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EVOLUTION OF THE SEISMIC PROVISIONS OF THE NATIONAL BUILDING CODE OF CANADA

A.C.Heidebrecht[1]

ABSTRACT

This paper describes the evolution of the seismic provisions of the National Building Code of Canada (NBCC), beginning with the status of NBCC as a model code. The major changes of seismic provisions are traced from the 1953 to the 2005 editions of NBCC. The most recent changes from NBCC 1995 to NBCC 2005 are presented and discussed in more detail, including numerical comparisons of seismic design forces for typical building structures located in regions of high, moderate and low seismicity. The paper includes a discussion of the implications of these changes for seismic design practice and comments on potential future directions for seismic code development.

Introduction

Any presentation of the evolution of seismic provisions for design of buildings in Canada needs to indicate why seismic provisions are necessary, especially since there may be, in some circles, a perception that Canada is not subject to damaging earthquakes. Lamontagne et al.W (Geological Survey of Canada 2007) provide a listing of significant earthquakes felt in Canada from 1600 to 2006. In a companion paper (Seismological Research Letters 2008), the same authors tabulate the characteristics of 28 of these events which they rate as major or very significant. Most of these 28 events, which occurred in several regions of the country, had magnitudes of 6 larger and caused either damage to buildings and/or environmental damage, e.g. tsunamis or landslides. A significant proportion of the Canadian population lives in cities and towns which are susceptible to future damaging earthquakes; consequently, there is a need for seismic design provisions to protect buildings and their occupants from the effects of such earthquakes.

History of NBCC Seismic Provisions

The National Building Code of Canada (NBCC) is a “Model Code”, i.e. it serves as a definitive resource for the actual building codes which are put into law by the various provinces, which have the responsibility for regulating building requirements. The first edition of NBCC in

[1]Professor Emeritus, Dept. of Civil Engineering, McMaster University, Hamilton, Ontario, Canada L8S 4L7

1941 contained seismic provisions in an appendix, based on concepts presented in the 1937 United States Uniform Building Code (UBC); specific seismic provisions in the code proper did not appear until the 1953 edition. There have been ten editions since 1953 up to and including the edition which is currently in use, i.e. NBCC 2005.

Major Changes in Use of Seismic Hazard Information in NBCC - 1953 to 2005

The history of the determination of seismic design forces from 1953 to 2005 is summarized in Table 1; this table focuses on the nature of hazard information used to determine seismic design forces. That perspective is of particular interest since major changes in code provisions have normally been driven by improved knowledge of seismic hazard.

As shown in the table, four generations of seismic hazard information have been used in NBCC during this period of time:

1. The four seismic hazard zones introduced in NBCC 1953 using a seismic zoning map developed by J.H.Hodgson (1956) based on estimated damage potential from future earthquakes; zone 0 = no damage, zone 1 = minor damage, zone 2 = moderate damage and zone 3 = major damage.
2. The first probabilistic mapping of seismic hazard was introduced in NBCC 1970. Milne and Davenport (1969) applied Gumbel's extreme value method to statistical information derived from studies of Canadian earthquakes from 1900 to 1963 to calculate values of peak ground acceleration (PGA) with an annual probability of exceedence of 0.01.
3. In NBCC 1985, peak ground velocity and acceleration were both determined at a probability of exceedance of 10% in 50 years by applying the "Cornell-McGuire" method to 32 earthquake source zones in Canada and adjacent regions (Basham et al. 1985); these parameters were mapped with seven zones to provide a finer subdivision of zoning in moderate hazard regions and additional zones in regions of high hazard.
4. For NBCC 2005, seismic hazard was recomputed as spectral acceleration values at a 2% in 50 year probability of exceedance using a hazard model (Adams and Atkinson 2003) which incorporates new knowledge from recent earthquakes, new strong ground motion relations, measures of uncertainty and a more systematic approach to reference site conditions.

Several significant observations can be drawn from the above and from Table 1.

- There has been a movement from general hazard zones which are not at all associated with ground motions through zones which are directly based on peak ground motion values to location-specific spectral accelerations.
- There has also been a change in the probability level at which the ground motion parameters have been determined, attempting to determine seismic design forces at probabilities which are closer to those at which some damage can be expected during strong seismic ground motions.

