CORRELATION OF STATIC AND DYNAMIC EARTHQUAKE ANALYSIS OF THE NATIONAL BUILDING CODE OF CANADA 1977

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SYNOPSIS

The meaning of the National Building Code (1977) is analyzed with respect to seismic force levels. The quasi-static force is correlated with ground acceleration levels. The level of risk actually associated with the NBC 'major earthquake' is examined. The authors do not set out to criticize the code which represents the state-of-the-art based on both experience and theory. The intent is to clarify without comment.

RESUME

L'aspect du Code National du Bâtiment (1977) quant aux niveaux de force sismique est étudié. La force quasi-statique est en corrélation avec les niveaux d'accélération du sol. Le niveau de risque actuellement associé avec le "violent tremblement de terre" du CNB est examiné. Les auteurs n'ont pas l'intention de critiquer le Code qui représente l'état des connaissances basées sur l'expérience et la théorie. Le but est de clarifier sans commentaire.

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INTRODUCTION

In the experience of the authors there is some confusion as to the exact meaning and implications of the seismic provisions of the National Building Code (NBC)(1) with respect to the expected ground motion associated with a major earthquake. This is particularly significant when an engineer wishes to make a dynamic analysis in some unusual situation (for example, to study the amplification of the free-field motion by a soil layer), so that he is not following exactly the procedures outlined in the Code or in Commentary K (2); he can then easily be misled in selecting the appropriate ground motion. The essential purpose of this paper is simply to clarify the meaning of the Code with respect to ground motion levels. It must be emphasized that the authors are stating implications of the Code procedure, with which they do not necessarily agree or disagree, but which they feel follow inevitably from the Code provisions.

The Code states that the design loading due to earthquake motion should be determined either by the specified quasi-static procedure or "by a dynamic analysis provided that the assigned horizontal design ground acceleration is not less than that given in the Table of Climatic Data in Part 4 " of the Code.*

Commentary K outlines a procedure for performing a dynamic analysis, stating that "a probability of exceedance of 0.01 per annum (or the "100 year" earthquake) was taken as the standard risk level for the determination of peak ground acceleration for the seismic design of buildings in Canada".

In the authors' experience many have been misled by these statements in that they appear to imply that the 100 year earthquake represents the major design earthquake. We realize that the procedures given in the Code and Commentary K do not in fact lead to the 100 year earthquake as the major design earthquake; the reason for these comments is that they give the appearance of doing so.

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* This Table gives the 100 year accelerations.

Previous authors (Rainer (3); Tso and Bergmann (4,5); Otani and Uzumeri (6); Uzumeri et al (7)) have noted the lack of agreement between the quasi-static analysis and the dynamic analysis of Commentary K. More recently Uzumeri et al (8) have presented a critical review of the development of the Code, and have touched upon the question discussed in this paper.

This paper will shed more light on the differences between the quasi-static and dynamic analyses, and will deduce the risk or acceleration levels that are actually associated with the procedure for quasi-static analysis given in the Code.

The Quasi-Static Analysis

In the 1970 Code the design base shear, i.e. the working load base shear, was expressed as

$$V = \tfrac{1}{4}\, RKCIFW \qquad (1)$$

R was a zone factor to be used with the seismic zoning map of Canada. The boundaries of the zones were based on contours of the expected peak ground acceleration for the 100 year earthquake, but the force levels themselves were based on earlier codes and, ultimately, on empirical observations of seismic performance. In the 1975 and 1977 Codes the design base shear was given by

$$V = ASKIFW \qquad (2)$$

where A = assigned horizontal design ground acceleration for the zone in question, which was the acceleration of the 100 year earthquake, as a fraction of gravity. The code writers had decided to introduce some easily understood physical quantity into the zoning procedure. For this purpose they chose, quite arbitrarily, the 100 year earthquake for A; then, they put

$$AS = (0.8)\, \tfrac{1}{4} RC \qquad (3)$$

(The 0.8 was included for reasons irrelevant to the present argument; the J-factor on the overturning moment had been increased, so that a slight decrease in base shear was felt to be warranted.) Thus the 1975 Code was calibrated against the 1970 Code, and the acceleration of the 100 year earthquake was included, to link the force level, however remotely, to a significant ground motion parameter. The actual base shear, however, remained rooted in the empirical observations of earlier code provisions, and, it must be emphasized, the 100 year earthquake was not the basis of the specified force levels.

