A new foundation factor for the Canadian code

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ABSTRACT: Results of a parametric study on site response effects due to earthquake ground motions are used to develop a new foundation factor for the National Building Code of Canada. This foundation factor takes into account the resonance effect at the coincidence of the structure and site periods, intensity level and frequency content of the earthquake motions. The validity of the proposed foundation factor is investigated using actual sites that have been subjected to recorded earthquake motions.

1 INTRODUCTION

It is well known that site response effects have a significant influence on the behaviour of structures during strong earthquakes. The importance of these effects was especially demonstrated during the 1985 Mexico City earthquake, when site amplification caused extensive damage and collapse of many buildings. These effects depend on a number of parameters, the most important of which are characteristics of the soil, coincidence of the structure and site periods, intensity and frequency content of the earthquake motion.

In the seismic provisions of the National Building Code of Canada (NBCC) 1990 (Associate Committee on the National Building Code 1990), the site effects are represented by a foundation factor. The soil conditions are categorized into four types, and values are assigned to the foundation factor depending on soil type and depth. In order to evaluate the code foundation factor, an extensive investigation of site response has been carried out (Heidebrecht et al. 1991). One phase of this investigation is the parametric study of site response effects (Elhmadi et al. 1990). It was found that the NBCC 1990 foundation factor underestimates the effect of soil amplification, especially in the neighbourhood of the site period. Based on the results from the parametric study, a new foundation factor is proposed (Elhmadi and Heidebrecht 1991), which takes into account the resonance effect when the structural and site periods coincide, intensity level and frequency content of the earthquake motion. The purpose of this paper is to present an overview of the parametric study, and to discuss the main features of the new foundation factor.

2 PARAMETRIC STUDY

Four categories of soil deposits are considered in the parametric study. These categories are: (i) normally to lightly overconsolidated clay (NC), (ii) heavily overconsolidated clay (OC), (iii) alluvial sand and silt (AS), and (iv) dense sand (DS). For each category, four site thicknesses are considered, i.e. 5, 15, 40 and 100 m. The soil properties required for the site response analysis are based on measured data from actual sites located in eastern Canada, western Canada and the United Kingdom. Figure 1 shows the small strain shear modulus, G_0, versus depth for the four soil categories.
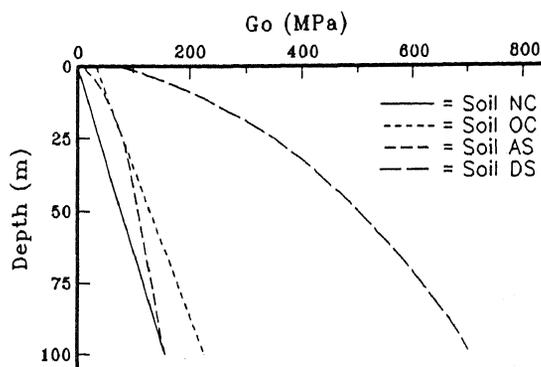

Figure 1. Low-strain shear modulus profiles for all four soil categories.

In the parametric study, the soil deposits are modeled as one-dimensional systems with propagation of shear waves only in the

vertical direction. A nonlinear response analysis is performed by using a hysteretic stress/strain relationship for the behaviour of the soil under seismic excitations.

For the seismic analysis of the soil deposits, three ensembles of actual time histories recorded on rock or stiff soil were selected. Each ensemble contains 15 different time histories. These three ensembles were chosen to represent earthquake motions with different frequency content. As the ratio of peak ground acceleration, a, to peak ground velocity, v, represents a measure of the frequency content of the seismic motion, the selection of the records was carried out based on their a/v ratios. Note that NBCC 1990 uses peak ground velocity to scale the ground motion intensity and three ranges of a/v ratio (i.e. three zonal combinations) to define different force coefficients for short period structures, with periods below 0.5 s. The three ensembles and their relationships to the zonal combinations in NBCC 1990 (Z_a>Z_v, Z_a=Z_v and Z_a<Z_v) are defined as follows: H - high a/v ratios, mean a/v ≈ 2 (a in g, v in m/s) for Z_a>Z_v; I - intermediate a/v ratios, mean a/v ≈ 1 for Z_a=Z_v; and V - very low a/v ratios, mean a/v ≈ 0.5 for Z_a<Z_v, where Z_a and Z_v represent respectively acceleration and velocity related seismic zones. The predominant periods for H, I and V ensembles are around 0.15, 0.3 and 1.0 s respectively.