While the historical trend has been to move towards a more explicitly rational use of ground motion parameters in determining seismic design forces, the actual levels of those design forces have remained more or less constant during a period of about 40 years (to NBCC 1995), independent of changes in ground motion parameter (from peak ground acceleration to peak

Table 1. History of use of natural hazard information for the determination of seismic design forces in National Building Code of Canada (NBCC).

<table>
<tr><th>NBCC edition</th><th>Nature of hazard information</th><th>Manner in which hazard information is used to determine seismic design forces</th></tr>
<tr><td>1953 through 1965</td><td>four zones (0,1,2,3) based on historical earthquake activity</td><td>base shear coefficients are prescribed for design of buildings in zone 1; these are doubled for zone 2 and multiplied by 4 for zone 3</td></tr>
<tr><td>1970</td><td rowspan="2">four zones (0,1,2,3) with boundaries based on peak acceleration at 0.01 annual probability of exceedance</td><td>base shear coefficient includes a non-dimensional multiplier (0 for zone 0, 1 for zone 1, 2 for zone 2 and 4 for zone 3)</td></tr>
<tr><td>1975 through 1980</td><td>base shear coefficient includes factor "A" equal to the zonal peak acceleration (0 for zone 0, 0.02 for zone 1, 0.04 for zone 2 and 0.08 for zone 3); seismic response factor is adjusted so that base shear is approximately 20% below that in NBCC 1970</td></tr>
<tr><td>1985</td><td rowspan="2">seven(0 to 6) acceleration and velocity related zones with boundaries based on 10 % probability of exceedance in 50 years</td><td>base shear coefficient includes zonal velocity "v" which is numerically equal to peak ground velocity in m/s (values are 0, 0.05, 0.10, 0.15, 0.20, 0.30 and 0.40); value of seismic response factor is adjusted by calibration process so that seismic forces are equivalent, in an average way across the country, to those in NBCC 1980 (Heidebrecht et al. 1983)</td></tr>
<tr><td>1990 and 1995</td><td>elastic force coefficient includes zonal velocity "v" (as above) with total seismic force V calculated as elastic force divided by force reduction factor and then multiplied by a calibration factor of 0.6; seismic response factor is modified to maintain same design force for highly ductile systems as in NBCC 1985</td></tr>
<tr><td>2005</td><td>location-specific uniform hazard spectral acceleration values at 0.2, 0.5, 1.0 and 2.0s, with linear interpolation, at 2% probability of exceedance in 50 years</td><td>total seismic force V calculated directly from spectral acceleration using elastic dynamic analysis; static analysis, which is allowed in many situations, uses various factors intended to simulate dynamic response; no calibration factor is applied but forces in the short period range are reduced by 1/3 for structures with limited ductility or higher.</td></tr>
</table>

ground velocity), changes in methodology and changes in probability level. There was a deliberate 20% reduction in design forces from NBCC 1970 to 1975, reflecting a sense that design forces could be reduced slightly without compromising the level of protection. Actually, that change was also accompanied by a comparable increase in the overturning moment reduction factor for buildings with periods longer than about 0.5 s; the effective level of protection for medium to long period buildings sensitive to overturning was therefore about the same as in the previous code. Due to the shift from peak ground motion values to spectral accelerations in NBCC 2005, it is not feasible to make broad comparisons of design forces with the previous code; a few comparisons for particular situations are included later in this paper.

Major Changes 1995 to 2005

The remainder of this paper focuses on the major changes from the 1995 to the 2005 editions of NBCC. Since NBCC 2005 is the code now in use, it is important to know the substantive changes from a code which had been in use for the prior 10 years and the reasons for those changes. It is this author's view that the changes from NBCC 1995 to 2005 were the most significant of any edition-to-edition changes in seismic code provisions since such provisions were initially included in the code in 1953. Table 2 summarizes the major changes from NBCC 1995 (Associate Committee on the National Building Code 1995) to NBCC 2005, excluding seismic hazard determination which is described in Table 1. These changes are highlighted below; a more detailed overview is given by Heidebrecht (2003).

