THE SEISMIC SITE RESPONSE IN WINNIPEG BASED ON A DATABASE OF BOREHOLE INFORMATION

Mohammad Katebi, Pooneh Maghoul, Ahmed Shalaby & Aftab Mufti
Department of Civil Engineering– University of Manitoba, Winnipeg, MB, Canada

ABSTRACT
Local topographical and geological conditions of the site (seismic site effect) have a large influence on seismic amplification of the ground shaking. From the perspective of the seismic hazard, the seismic site effects should be considered for the seismic design and land use planning. Recently, Manitoba has adopted an amendment to Manitoba Building Code (MBC) to take into account the seismic design for buildings. However, there is no available data regarding the dynamic properties of Winnipeg soil. This paper consists of a preliminary study to evaluate the seismic amplification due to soil layers and provide the design spectra for the seismic hazard of the 2475 year earthquake (2% exceedance in 50 years). For this purpose, the shear wave velocity for each layer of the soil deposits is determined by using a database of stratigraphic and in-situ tests information from reconnaissance boreholes in different locations in the City of Winnipeg.

RÉSUMÉ
Les conditions topographiques et géologiques locales du site (effets de site sismiques) ont une grande influence sur l'amplification sismique et doivent être pris en compte pour la conception parasismique pour évaluer l'aléa sismique. Récemment, le Manitoba a adopté un amendement au Code du Bâtiment du Manitoba pour tenir compte de la conception parasismique des bâtiments. Cependant, il n'y a pas de données disponibles sur les propriétés dynamiques du sol de Winnipeg. Cet article consiste en une étude préliminaire pour évaluer l'amplification sismique due aux couches de sol et fournir les spectres de conception pour le séisme maximum probable (probabilité de dépassement de 2% sur 50 ans). À cette fin, la vitesse moyenne des ondes de cisaillement pour chaque couche de sol est déterminée à l'aide d'une base de données d'essais stratigraphiques et in-situ provenant de forages de reconnaissance dans différents endroits de la ville de Winnipeg.

1 INTRODUCTION

Local topographical conditions and the geological characteristics of the site have a large influence on seismic amplification of the ground shaking. This phenomenon, known as the *seismic site effect,* is one reason that an earthquake may cause heavy damage to a building at one place, while a building of similar construction a block or two away may be completely unaffected. The amplitude, frequency content, and duration of ground motion can be affected by the site conditions. For example, during the magnitude 7.2 Vancouver Island Earthquake in 1946, most of the damaged chimneys in Port Alberni were in areas built on thick soft soils. Houses built on rock exhibited little damage.

When a soil is horizontally layered (i.e., one-dimensional (1-D) soil structure), the soil layers are predominantly subject to a horizontal motion from the bedrock. The fundamental phenomenon responsible for the ground motion amplification over soft sediments in a 1-D soil structure is that the energy content of incoming waves are assumed to be constant while traveling from the bedrock into the soft soil. The speed of waves, however, is much slower in soft soil compared to the bedrock so the amplitude of the waves increases to maintain a constant energy content. As a result, in soft soils, waves are slower but with larger amplitudes, while in bedrock waves are faster with smaller amplitudes. When the surface sediments form a two-dimensional (2-D) or three-dimensional (3-D) structure, i.e., lateral heterogeneities such as thickness variations are present, the wave trapping affects the surface waves which develop on these heterogeneities, and thus reverberate back and forth.

From the point of view of considering geotechnical and safety hazards, it is important to study how local topographical and geological characteristics will impact infrastructure response to seismic movements.

Some building codes such as National Building Code of Canada 2015 (NBCC) consider 1-D site effects for only one layer of soil for the structural design. 2-D and 3-D solutions are often considered too complex to be imported, in a practical way, into building codes in order to be implemented by engineers. NBCC 2015 classifies the soil condition of a site into six levels from A to F based on the average shear velocity in the top 30 m of the site, $V_{s,30}$. Using the soil classification in NBCC 2015 in conjunction with 2015 seismic hazard maps of Canada, one is able to determine the seismic spectrum for the structural design corresponding to any location in Canada. While this approach is very effective and easy to be used by engineers, it might underestimate the seismic site effects not only because of the one-dimensional limitations of the solution but also because of oversimplifying the dynamic properties of ground's multi-layered structure.

