead load (see Division B p 4-28 in NBCC 2005, p 250 in Heidebrecht 2003, & p 289 in Humar and Mahgoub 2003)
11. Deflection and drift limits	Elastic lateral interstorey deflection shall not exceed $0.01h_s$ for post-disaster buildings and $0.02h_s$ for all other buildings under storey loads distributed from V_eR and incorporating the effects of torsion (see p 152 in NBCC 1995).	Elastic lateral interstorey deflection shall not exceed $0.01h_s$ for post-disaster buildings, $0.02h_s$ for schools and $0.025h_s$ for all other buildings under storey loads distributed from $V_eR_dR_o/I_E$ and incorporating the effects of torsion. These requirements are more restrictive because they are based on the event with return period of 2500 years other than 475 years in 1995 NBCC (see Division B p 4-31 in NBCC 2005, & p 283 to 285 in DeVall 2003).

Because of many significant changes from 1995 NBCC to 2005 NBCC, in particular the changes in geological distribution of seismic hazards, seismic design loads for the same building but based on different design codes may have significant differences. Heidebrecht (2003) has investigated the impacts of the code changes on the design base shear for the most common types of structure, located in three cities, i.e. Vancouver, Montreal and Toronto, which not only have large population, but also respectively represent high, moderate and low seismic hazard. His results show that as a general trend the design forces based on 2005 NBCC increase from 1995 NBCC for the buildings with short fundamental period (by about 50% in Vancouver for T < 0.5 s), and decrease for the buildings with long fundamental period (by more than 10 % in Toronto for T > 1.0 s). Even though the new code provides more consistency and uniformity in level of seismic protection throughout the country, the seismic design forces may change significantly from the previous code. In addition, although there are some systematic influences, the reasons for changes in design force for a given structure are complex (see p 254 in Heidebrecht 2003), and a site-specific calculation is required to take into account randomness in the changes.

Scores in Screening Process based on the 2005 NBCC

As mentioned earlier, the scores in screening process are related to the seismic risk for the particular building subjected to design earthquake loads in the currently effective NBCC (p H-6 in Kulkarni 1999). Since the seismic design loads have been changed significantly from the 1995 NBCC to the 2005 NBCC, the scores assigned to a specific building should be adjusted based on comparison of the design earthquake loads in the 2005 NBCC to those in the 1995 NBCC. In the present study, adjustments for the Structural Index, Non-Structural Index and Seismic Priority Index are proposed as below:

$$SI\_2005 = A \cdot B \cdot C \cdot D \cdot E \cdot V_e\_2005 / V_e\_1995$$

$$NSI\_2005 = B \cdot E \cdot F \cdot K\_2005 / K\_1995$$

$$SPI\_2005 = SI\_2005 + NSI\_2005$$

in which the subscripts 1995 and 2005 denote the years of NBCC, V_e represents static base shear (see p 147 in NBCC 1995, & Division B p 4-28 in NBCC 2005), whereas K is the required lateral interstorey stiffness, which is determined as the ratio of specified load to permissible interstorey drift (see p 152 in NBCC 1995, & Division B p 4-31 in NBCC 2005).

As listed in Aspect 10 of Table 1, the base shears are calculated as follows:

$$V_e\_1995 = vFS(T)I_{E95}UW / R$$
$$V_e\_2005 = F_{av}S_a(T)I_{E05}M_vW / R_dR_o$$

in which all the symbols have been introduced in the respective aspects of Table 1.

Thus, the ratio between the design base shears specified in the two design codes is obtained as below:

$$V_e\_2005/V_e\_1995 = \frac{S_a(T)M_v}{vS(T)} \frac{F_{av}}{F} \frac{1/R_dR_o}{U/R} \frac{I_{E05}}{I_{E95}}$$

where the first item $\frac{S_a(T)M_v}{vS(T)}$ is the change in the design value of the seismic response, whose effect on the seismic indices is represented by the seismicity factor *A*; the second item $\frac{F_{av}}{F}$ denotes the change in the soil condition factor, whose effect on the seismic indices is represented by the factor *B* for soil conditions; the third item $\frac{1/R_dR_o}{U/R}$ represents the changes in the structural seismic behaviors, whose effect on the seismic indices is represented by the structure factor *C* and the irregularity factor *D*; the last item $\frac{I_{E05}}{I_{E95}}$ corresponds to the change in the importance factor, whose effect on the seismic indices is represented by the building importance factor *E*. Therefore, it can be concluded that the ratio between the base shears in two design codes incorporates modifications to all the factors for evaluating the seismic indices.

Because calculating the base shear and stiffness is often tedious and easy to make errors, a computer software is developed to calculate the scores. Restrictions to some types of structure and limitations to structure height at certain level of seismic intensity are also included explicitly in the software. Thus, the inspectors equipped with an ordinary notebook can easily handle all the related calculations in a minute, not slower than dealing with the related forms.

Examples

(1) Old Residential Wood Frame Building Located in Seismic Zone 5

A residential four-storey wood frame building is located in Port Alberni, BC with Z_a = Z_v = 5, $v = 0.30$, $S_a(0.2) = 0.75$, $S_a(0.5) = 0.55$, $S_a(1.0) = 0.30$ and $S_a(2.0) = 0.16$. The building was built in 1926 with stud walls of 12 m height and brick veneer. The first floor forms a weak storey occupied by garages. Pounding risk and deteriorations are also observed during inspection. The foundation is built of bricks and placed on soft clay of total thickness > 10m. Roof is made of diagonal sheathing. The scores in the screening process based on the NRCC Manual (NRCC 1993) are listed in Table 2. Details are available in p 80-81 of the manual. Since *SPI* = 36.3 > 30, the structure is considered as seismic hazardous.