Site Effects

It has long been recognized that the amplification of seismic motions from rock to soil sites can be significant, especially for sites with soft soil conditions. The site factor approach adopted in NBCC 2005 is an adaptation of that used in NEHRP 2001 (Building Seismic Safety Council 2001) which is based largely on research done by Borcherdt (1994). The substantive impacts of this change are to include: a) short period amplification, b) non-linearity of site amplification, i.e. amplification decreasing with increasing levels of rock motion, and c) de-amplification of seismic motions at rock or hard rock sites, i.e. those having shear wave velocities higher than that of the reference site condition, which is described as "very dense soil and soft rock".

Irregularities

NBCC 1995 had no specific requirements for vertical irregularities, although it did require that building design take into account the effect of setbacks. The significant effect of such irregularities on the performance of structures during earthquakes is recognized in NBCC 2005 by defining six types of irregularity (stiffness, mass, geometric, discontinuities (in-plane and out-of-plane) and weak storey) and specifying restrictions applicable to the different types. Restrictions include: **analysis** (i.e. requiring dynamic rather than static analysis), **design** (e.g. specific requirements associated with diaphragms, openings and discontinuities) and **use** (e.g. restrictions in use related to type and level of seismicity). One of the major use restrictions is the prohibition of weak storeys in regions of moderate to high seismicity.

Table 2. Summary of Major Changes in Seismic Provisions, NBCC 1995 to 2005

Category	NBCC 1995	NBCC 2005
Site effects	Single foundation factor F ranging from 1.0 to 2.0 for four foundation categories; short period force cap equivalent to F of 1.0 for all sites	Site factors F_a and F_v with values dependent upon spectral accelerations at 0.2s and 1.0s respectively (direct adaptation of approach used by NEHRP*)
Vertical irregularities	No specific requirements	Six types defined with restrictions on analysis and design for each type
Torsion	Static torsional moments include amplified natural eccentricity and accidental eccentricity 0.1 x plan dimension; same accidental eccentricity added to 3D dynamic analysis	Torsional sensitivity defined on basis of ratio of max edge displ to ave displ; dynamic analysis required for torsionally sensitive structures; static method may be used for non-sensitive structures, with no amplification of natural eccentricity
Structural system force modification factors	Single factor R; values range from 1.0 (e.g. unreinforced masonry) to 4.0 (e.g. steel or RC moment-resisting frame)	Ductility related factor R_d (range 1.0 to 5.0) and system overstrength factor R_o (range 1.0 to 1.7); product R_dR_o for actual systems ranges from 1.0 to 7.5
Analysis	Equivalent static load prescribed; dynamic analysis permitted	Dynamic analysis prescribed (normally linear modal response or numerical integration); equivalent static load permitted as exception (e.g. low seismicity, most regular structures and short period irregular structures)

*National Earthquake Hazards Reduction Program (Building Seismic Safety Council 2001)

The consideration of torsional effects for all structures continues to be a requirement but NBCC 2005 requires dynamic analysis for structures which are torsionally flexible, based on studies (e.g. Humar et al 2003) which show that a static approach cannot consistently represent torsional effects for such structures.

Structural Systems

NBCC 1995 specified a force modification factor R, which was equivalent to the maximum system ductility capacity, for a number of types of lateral force-resisting systems for which the design and detailing requirements were specified in the materials standards published by the Canadian Standards Association (CSA). As noted in Table 2, NBCC 2005 specifies both a ductility related factor R_d and an overstrength related factor R_o for each structural system; the product R_dR_o appears as a composite reduction factor in the denominator of the expression for calculating the seismic design force V. NBCC 2005 also includes height limits for structural systems having limited ductility when these are to be built in regions of high seismicity.

Analysis

As indicated in Table 2, NBCC 2005 specifies dynamic analysis as the “default” method of analysis, with static analysis permitted as an exception. Static analysis, which is referred to as the Equivalent Static Force Procedure (ESFP), may be used when relatively small ground motions are expected, for moderate height (less than 60m) regular structures and for low (height less than 20 m) short period irregular structures provided that the irregularity is not torsional sensitivity. These exceptions are such that many building structures can in fact be designed using static analysis. Linear methods of dynamic analysis (either modal response or numerical integration time history) are specified although nonlinear dynamic analysis is permitted provided that a special study is performed.