Recently, Manitoba has adopted an amendment to Manitoba Building Code (MBC) to take into account the seismic design for buildings and provide direction to its consultants and design-build contractors. However, there is currently no available data regarding the dynamic properties of Winnipeg soil.

This paper is a first-attempt to develop a seismic microzonation map for the City of Winnipeg. The objective of seismic mircozonation is the determination of the spatial distribution of the amplification of ground motion (e.g. ground acceleration, response spectrum) resulting from local soil structure and, if necessary, from the topography of the rock basement (2D and 3D effects of sedimentary valleys). This requires large-scale mapping of the distribution of soft soils and their physical properties using geological, geotechnical and geophysical methods. Thereby, the previously determined spectral response for the firm ground (2015 seismic hazard maps of Canada, site class C) can be modified for the actual local conditions using the site-specific spectral response obtained for the site investigated in the microzonation study.

In this paper, a nonlinear earthquake site response analyses of layered soil deposits for the city of Winnipeg is carried out using the computer program NERA. Borehole logs around the city are used to gather information about the stratigraphy of the Winnipeg soil. The empirical relationships provided in the literature are used to approximately estimate the shear wave velocity of each soil sub-layer. The results of the study in the form of response spectra in different areas of the city are compared with the response spectra developed by NBCC 2015. Finally, a design spectra is presented as an estimation of the spectral response of the layered soil deposits of Winnipeg based on information from twenty boreholes.

2 GEOTECHNICAL INVESTIGATION

‘’*Winnipeg is situated in the flat terrain of the Canadian prairies on the bed of former glacial Lake Agassiz. Underlying the city is a stratified deposit of lacustrine clays and silts with unique engineering properties; in particular volume change potential and low residual shear strengths. The till deposits that underlay the lacustrine clay can be cemented or non-cemented, may contain cobbles and boulders and are often water bearing.*’’ (Skaftfeld 2014).

Twenty boreholes are selected from different locations in Winnipeg in a manner to best represent the layered deposits of the sediment. The locations of the boreholes are shown in Figure 1. The boreholes are to the depth of the bedrock. Based on the borehole information, the soil of Winnipeg is mainly clay and silt with trace of sand and gravel. Table 1 gives a general description of soil layers according to the borehole logs. The depth to the bedrock varies from 5.5 m to 17.8 m. The shallow bedrock in Winnipeg is mainly limestone. The quality of the shallow limestone bedrock in Winnipeg varies significantly from place to place. The shear wave velocity of the bedrock depends on various factors such as the fracture spacing, fracture density, hardness and weathering. Unfortunately, there is no information regarding the shear wave velocity of the limestone bedrock in Winnipeg. As a result, the SPT values from the boreholes are used to estimate the shear wave velocity of the shallow limestone bedrock using different published correlations according to Wair et al. (2012). The shear wave velocity of the shallow limestone bedrock is estimated to be 500 m/s with the unit weight of 22 kN/m^3.

