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Foundation Factors for Seismic Design

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ABSTRACT

Foundation factors are used in seismic codes to capture the effects of local soil conditions on ground motions, and hence, on seismic design forces. This paper reviews recent developments in the United States in categorizing site conditions for seismic codes and assigning rational values to associated foundation factors. The studies are evaluated in the context of the major review which has been undertaken of the seismic provisions of the National Building Code of Canada for the year 2000.

INTRODUCTION

The seismic provisions of the National Building Code of Canada (1990) incorporate the effects of local soil condition on design ground motions by classifying the wide variety of possible soil conditions into four categories and assigning a foundation factor, F, to each category. The foundation factors vary from 1.0 to 2.0 as shown in Table 1. F increases as the site stiffness decreases. Sites underlain by deposits of very soft to soft fine-grained soils with depths greater than 15 m are assigned a foundation factor F = 2.0. The first three foundation factors are based primarily on research on site effects reported by Seed et al. (1976). The factor F = 2.0 was added as a result of the observation of large amplifications of incoming earthquake motions in the clay deposits of Mexico City during the September 19, 1985 earthquake in Mexico due to soil-structure resonance. The factor, F, reflects experience with these soil conditions in the field, and in an approximate way integrates the effect of possible soil amplification and soil-structure resonance into the estimation of the seismic design forces for buildings having no unusual structural characteristics.

In the National Building Code of Canada (1995), the equivalent lateral seismic force representing elastic response, V_e, is given by,

Table 1 - Foundation Factors, F (NBCC, 1995)

Categories	Type and Depth of *Soil* Measured from the *Foundation* or *Pile* Cap Level	F
1	*Rock*, dense and very dense coarse-grained *soils*, very stiff and hard fine-grained *soils*; compact coarse-grained *soils* and firm and stiff fine-grained *soils* from 0 m to 15 m deep.	1.0
2	Compact coarse-grained *soils*, firm and stiff fine-grained *soils* with a depth greater than 15m; very loose and loose coarse-grained *soils* and very soft and soft fine-grained *soils* from 0 m to 15 m deep.	1.3
3	Very loose and loose coarse-grained *soils* with depth greater than 15 m.	1.5
4	Very soft and soft fine-grained soils with depth greater than 15 m.	2.0

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$$V_e = v \cdot S \cdot I \cdot F \cdot W \quad (1)$$

where v is the zonal velocity ratio, S is the seismic response factor, I is the importance factor, F is the foundation factor, and W is the weight of the building.

The factor, F, representing site conditions, appears directly in the equation for calculating the design base shear. It is evident that F can have a major impact on the elastic base shear.

Following trends towards more rational specifications of seismic design forces for buildings, extensive research efforts are being made to provide a rational basis for quantifying foundation factors and for classifying the different types of foundation soils. A interesting development is the identification of foundation conditions which should not be considered amenable to the foundation factor approach but for which specific studies should be mandated. These studies are being conducted by a consortium of Universities in the United States and by the U.S. Geological Survey (Martin, 1994; Martin and Dobry, 1994). All of these developments are under review for NBCC 2000 by the Canadian National Committee for Earthquake Engineering (CANCEE).

The objective of the paper is to review these developments in the context of potential incorporation in the Canadian code and against the background of the latest information from field data from U.S.A. and Japan (the two Hokkaido earthquakes) on foundation effects.

Before examining these developments, the effect of local soil conditions on ground motions will be reviewed briefly and some general observations will be made on the use of foundation factors to represent these effects.

GENERAL OBSERVATIONS ON FOUNDATION FACTORS

The foundation factor is an index of the effects of local soil conditions on the seismic forces generated in a structure during an earthquake. There are two key elements in establishing a foundation factor. One is to characterize a particular soil condition, and then to assign a numerical value to the foundation factor for that soil category. Two approaches are possible: one is to select a limited number of soil categories which can effectively represent the wide variety of soil conditions encountered in practice. The other approach is to devise a characterization method that allows a continuous distribution of foundation factors. Obviously the second procedure would be preferable provided that such categorization were feasible and practical. Both of these approaches have been pursued by researchers in the United States.

Local soil conditions affect ground motions through two distinct mechanisms. The lower impedances of surface layers relative to bedrock result in amplification of the incoming waves. The extent of the amplification depends on two factors, the ratio of the impedance of the bedrock to the impedance of the surface layers and, the relationship between characteristic frequencies of the surface layers and the high energy frequencies of the bedrock motions. For example, for a uniform elastic surface layer if the wave motion in the bedrock has the same period, as that of the elastic surface layer, then the amplification of the motion in the surface layer according to Okamoto (1973) is,

$$A = 2/\kappa \quad (3)$$

where κ, the impedance ratio is $\rho_S c_S/\rho_R c_R$. Here ρ is the mass density, c is the shear wave velocity and S and R refer to the surface layer and underlying rock, respectively. This equation represents the combined effects of the impedance ratio and soil-structure resonance.