Design Force Comparisons NBCC 1995 to NBCC 2005

The effects of changes in seismic provisions on design forces can be visualized most clearly by comparing design forces for a few specific situations. Figure 1 shows changes in force levels for ductile reinforced concrete wall structures located in Vancouver (a location of high seismicity) for three site conditions: hard rock, soft rock/dense soil, and soft soil. In this and the following figure, the thin lines show the NBCC 1995 values and the thick lines the NBCC 2005 values. In NBCC 1995, there was no distinction between soft rock/dense soil and hard rock; the reason for including this distinction in NBCC 2005 is that, as noted previously, hard rock actually de-amplifies ground motion (in comparison with motions on the reference site condition). That de-amplification ranges from 25% to 50%, depending upon the seismic hazard level and the period range. The effect of de-amplification means that NBCC 2005 design forces on hard rock sites are lower than the NBCC 1995 values at almost all periods, and are substantially lower in the low and high period ranges.

Figure 2 shows changes in force levels for conventional steel frames located on the same three different site conditions in a low seismicity location, namely Toronto. Comparing force levels in Toronto for this type of structure is important because limited ductility capacity structures are more likely to be used in a low seismicity location. The effect of including the hard rock site category in NBCC 2005 has the effect of reducing forces to levels which are below those in NBCC 1995 for all periods. However, the low and intermediate period design forces on soft soil sites in NBCC 2005 are much larger than those in NBCC 1995. This increase occurs because there is significant amplification on soft soil sites for all periods whereas NBCC 1995 did not include any amplification in the short period range. This amplification is particularly significant for low levels of ground motion, i.e. at locations with low seismic hazard.

Implications of NBCC 2005 Provisions for Seismic Design and Level of Protection

While several other factors have a significant impact on level of protection (e.g. quality of construction), in this context the level of design base shear is taken as a proxy for level of protection. The changes listed below are deemed to have the most significant effect on level of protection. Other changes also have some impact, but none on their own are likely to match those listed here:

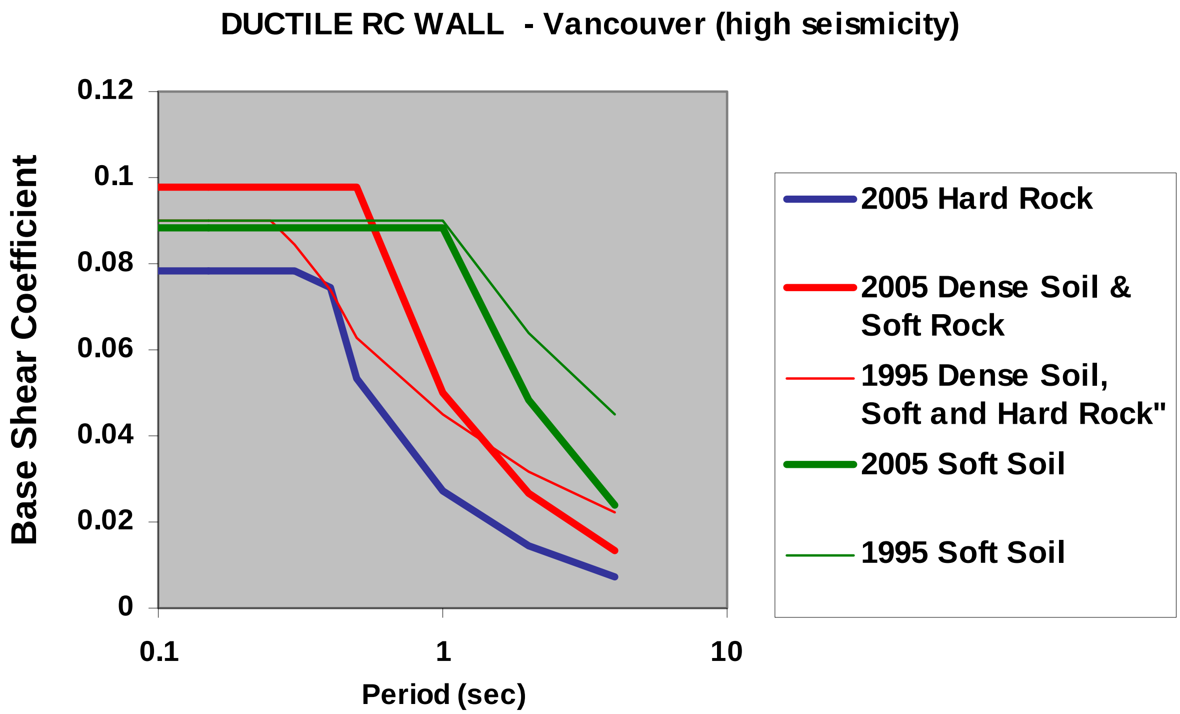

Figure 1 Base Shear Coefficient Comparisons for Ductile Reinforced Concrete Wall Structures in Vancouver

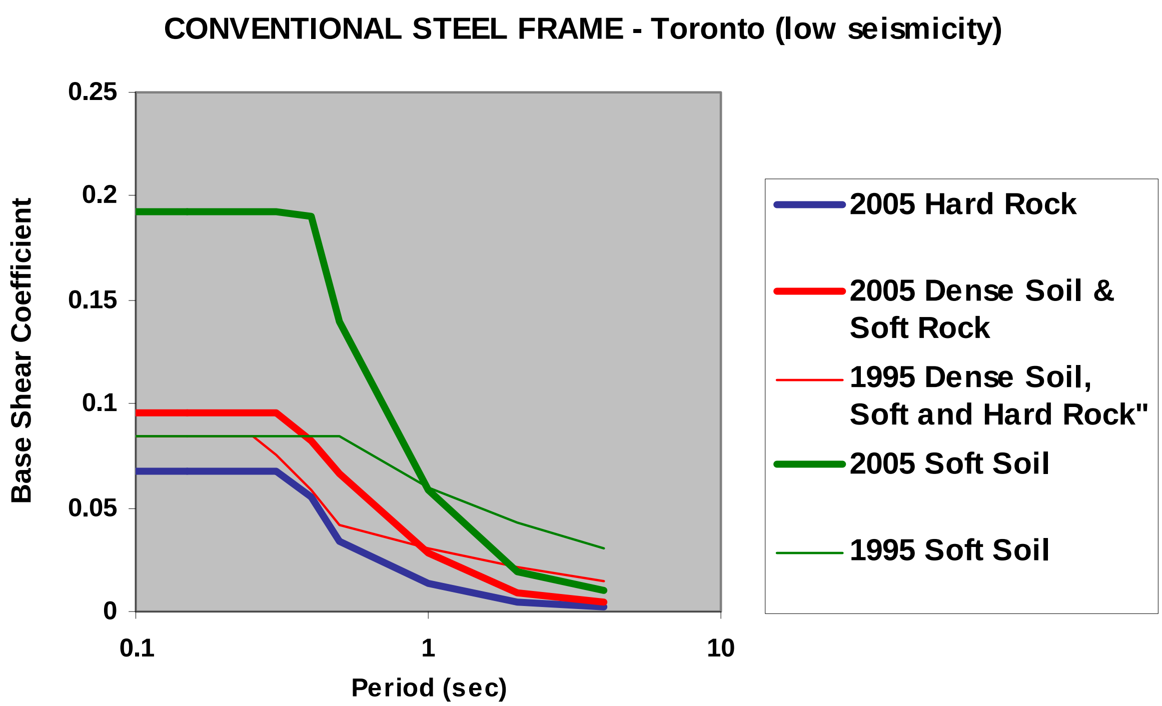

Figure 2 Base Shear Coefficient Comparisons for Conventional Steel Frame Structures in soft rock/dense soil).

a) The impact of changes in seismic hazard is probably the largest single factor in improving the level of protection; a methodology which provides period-dependent spectral accelerations on a location-specific basis is the key to providing a more consistent level of protection.

b) The use of more rational site factors, recognizing short period amplifications and non-linearity, improves the level of protection; also the use of site categories which are defined quantitatively should improve the consistency in classifying sites.

c) The specification of the different types of irregularity, including torsional sensitivity and the corresponding restrictions on analysis, design and use, reduces the vulnerability of irregular structures.

d) The explicit delineation between structural types on the basis of minimum overstrength results in a relative range of force reduction of 7.5 in NBCC 2005 compared with a range of 4.0 in NBCC 1995; the relative increase of design loads for the less ductile structural systems reduces the vulnerability of such structures.