Weak storey is permitted by the 1995 NBCC, as long as failure at the point of discontinuity in columns or shear walls will not occur before the capacity of the remaining portion of the structure has been realized (Clause 4.1.9.3 (4) in p 152 of the 1995 NBCC). However, in the 2005 NBCC the weak storey is forbidden for all regions with $F_a S_a(0.2) I_E \geq 0.2$ (Clause 4.1.8.10 (1) in Division B p 4-27 of NBCC 2005). Therefore, the building under consideration is not permitted, and must undergo a detailed seismic evaluation.

For comparison purpose only, the base shear can be determined using the equations for buildings situated at a site with $F_a S_a(0.2) I_E < 0.2$. In this case $R_d R_o$ is taken as 1, and the upper bound for the base shear is not applicable (see Item 4 in p 282 of DeVall 2003). Thus, the following results are obtained: Period T = 0.32 s, $V_e\_1995 = 0.18W$ and $V_e\_2005 = 0.825W$ with W denoting the dead load, yielding $V_e\_2005 / V_e\_1995 = 4.58$ and $SI\_2005 = 111.5$. It can be further obtained that $K\_2005 / K\_1995 = 1.22$ and $NSI\_2005 = 14.7$. Consequently, the Seismic Priority Index becomes 126.2, almost four times of the score based on NRC Manual.

(2) Two-Storey Steel Framed Building Located in Seismic Zone 5

A two-storey steel framed building of height 10.0 m was built in 1956 in Port Alberni, BC, the same city as in the previous example. The building has 36.6 X 36.6 m (120 X 120 ft) in plan with 6.1 X 6.1 m (20 X 20 ft) bays. This building is underlain by stiff soil. There are no structural walls. The exterior walls have windows all around and the interior walls form non-structural partitions. The floor is made of steel deck connected to steel columns. There are frames in both transverse and longitudinal directions. The top and bottom flanges of the beam are connected to the flanges of columns with clip angles. Thus, the building is a frame structure in both directions with some small moment resisting capacity.

The building is assessed by following the proposed procedures. The scores are shown in Table 2. The Seismic Priority Index *SPI*_2005 = 3.75 is much less than the value of *SPI* = 6.0 obtained according to NRC Manual (see p 82 to 83 in NRCC 1993). Since this index is less than 10, the seismic priority is low.

(3) Single-Storey Industrial Building Located in Seismic Zone 4

A single-storey industrial building of height 10.5 m was built in 1942 in Vancouver, BC with $Z_a = Z_v$ = 4, $v = 0.20$, $S_a(0.2) = 0.94$, $S_a(0.5) = 0.64$, $S_a(1.0) = 0.33$ and $S_a(2.0) = 0.17$. This building is underlain by soft soil. The structure is classified as a braced steel frame in the longitudinal direction and a steel moment frame in the transverse direction. The occupancy is as high as a school because may people work in the building. There exist both the vertical and horizontal structural irregularities. However, no obvious non-structural hazards are found.

The building is evaluated according to the proposed procedures. The scores are shown in Table 2. The Seismic Priority Index based on NRC Manual (NRCC 1993) is *SPI* = 15.5 with a medium priority. However, its new value is *SPI*_2005 = 22.7. Since the value is greater than 20.0, the seismic priority is upgraded to “high”.

Table 2. Scores of three buildings in examples.

Scores	Four storey building with wood frames & weak storey	Two storey building with steel moment frames	Industrial building with steel frames
A : Factor for seismicity	3.0	3.0	2.0
B : Factor for soil conditions	2.0	1.3	1.5
C : Factor for structure type	1.2	1.2	1.5
D : Factor for structure irregularities	3.4	1.0	2.0
E : Factor for building importance	1.0	1.0	1.5
F : Factor for non-structural hazards	6.0	1.0	1.0
SI : Structural index in [1 & 2]	24.5	4.7	13.2
NSI : Non-structural index in [1 & 2]	12.0	1.3	2.3
SPI : Seismic priority index in [1 & 2]	36.3	6.0	15.5
V_e_2005/V_e_1995 : Base shear ratio	4.58	0.57	1.47
K_2005/K_1995 : Stiffness ratio	1.22	0.82	1.47
*SI*_2005 : New structural index	111.5	2.68	19.4
*NSI*_2005: New non-structural index	14.7	1.07	3.3
*SPI*_2005 : New seismic priority index	126.2	3.75	22.7

Note: [1] represents (Kulkarni 1999), while [2] denotes (NRCC 1993)

Conclusions

In the present study, the 1999 DND Strategy for seismic considerations in existing buildings is revised based on the 2005 NBCC. The Structural Index is multiplied by the ratio of the design base shear in the 2005 NBCC to that in the 1995 NBCC, while the Non-Structural Index is multiplied by the ratio of the required interstorey lateral stiffness in the 2005 NBCC to that in the 1995 NBCC. Thus, both the indexes can represent the seismic risks of the assessed building under the design loads in the currently effective NBCC. Corresponding computer software is developed to implement required calculations.

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