If the difference in density between rock and soil is neglected and the wave velocity in the underlying regional rock is assumed constant, then the amplification due to impedance depends strongly on the wave velocity in the surface layer. The impedance approach, for site characterization, has been followed by Borcherdt (1994) who has expressed the site amplification factor as a function of the time average shear wave velocity in the top 30 m of a site, V_{30}. The characteristic of this approach to site amplification is that it provides a continuous range of amplification factors.

The softer the surface layer the lower the shear wave velocity, and the higher the impedance amplification factor. The foundation factor in NBCC (1995) shows the same trend; the softer soils have the higher amplification factors. The effect of site period cannot be captured directly by an index. The site period depends not only on the shear wave velocity but on the thickness of the surface layers. Therefore, the different thickness specifications for the foundation factors in NBCC (1995) indirectly incorporates some of the effects of site period.

Another approach, involving the use of distinct site categories as in present codes, has been followed by the NEHRP (National Earthquake Hazard Reduction Program) guidelines for seismic design. For the 1994 guidelines, a working committee has recommended that the site categories be defined by ranges in shear wave velocity in the top 30 m of the site. However, for use in practice, complementary site category definitions based on standard penetration blowcounts and undrained shear strength have been made available. The result of these changes is a clearer definition of site categories.

Both of these approaches will now be presented in summary form, beginning with the new approach recommended for the NEHRP (1994) guidelines.

SITE CATEGORIES AND FOUNDATION FACTORS RECOMMENDED FOR 1994 NEHRP GUIDELINES

In 1992, a three-day meeting was held at the University of California entitled *"Workshop on Site Response During Earthquakes and Seismic Code Provisions"*. The workshop was attended by code committee members of the major U.S. groups involved in the development of building codes, geotechnical engineers and seismologists engaged in research on site effects and representative users of code guidelines from major consulting firms. Draft proposals for new definitions of site categories and values of the associated foundation factors were presented for discussion by Borcherdt (1992), Dobry et al. (1992) and Seed (1992). These proposals have much in common and a consensus was reached on what form modifications to the existing seismic provisions for site effects should be adopted in the U.S.

Site categories were specified in terms of the average shear wave velocity, V_{30}. The recommended site categories are shown in Table 2. Site specific geotechnical investigations and dynamic site response analyses are recommended for soils falling into Category E.

A two-factor approach was adopted for constructing free-field acceleration response spectra as shown in Fig. 1. The factor, F_a, is used for the short period motion and the factor, F_v, for the longer period motion. Together the factors are intended to cover the period range from 0.2s - 3.0s.

Table 2 - Preliminary Site Classification for Seismic Site Response.

Current Categories (approx.)	Site Class	Site Class Name/Generic Description[5]	Site Class Definition[1,3,4,5]
F1	A[0]	Hard Rock	$\overline{V}_s$ > 5,000 ft/sec
F1	A	Rock	2,500 ft/sec < $\overline{V}_s$ < 5,000 ft/sec
F1 and F2	B	Hard and/or stiff/very stiff soils; most gravels	1,200 ft/sec < $\overline{V}_s$ < 2,500 ft/sec
F1 and F2	C	Sands, silts and/or stiff/very stiff clays, some gravels	600 ft/sec < $\overline{V}_s$ < 1,200 ft/sec
F3 and F4	D_1	Profile containing a small-to-moderate total thickness H of soft/medium stiff clay	$\overline{V}_s$ < 600 ft/sec and/or 10 ft < H < 50 ft
F3 and F4	D_2	Profile containing a large total thickness H of soft/medium stiff clay	$\overline{V}_s$ < 600 ft/sec and/or 50 ft < H < 120 ft
	(E)[2,6]	(E_1) - Soils Vulnerable to Potential Failure or Collapse Under Seismic Loading: (Liquefiable Soils, Quick and Highly Sensitive Clays, Collapsible Weakly-Cemented Soils, etc.). (E_2) - Peats and/or Highly Organic Clays: (H > 10 ft of peat and/or highly organic clay). (E_3) - Very High Plasticity Clays: (H > 25 ft with PI > 75%). (E_4) - Very Thick "Soft/Medium Stiff Clays" (H > 120 ft).	

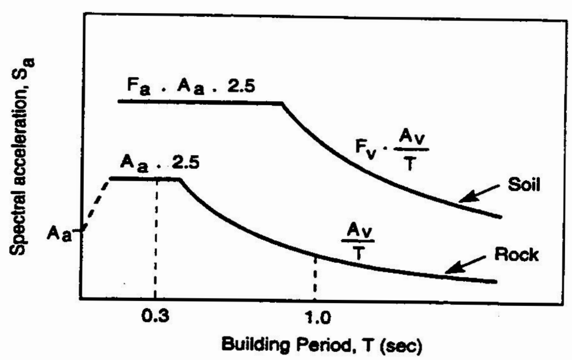

Figure 1. Development of design spectra using period dependent site amplification factors (after Martin & Dobry, 1994).