Issues for Future Development of NBCC Seismic Provisions

The author's participation in the development of the NBCC seismic provisions since the late 1960s has stimulated thinking about the role of seismic codes and their current and future development. This part of the paper raises some of the issues which have arisen without attempting to suggest particular solutions or directions; these issue are applicable to seismic code development in other parts of the world as well.

Prescriptiveness

The seismic provisions of NBCC 1995 and previous editions tended to be quite prescriptive with regard to aspects such as: calculation of the static seismic load, the distribution of that load with height and calculation of torsional moments. The NBCC 2005 provisions, while somewhat more complex, continue that trend, including some additional prescriptive requirements, e.g. concerning the input for dynamic analysis. However, knowledgeable designers often prefer less prescriptive provisions so that they have more flexibility in choosing how to meet stated performance requirements. In theory, the objective-based code approach of NBCC 2005 should provide the opportunity for "alternate solutions" which meet the stated objectives and functional requirements. Nevertheless, regulatory bodies (e.g. those who approve building plans on behalf of a municipality) are more likely to approve designs which use the detailed prescriptive requirements in the code. This can stifle innovation in design and prevent the development of better methods to achieve seismic protection.

Performance Expectations

Traditionally, performance expectations associated with use of NBCC seismic provisions have not been included in the code and are only stated in very general terms in the commentary.

The expected performance of structural systems with different levels of ductility capacity when subjected to the design ground motions are understood by those involved in developing the code and by a few very knowledgeable designers. Performance-based engineering approaches, e.g. such as developed by the Structural Engineers Association of California (Vision 2000 Committee 1995) have gained prominence in seismic design and it is likely that codes will need to reflect that trend, which includes more explicit performance objectives than is the case in the NBCC 2005 and previous editions of NBCC.

Design Processes for Low and and Moderate Seismicity (LMS) Regions

The NBCC seismic provisions, in the 2005 edition and in previous editions, are based predominantly on the needs and concerns of high seismicity regions. Various code provisons (e.g. large force reductions for structures with high ductility capacity) explicitly or implicitly arise from codes, practice and experience in regions of high seismicity. In particular, most lessons learned from damage during earthquakes have been the result of investigations of moderate to large earthquakes occurring in regions of high seismicity. However, while some level of seismic protection is necessary in low to moderate seismicity (LMS) regions, the design processes which would be best for those situations are not necessarily the same as for high seismicity regions. This is particularly important for the NBCC, which is a model code for a country in which a large proportion of the population resides in LMS regions. Consequently, it is this author's view that the development of an alternate design process for these regions should be included in the development of future NBCC seismic provisions.

Conclusions

The seismic provisions of the NBCC have been updated at frequent intervals over a period of approximately 50 years. Updating on a frequent basis is needed to recognize:

a. Lessons learned from damage which has occurred during major earthquakes around the world.

b. Results of earthquake engineering research conducted in Canada and elsewhere.

c. Changes made in seismic codes in other countries.

Of the NBCC seismic provision updates over the 50 year period, the changes incorporated in the NBCC 2005 seismic provisions are probably the most substantial. The NBCC 2005 provisions should, if used effectively, provide for an improved and more consistent seismic level of protection. However, these changes make seismic design significantly more complex, which could have a negative effect because the less knowledgeable designers may not use its provisions appropriately; designers in regions of low to moderate seismicity are likely to view this additional complexity as unwarranted. The development of the NBCC 2005 provisions has raised certain issues, e.g. complexity, prescriptiveness, and performance objectives, which are of ongoing concern in the development of seismic codes, whether in Canada or elsewhere in the world.

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