For the purposes of the parametric study, all the time histories were scaled to four levels of peak ground velocity, representing different intensity levels of the earthquake motion. These levels correspond to v=0.05, 0.1, 0.2 and 0.4 m/s. For each site and value of v, surface acceleration time histories were computed using each time history in each ensemble as input motion at the base of the soil deposit (rock level). The surface motions were then used to compute dynamic foundation factors, as described in the next section.

3 DYNAMIC FOUNDATION FACTORS

For structures of normal importance, the elastic base shear, V_e, in the NBCC 1990 is defined as

$$V_e = F(vSW) \tag{1}$$

in which F is the foundation factor, having a value of 1 for rock or stiff soil sites and a value of 1.3 to 2 for other site conditions; v is the zonal horizontal velocity coefficient, equivalent to peak velocity in m/s; S is the seismic response factor or unit velocity base shear coefficient given as a function of the fundamental structural period and has three branches for periods below 0.5s; and W is the dead load. Note that NBCC 1990 bounds the base shear by specifying an upper limit on the product FS, namely, FS need not

be greater than 4.2 when Z_a>Z_v, nor greater than 3.0 when Z_a=Z_v or Z_a<Z_v.

In order to evaluate the NBCC 1990 foundation factor F, it is necessary to compare the code base shear from equation (1) with the surface base shear resulting from the response analysis. The base shear at the surface level is designated by V_s and can be expressed in the following form:

$$V_s = C_{rs}vW \tag{2}$$

where C_{rs} is the dynamic unit velocity elastic base shear coefficient for input motion at the rock level and structures located at the surface, and v is the peak velocity of the rock motion. For easier comparison, equation (2) can be rewritten as follows:

$$V_s = (C_{rs}/S)vSW = F^*(vSW) \tag{3}$$

The quantity F^* is a "dynamic" foundation factor which can be compared with F in equation (1).

In the parametric study, the base shear coefficients C_{rs} were computed for each of the surface level time histories for two types of structures, i.e. uniform frame and (shear) wall structures. Simple continuum models of frame and wall structures were used (Heidebrecht and Stafford Smith 1973). The computation was performed using five modes and 5% modal damping. For each site and each set of input motion (H, I and V ensemble; v=0.05, 0.1, 0.2 and 0.4 m/s), the mean plus one standard deviation (M+SD) dynamic foundation factors, F^*, for various fundamental structural periods, T, were computed.

The results showed that in the neighbourhood of the site period, the computed F^* factors exceed significantly those specified in NBCC 1990. As expected, the largest amplifications occur when the site period and the predominant period of the seismic motion are relatively close. Figure 2 is typical for this situation. Presented in this figure are the computed F^*
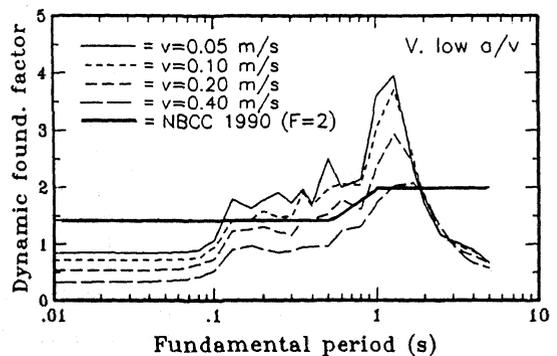

Figure 2. Dynamic foundation factor spectra for site NC, 40 m thickness; frame structures.

factors for frame structures, for site NC, 40m in depth, subjected to the V ensemble; both, the site period and the predominant period of the V ensemble are about 1 s. This figure also shows the NBCC 1990 foundation factor for this site, F=2; note that the lower level at short periods is due to the imposed bound on the product FS. It can be seen that for periods around 1 s, the computed dynamic foundation factors are much larger than the code value, especially for low intensity levels.

Figure 2 also clearly shows the effect of the intensity level, v, on the foundation factor, F^*. The values of F^* are a decreasing function of v. This is because low intensity motions·produce nearly linear responses (low energy absorbtion and damping) which lead to higher amplifications, while the opposite is true for high intensity motions.