The amplification factors were drawn from the results of hundreds of site response analyses using both equivalent linear and nonlinear methods. The analyses were all calibrated first on data from the 1989 Loma Prieta earthquake. The factors, F_a and F_v, reflect the nonlinear response of soil to strong shaking. Hence, they become smaller as the acceleration increases. Values of F_a are given in Table 3, and of F_v in Table 4, for different levels of peak ground accelerations. The values for F_a are mean values. The values of F_v, derived in the research studies, were highly variable depending on site conditions and input motions. Therefore F_v values are given at the mean plus one standard deviation level.

Table 3. Values of F_a as a Function of Site Conditions and Shaking Intensity (Martin & Dobry, 1994).

Shaking Intensity ⇒ Site Class ⇓	$A_v = 0.1$ g	$A_v = 0.2$ g	$A_v = 0.3$ g	$A_v = 0.4$ g	$A_v = 0.5$ g
(A_0)	0.8	0.8	0.8	0.8	0.8
A	1.0	1.0	1.0	1.0	1.0
B	1.2	1.2	1.1	1.0	1.0
C	1.6	1.4	1.2	1.1	1.0
D_1	2.5	1.7	1.2	0.9	(--)[1]
D_2	2.0	1.6	1.2	0.9	(--)[1]
(E)	(--)[1]	(--)[1]	(--)[1]	(--)[1]	(--)[1]

[1] Site-specific geotechnical investigations and dynamic site response analyses should be performed.

Table 4 - Values of F_v as a Function of Site Conditions and Shaking Intensity (Martin & Dobry, 1994).

Shaking Intensity ⇒ Site Class ⇓	$A_v = 0.1$ g	$A_v = 0.2$ g	$A_v = 0.3$ g	$A_v = 0.4$ g	$A_v = 0.5$ g
(A_0)	0.8	0.8	0.8	0.8	0.8
A	1.0	1.0	1.0	1.0	1.0
B	1.7	1.6	1.5	1.4	1.3
C	2.4	2.0	1.8	1.6	1.5
D_1	3.5	3.2	2.8	2.4	(--)[2]
D_2	3.5	3.2	2.8	2.4	(--)[2]
(e)	(--)[2]	(--)[2]	(--)[2]	(--)[2]	(--)[2]

[2] Site-specific geotechnical investigations and dynamic site response analyses should be performed.

To facilitate the use of the site categories in practice, complementary descriptions are being developed for the site categories in terms of standard penetration resistance and undrained shear strength. These factors can be correlated to shear wave velocity for sands and clays.

CONTINUOUS SITE FACTORS

Borcherdt (1994) offers a different approach to site characterization and the specification of the amplification factors F_a and F_v. He uses V_{30} as a continuous measure of site conditions and expresses F_a and F_v as continuous functions of V_{30}.

The short period amplification factor F_a in this case, corresponds to the average Fourier spectral ratios for recorded motions over the period range 0.1s - 0.5s. Amplification factors were determined for 35 instrumented sites using records obtained during the 1989 Loma Prieta earthquake. The amplification is determined with respect to the Franciscan rock formation in California, which is designated as firm to hard rock. This classification corresponds to Category A in the NEHRP guidelines. The mid-period factor F_v is similarly defined for the period range 0.4s - 2.0s. The variation of these factors and the corresponding factors for intermediate and long period ranges are shown in Fig. 2. This figure clearly demonstrates the need to have different amplification factors for the