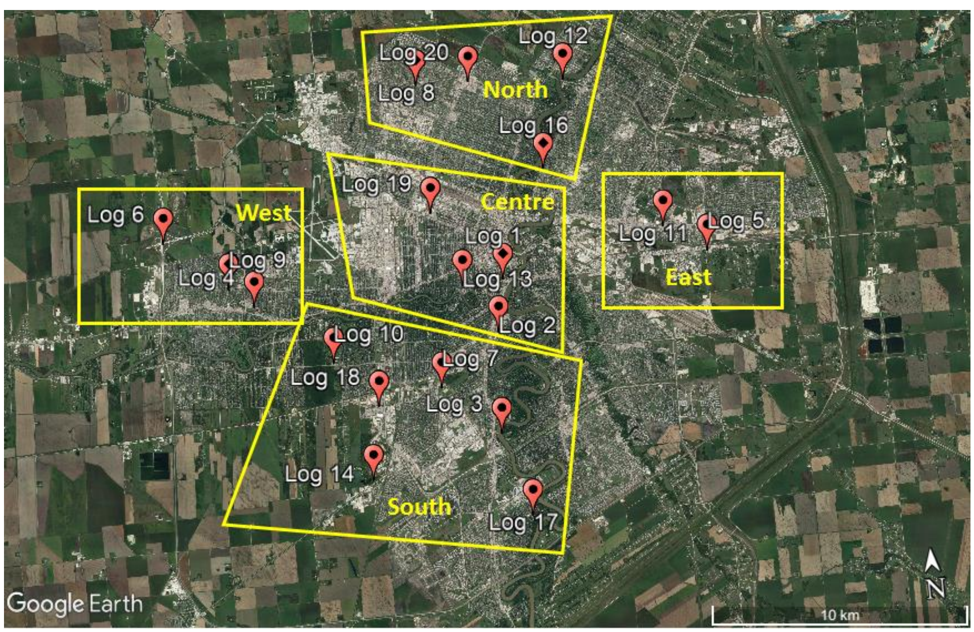

Figure 1. The locations of boreholes

For soil layers, the undrained shear strength is mainly used to estimate the shear wave velocity using Equation 1 according to Dickenson (1994):

$$V_s = 23\, {S_u}^{0.475} \qquad [1]$$

where V_s is measured in m/s and S_u is measured in kPa. The undrained shear strength is measured for every meter of the soil by Torvane and Pocket Pen. The unit weight of the soil used in the analysis, determined from the standard unit weight test (ASTM D7263), is included in the borehole logs. The soil is divided into several layers (typically four) with regard to the dynamic properties of the soil and the depth of the water table as shown in Table 1.

Table 1. Summary of borehole information

Borehole	Number of layers	Depth to bedrock (m)	General soil description	Shear Wave Velocity (m/s)	Unit weight range (kN/m^3)
1	6	13.5	2m of clay fill, mainly clay (Lacustrine)	70 - 180	16.5 – 19.0
2	5	14.6	1m of clay fill, mainly high plastic clay with trace of sand	100 - 150	16.5 – 18.0
3	6	15.3	10 m of silty clay (alluvial); 1 m of sand and gravel; 2 m of clay (Glaciolacustrine)	100 - 160	17.5 - 18.7
4	4	10	1 m of clay fill; 2 m of high plasticity clay; 3 m of low plasticity silt till	100 - 230	16.5 – 20.0
5	4	18.3	1 m of clay fill; 1 m of sand fill; 16.3 m of clay; trace of sand and gravel	90 - 140	16.5 - 19.2
6	4	5.5	4 m of Silty clay; 1.5 m of silt till with some sand and gravel	140 - 180	17.0 - 18.2
7	3	10	7 m of silty clay; 3 m of silt till with trace of sand and gravel	140 - 180	17.0 - 18.2
8	5	16.5	13 m of Silty clay; 3 m of silt (till)	140 - 160	16.3 - 18.5
9	6	14	1.5 m of clay fill; 1.5 m of clay (alluvial); 2.5 m of clay (lacustrine); 2 m of silt (till); 6.5 calcareous mudstone	130 - 180	16.5 – 20.0
10	4	11.5	1 m of clay fill; 7 m of high plasticity clay; 3.5 m of silt till	150 - 230	16.5 - 18.2
11	5	16.8	1 m clay fill; 13.5 m clay; 2.3 m of silt	120 - 160	16.5 - 18.5
12	7	17	1.5 m clay (alluvial); 13.5 m clay (lacustrine); 2 m silt	90 - 200	17.0 - 18.8
13	7	12.8	9.5 m clay; 3.3 m silt (till)	130 - 280	16.5 - 19.2
14	6	17	12.5 m of clay; 4.5 m of silt (till);	90 - 190	16.5 - 18.2
15	5	7.7	1.5 m clay fill; 1.5 m clay (alluvial); 3 m clay lacustrine; 1.7 m silt (till)	150 - 200	17.5 - 18.2
16	3	14.5	3 m clay (fill); 11.5 clay (silty)	120 - 150	16.0 - 16.8
17	7	17.8	0.5 m sand and gravel fill ;15 m clay; 2.3 m clay (till)	100 - 190	17.0 – 18.0
18	5	13.2	11.5 m silty clay; 1.7 m silt (till)	120 - 210	16.0 – 18.0
19	5	15.5	1.5 clay (fill); 1.5 m silt and clay with trace of sand and gravel; 11.5 m silty clay; 1 m silt (till)	90 - 160	16.2 – 18.0
20	4	15.5	1.5 m low plasticity silt; 12 m silty clay; 2 m silt (till)	120 - 220	16.5 – 18.0

The stress-strain behaviour of soil is an important factor for the seismic analysis, and the soil shear modulus (G) is strongly dependent on the strain level. By knowing the maximum shear modulus of the soil, the shear response at different strain levels can be calculated using published modulus reduction curves. In this study, the maximum shear modulus is calculated using Equation 2:

$$G_{max} = \rho . V_s^{\,2} \qquad [2]$$

The modulus reduction curve for clay published by Seed and Sun (1989) is used for this analysis as shown in Figure 2.