The significance of the 100 year earthquake is that it forms the basis for the zoning map. If the 50 year, or 200 year, earthquake had been used rather than the 100 year earthquake, the adjustment in S would have been made in Eq.(3) to keep the force levels in each zone the same as at present, although the zone boundaries might have been a little different.

Commentary K Dynamic Procedure

The 1975 Code first permitted a dynamic analysis to be used in lieu of the quasi-static analysis, and except for the important rider that the base shear calculated by the dynamic procedure must not be less than 90% of the base shear obtained from the equivalent quasi-static approach, the 1977 Code remains unchanged in this respect.

Although Commentary K specifically states that "a probability of exceedance of 0.01 per annum (or the 100 year earthquake) was taken as the standard risk level for the determination of peak ground acceleration for the seismic design of buildings in Canada", if the procedures of Commentary K are followed, the ground acceleration actually specified is

$$\text{'ground acceleration'} = \lambda AIF \qquad (4)$$

where λ is the appropriate load factor (the forces derived from the Commentary K analysis are to be taken as working level forces). Typical values of the load factor are 1.5(NBC 1977) or 1.8(CSA A23.3). In Vancouver, where $A = 0.08$, these would lead to ground accelerations (with $I=F=1$) of 0.12g or 0.144g, with corresponding probability levels of exceedance of 0.0059 per annum (170 year earthquake) and .0047 per annum (215 year earthquake).

It is thus apparent that, at least for Vancouver, the dynamic analysis method of Commentary K assumes a return period in the order of 200 years as the appropriate minimum risk level for ordinary structures.

Ground Acceleration for Correlation with Static Analysis

The quasi-static procedure gives seismic forces which, if used in design, should produce a structure which behaves appropriately in a major earthquake; we will now deduce the peak ground acceleration that would have to be used in the dynamic analysis procedure to produce a base shear equal to the quasi-static base shear.

Starting from the quasi-static procedure:

$$\text{'working level base shear force'} = ASKIFW \qquad (5)$$

$$\text{'yield level base shear force'} = ASKIFW\lambda \qquad (6)$$

The 'equivalent elastic model base shear force', which we define as the base shear which would be developed in a hypothetical structure of equal stiffness and mass but which would remain elastic throughout the earthquake, is

$$\text{'equivalent elastic model base shear force'} = ASKIFW\ \lambda\ \mu \qquad (7)$$

where μ is the system ductility ratio. This follows from the observation (9) that the elasto-plastic structure will undergo approximately the same maximum displacement as the equivalent elastic model.

For structures with a small fundamental period an equal energy criterion is used instead of the equal displacement criterion, and μ is replaced in Eq. 7 by $\sqrt{2\mu-1}$.

Equation (7) implies an average horizontal acceleration of the mass of the structure as a fraction of the acceleration due to gravity given by

$$\text{'average acceleration'} = ASKIF\ \lambda\mu \qquad (8)$$

In a modal analysis the modal spectral acceleration is not the same as the average acceleration. Defining β as the ratio of the average acceleration to the modal spectral acceleration in the first, or dominant mode of the structure, the spectral acceleration is then given by

$$\text{'spectral acceleration'} = ASKIF\ \frac{\lambda\mu}{\beta} \qquad (9)$$

(For a single degree of freedom model with lumped mass $\beta = 1$; for the first mode of a uniform cantilever $\beta = 0.61$.)

Finally the peak ground acceleration, as a fraction of gravity, required to produce the above spectral acceleration is

$$\text{'peak ground acceleration'} = ASKIF\ \frac{\lambda\mu}{\beta D} \qquad (10)$$

where D is the dynamic amplification factor in the dominant mode. (D is the acceleration ordinate of the response spectrum given on page 115 of Commentary K, and is dependent on the period and damping assumed in the analysis.)

It must be emphasized that Eq.(10) yields the peak ground acceleration implied by the quasi-static procedure, i.e. if this peak ground acceleration is used in a dynamic analysis, the resulting base shear force should correspond to the base shear force found by the quasi-static procedure.