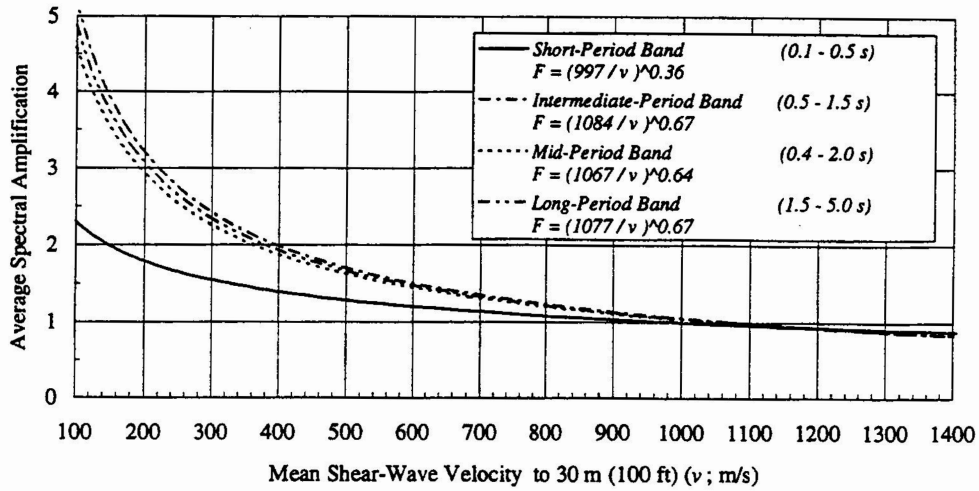

Figure 2. Average horizontal amplification factors, F, with respect to *Firm to Hard Rock* sites as a function of average shear wave velocity for different period ranges (from Borcherdt, 1994, used by permission of Earthquake Engineering Research Institute.

short-period range corresponding to the approximately constant spectral acceleration segment of the response spectrum, and the longer periods corresponding to the more or less constant velocity range. This essentially follows the approach advocated by Newmark and Hall (1982). The functional relationships between F_a, F_v and V_{30}, for the different period ranges, are given also in Fig. 2.

The amplification factors in Fig. 2 are valid up to peak bedrock accelerations up to 0.1g. For higher accelerations, the functional relationships were determined by extrapolation from the point 0.1g intensity level to the 0.4g level, using the data from the hundreds of site response analyses reported by Dobry et al. (1992) and Seed (1992).

The functional form of these equations are,

$$F_a = (1050/V_{30})^{m_a} \tag{4}$$

$$F_v = (1050/V_{30})^{m_v} \tag{5}$$

The exponents m_a and m_v depend on the intensity of shaking and are given in Table 5.

Table 5 - Values of Exponents m_a and m_v at Different Intensities of Shaking

Rock Acceleration	m_a	m_v
0.1	0.35	0.63
0.2	0.25	0.60
0.3	0.10	0.53
0.4	0.05	0.45

Borcherdt (1994) also developed a site categorization system with 5 categories which corresponds closely to the first 5 categories of the NEHRP (1994) guidelines. The categories are shown in Table 6. The amplification factors for the 5 categories are given in Table 7 as a function of the intensity of shaking. The factors compare closely with the NEHRP factors as would be expected since they are derived from the same data base.

Table 6. Definition of Site Classes (after Borcherdt, 1994).

Site Class		V_{30} m/s
SC-I		
SC-Ia	Hard rock	> 1400
SC-Ib	Firm to hard rock	700 - 1400
SC-II	Gravely soils and soft rock - thickness ≥ 10 m	375 - 700
SC-III	Stiff clays and sandy soils - thickness ≥ 5 m	200 - 375
SC-IV	Soft soils	< 200
SC-IVa	Soft soils ≤ 37 m thick	
SC-IVb	Soft soils > 37 m thick. Special study.	

Table 7 - Amplification Factors with Respect to SC-Ib (Borcherdt, 1994).

Rock Motion	Site Class - Shear Wave Velocity (m/s)				
	SC-Ia 1620	SC-Ib 1050	SC-II 540	SC-III 290	SC-IV 150
I (g)	*Short-Period Amplification Factor F_a*				
0.1	0.9	1.0	1.3	1.6	2.0
0.2	0.9	1.0	1.2	1.4	1.6
0.3	1.0	1.0	1.1	1.1	1.2
0.4	1.0	1.0	1.0	0.9	0.9
0.5					
I (g)	*Mid-Period Amplification Factor F_v*				
0.1	0.9	1.0	1.5	2.3	3.5
0.2	0.8	1.0	1.5	2.2	3.2
0.3	0.8	1.0	1.4	2.0	2.8
0.4	0.8	1.0	1.4	1.8	2.4
0.5					

CONCLUDING REMARKS

The guidelines for characterizing site conditions and assigning values for the foundation factors developed in the U.S., and the supporting data base will be a very important resource for the Canadian National Committee on Earthquake Engineering in the development of seismic provisions regarding site effects for the Year 2000 edition of the National Building Code. The data from earthquakes subsequent to the development of the NEHRP guidelines in Northridge, California, and in Japan off Hokkaido in 1994 and in Kobe in 1995, will provide valuable information. From the Northridge data, it seems that amplification factors corresponding to present site categories 1, 2 and 3, may have amplification factors less than those suggested by dynamic analysis or current values of the foundation factors. The high amplification factors in the NEHRP guidelines for low levels of excitation may not be appropriate for the large areas in Canada of low seismicity. It is also unlikely that shear wave velocity would be adopted in Canada as the sole criterion of site category. Descriptive classification may still prove the most practical with ambiguous cases being resolved on the basis of shear wave velocity or penetration resistance or undrained shear strength.

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