3 SEISMIC ANALYSIS

Seismic site response analysis is carried out in order to develop the site response spectra of top-of-soil in Winnipeg given the rock input motion. NERA program (Bardet and Tobita 2001) is used to model the waves propagated through the layered soil deposit, and the top-of-soil motions are estimated. NERA stands for Nonlinear Earthquake Response Analysis and was developed in 2001 based on the material model introduced by Iwan (1967) and Mroz (1967). NERA is basically configured according to SHAKE (Schnabel et al. 1972) and incorporates the more advanced theories for modelling the nonlinear behaviour of soil during earthquakes. The governing equation in a 1-D ground response analysis, as solved by the program, is presented in Equation 3:

$$\rho \frac{\partial^2 d}{\partial t^2} + \eta \frac{\partial d}{\partial t} = \frac{\partial \tau}{\partial z} \qquad [3]$$

Where, ρ is the soil density, d is the horizontal displacement, z is the depth, t is time, τ is the shear stress, and η is the mass-proportional damping coefficient.

3.1 INPUT MOTION

Selection of a proper input motion for the analysis is important due to uncertainties of earthquakes. According to guidelines such as *EM 1110-2-6050* (*1999*), more than one time-history bedrock motion should be used as the input motion for the analysis. The input motion should be representative of the rock motion of the site with respect to duration and the rock spectra.

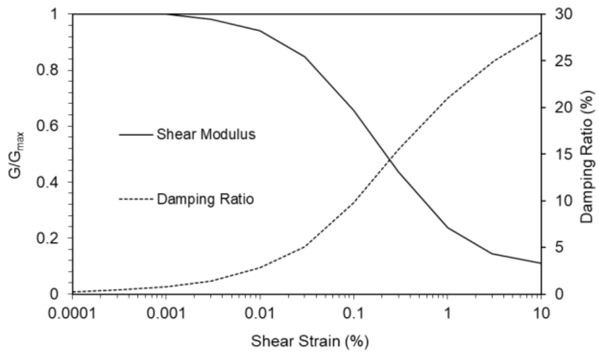

Figure 2. The shear modulus variation versus shear strain for clay

In this study, two historical earthquakes in Canada are used for analysis. Both ground motions are scaled to the peak ground acceleration of 2475 year earthquake of Winnipeg, which is 0.032g based on 2015 seismic hazard maps of Canada. The input motions used in this study are the 1988 Saguenay earthquake in Quebec with a magnitude of 5.9 Richter, Figure 3a, and the 2007 British Columbia earthquake with a magnitude of 5.6 Richter, Figure 3b.

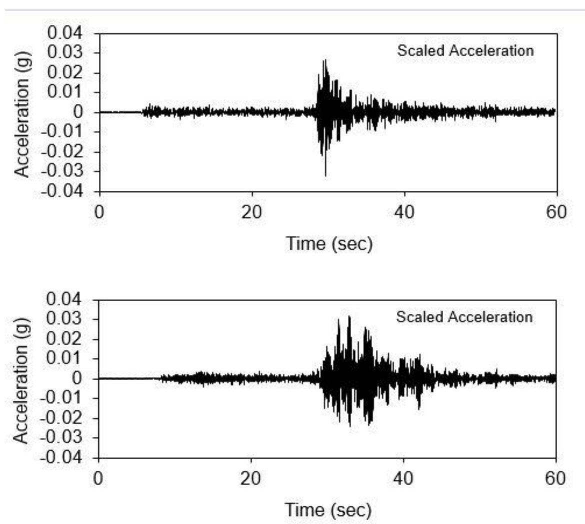

Figure 3. Scaled accelerogram data for: a) 1988 Saguenay earthquake in QB b) Jan. 9th, 2007 earthquake in BC

4 RESULTS

The seismic analysis is carried out for twenty boreholes and for each, as mentioned above, there are two different earthquakes as input motions. In total, there are forty (40) spectral response curves shown in Figures 4 to 8. They show the response spectra for Centre, West, North, South and East of Winnipeg respectively. The response spectra curve based on NBCC 2015 is also developed and plotted for comparison in each figure.