For the Vancouver area, which is representative of zone 3, the implied peak ground acceleration is plotted against fundamental period in Fig. 1. The return period of the implied peak ground acceleration is shown in Fig. 2. The return periods are based on recent estimates of the peak ground acceleration probability relationship for Vancouver.

It can be seen that the implied peak ground acceleration and return period of the major earthquake generally increase with the period of the structure. The central solid line is based on parameters that are reasonable for a ductile reinforced concrete frame building, while the dashed lines represent bounds on the choice of parameters for other structural types.

The discontinuity in the curves at a period of about .5 seconds is due to replacing μ by $\sqrt{2\mu-1}$ for lower periods in the final equation for ground acceleration. This change is recommended by Commentary K and arises from the substitution of an equal energy criterion for the equal displacement criterion in relating the behaviour of the real structure to the hypothetical elastic model. Clearly there should really be a transition region rather than a discontinuity.

Comments

From Fig.1 we can see that for long period structures the quasi-static design procedure implies that the structure must be designed for very large peak ground accelerations. Using the upper bound curve and considering a structure with a period of 4 seconds the implied peak ground acceleration is nearly 0.7g. If the dynamic analysis procedure was used for this structure the required peak ground acceleration would be 90% of the .7g or roughly .6g. At the other end of the scale, a structure with a period of .4 seconds with the lower bound characteristics, could be designed for an implied peak ground acceleration of only 0.06g. Figure 2 shows that the implied return periods for the two mentioned examples range from 1700 to 80 years.

The preceeding results were derived directly from the Code without the authors having to make any personal judgements. Despite the apparent anomalies the Code is based on successful experience and should not be changed without considerable caution. The authors have refrained from comment to this point in the hope that the paper will stimulate discussion. However it does seem to them that the spectrum represented by S in the quasi-static procedure is in certain cases probably being extended beyond its range of validity.

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APPENDIX - NOMENCLATURE

A - peak ground acceleration for the 100 year earthquake as a fraction of gravity.

C - $0.05/\sqrt[3]{T} \leq 0.1$, seismic coefficient

D - dynamic amplification factor for acceleration for the response spectra presented in Fig. K-1 of Commentary K.

F - foundation factor - normally 1.

I - importance factor - normally 1.

K - a coefficient related to the energy absorption capacity of the structure.

R - seismic zone factor (0,1,2 or 4) corresponding to seismic zones (0,1,2 or 3) respectively.

S - $0.5/\sqrt[3]{T} \leq 1.0$, seismic coefficient.

V - base shear.

W - building weight.

β - ratio of the average acceleration of a structure to the spectral acceleration of the first dominant mode of the structure.

λ - load factor.

μ - ductility factor.