4 PROPOSED FOUNDATION FACTOR

In order to develop a new foundation factor, examinations of various groupings of the results from the parametric study were carried out. Based on these examinations, a new classification of soil deposits and a new foundation factor are proposed for use in the NBCC. The soil deposits are classified as follows: Class 1 - deep cohesive (clay sites with depth greater than 10 m); Class 2 - deep cohesionless (alluvial sand and silt sites with depth greater than 10 m); Class 3 - shallow cohesive and cohesionless (clay, alluvial sand and silt sites with depth smaller than 10 m); and Class 4 - dense sand sites. A dynamic foundation factor, F^*, suitable for inclusion in the code is developed for each soil class, for a reference rock motion intensity corresponding to v=0.2 m/s. In order to capture the resonance effect at the site-structure period, the proposed F^* factor is given as a function of the ratio of the fundamental structural period, T, to the site period, T_s (i.e. F^* spectra in terms of T/T_s). Figure 3 shows the proposed F^* spectra for the four classes of soil deposits. As can be seen, the F^* spectra have a "trapezoidal" shape with the upper plateaus of the trapezoids in the neighbourhood of $T/T_s=1.0$. For Class 1 and Class 2, the design F^* spectra are independent of the a/v ratio; the maximum value, F^*_{max}, is 2.5 for Class 1, and 1.5 for Class 2. For Class 3 and Class 4, however, the results yield F^* spectra which depend on the a/v ratio, with maximum values of 2.5, 2.0 and 1.5 for H, I and V a/v ratio respectively. Note that the two flat low portions of the proposed spectra have $F^*=1$, indicating that there is no need to include soil amplification in those regions of T/T_s.

Because the proposed foundation factor spectra are defined for seismic motion intensity level of 0.2 m/s, a scaling coefficient, I_v, is proposed, which takes into
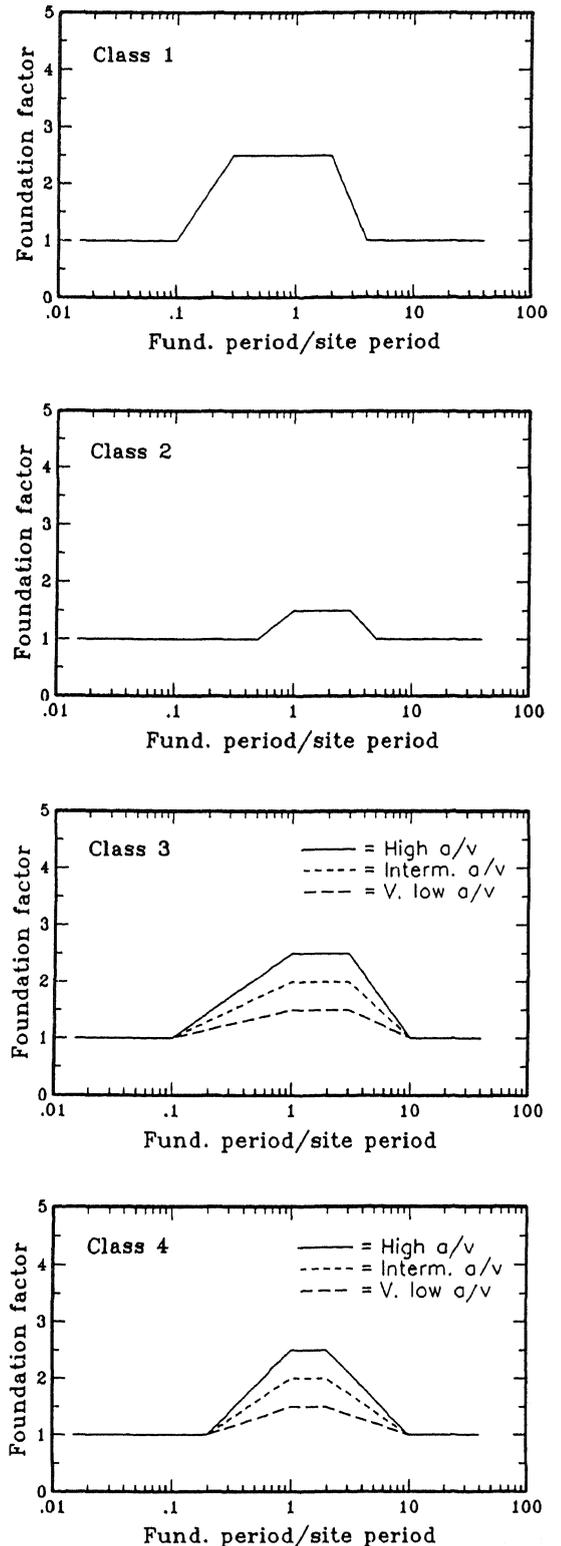

Figure 3. Proposed foundation factor spectra.

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