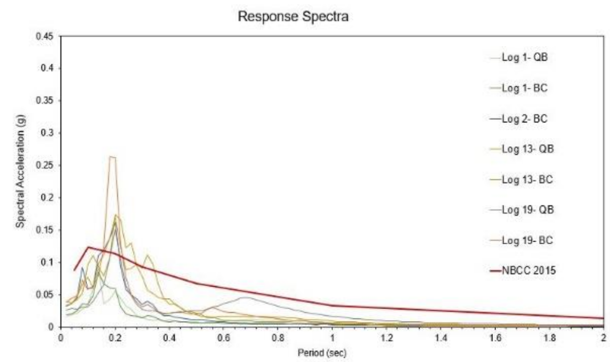

Figure 4. Response spectra for Winnipeg Centre

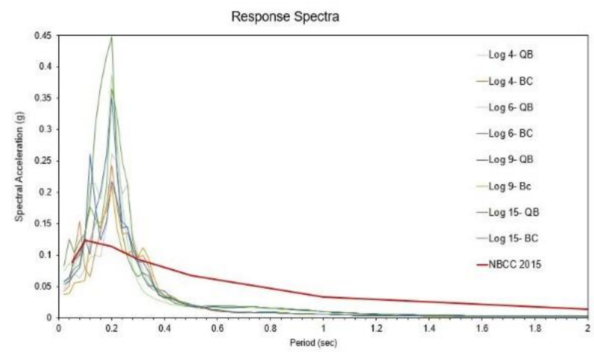

Figure 5. Response spectra for Winnipeg West

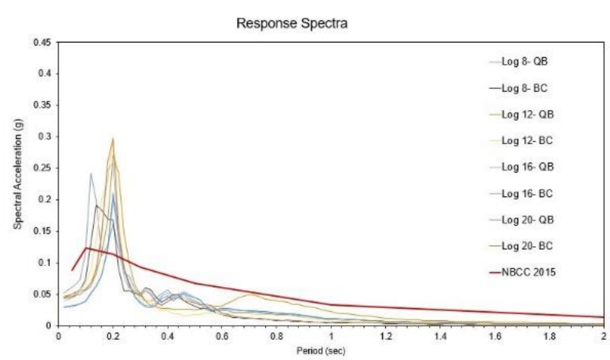

Figure 6. Response spectra for Winnipeg North

As shown in these figures, the response spectra developed based on NBCC 2015 for Winnipeg is conservative for structures with fundamental period greater than 0.4 seconds while it underestimates the response of structures with fundamental periods lower than 0.4 seconds. Since many low-rise buildings have a fundamental period less than 0.4 sec, the use of NBCC 2015 response spectra is not recommended for such structures. For this reason, the spectra for the city of Winnipeg based on the results of this study is smoothed and presented for design purposes in Figure 9 according to clause 1-6-2-1-4 of FEMA 356 (*Council, Building Seismic Safety 2000)* for risk levels equivalent to 2475 years. Table 2 presents site specific response acceleration parameters used to build the design spectra.