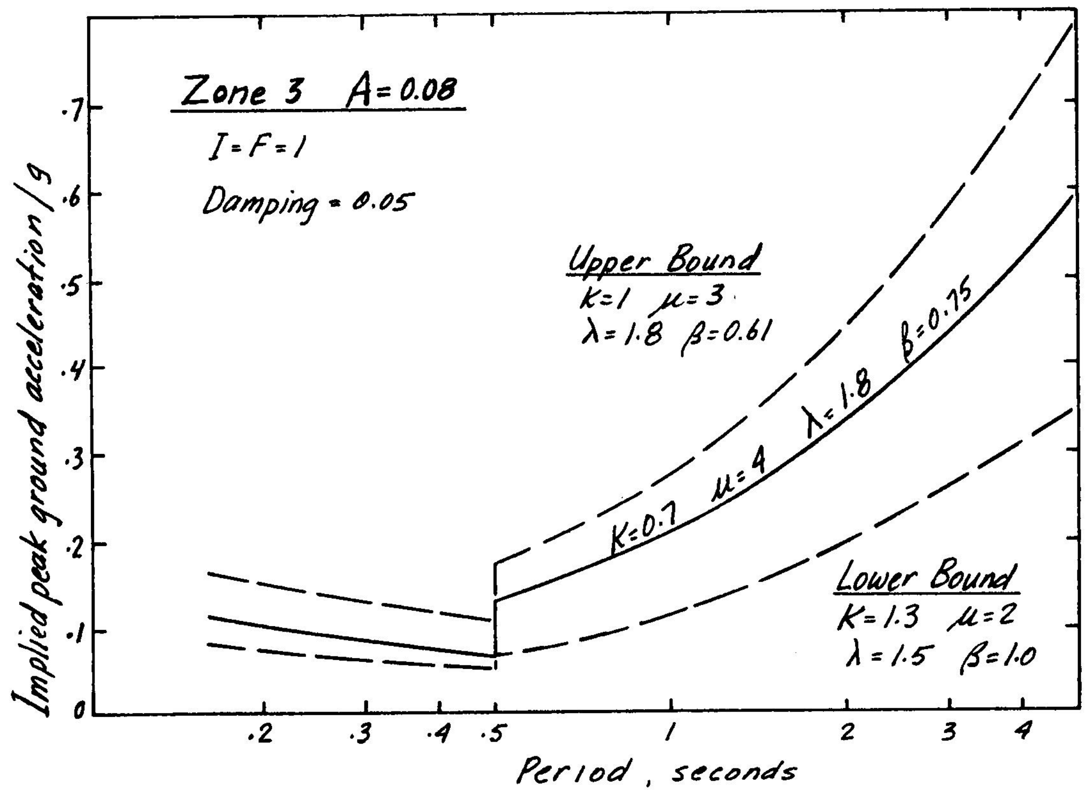

Fig. 1 Implied peak ground acceleration for zone 3 major earthquake

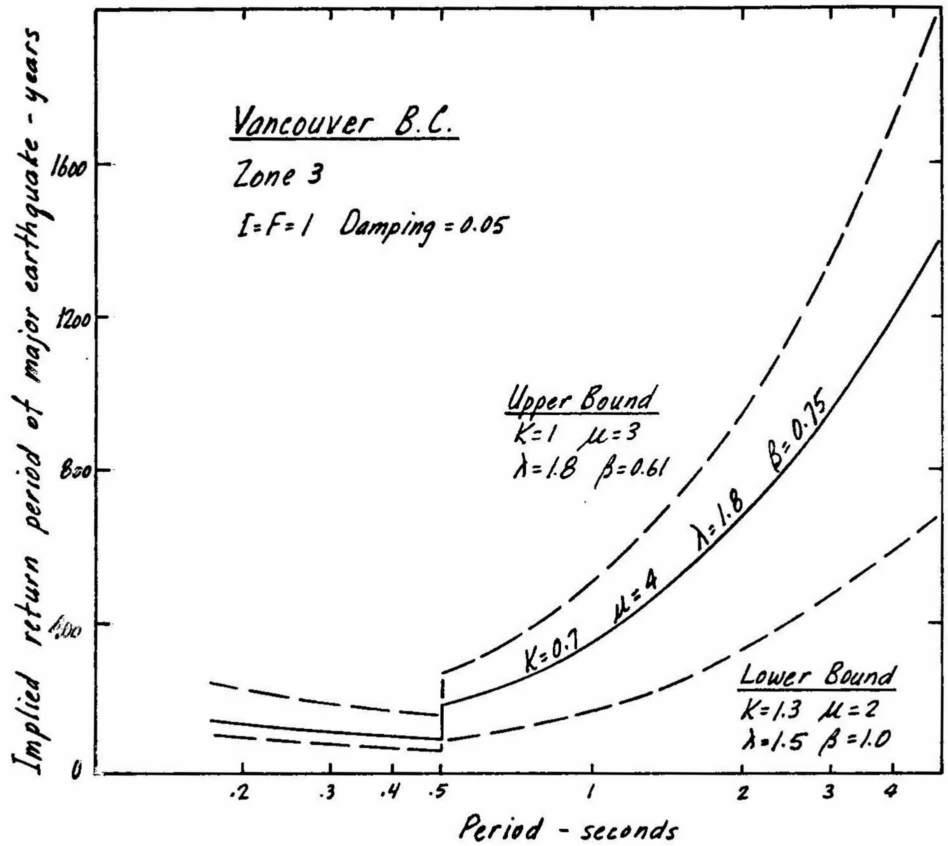

Fig. 2 Implied return period of major earthquake for Vancouver (zone 3)