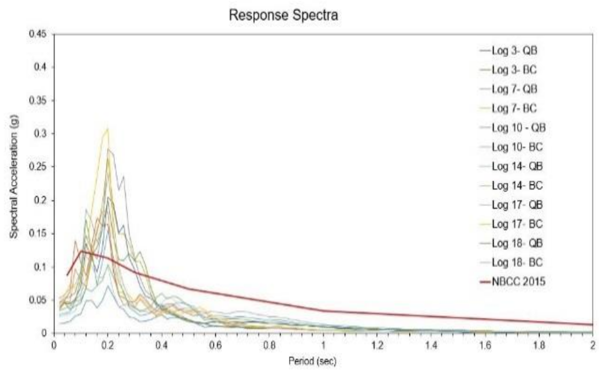

Figure 7. Response spectra for Winnipeg South

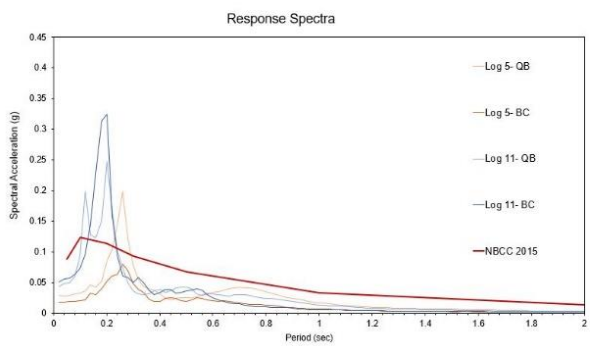

Figure 8. Response spectra for Winnipeg East

S_{XS} is the design response spectra at short-periods that should be selected from the site-specific response spectra at a period of 0.2 second and it should not be taken lower than 90% of peak acceleration of all periods. S_{XI} is the spectral response at period of 1 second. T_s, and T_0 is calculated by Equation 4 and Equation 5 respectively.

$$T_s = \frac{S_{XI}}{S_{XS}} \quad [4]$$

$$T_0 = 0.2T_s \quad [5]$$

It should be noted that the smoothing of design spectrum is carried out in order to remove the ups and downs in the response spectrum that are not desirable for design purposes. This is due to the challenges in determining modal shapes and frequencies of structures during intensive earthquakes when the behaviour of the structure is mostly nonlinear.

Table 2- Site specific response acceleration parameters

T_0	T_s	S_{XI}	S_{XS}	$PGA\ (g)$
0.03	0.17	0.05	0.3	0.032

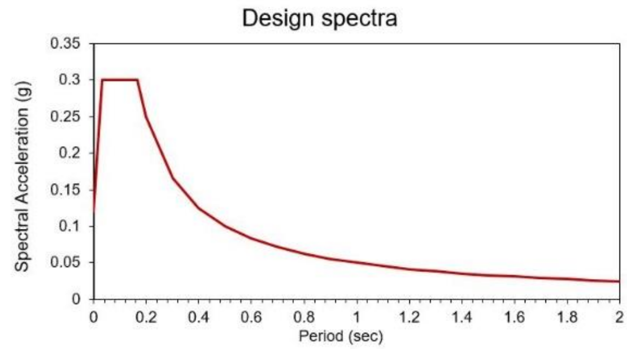

Figure 9. 2475-year earthquake design spectra for the city of Winnipeg

5 CONCLUSION

This paper is a first attempt to establish the design spectra for the city of Winnipeg soils based on borehole information. Published correlations are used to estimate the shear wave velocity in each layer, and a nonlinear earthquake response analysis is carried out using NERA. Two different Canadian time-history ground movement measurements are used as input motions for the analysis. The input motions are scaled to the peak ground acceleration of 2475 year earthquake of Winnipeg. This preliminary analysis showed that design spectra developed from NBCC 2015 are not reliable for structures with fundamental period lower than 0.4 seconds. Depending on the depth to the bedrock, depth of the water table, and dynamic properties of the soil layers the spectral acceleration can reach a maximum of 0.45 g.

For design purposes, the design spectra is developed using an average of the spectral response of all the boreholes used in this study. The design spectra presented in Figure 9, developed according to clause 1-6-2-1-4 of FEMA 356, is an estimate of the spectral response of the layered soil deposits of Winnipeg based on information from 20 boreholes.

The reliability of the design spectra developed in this paper can be enhanced by increasing the number of boreholes. Also, due to the lack of dynamic properties of Winnipeg soils, published correlations are used to estimate the shear wave velocity of the layered soil and bedrock. Further investigations are needed to measure the shear wave velocity of soil and bedrock directly. Some of the common methods for measuring the shear wave velocity include: Seismic Refraction Survey, Seismic Reflection Survey, Surface Wave Methods, Crosshole Method, Downhole Method and Suspension Logging.

6 ACKNOWLEDGEMENTS

This research was partially supported by University Research Grants Program (2018), University of Manitoba. We thank Prof. B. Gatmiri (*Transition écologique et solidaire,* Paris, France) who provided constructive comments that greatly assisted this research. We would also like to show our gratitude to TREK Geotechnical for sharing their database of reconnaissance boreholes in the City of Winnipeg during the course of this research.

7 REFERENCES

Bardet, J. P., & Tobita, T. (2001). NERA, A computer program for Nonlinear Earthquake site Response Analyses of layered soil deposits. Univ. of Southern California.Council, Building Seismic Safety (2000). "Prestandard and commentary for the seismic rehabilitation of buildings." Report FEMA-356, Washington, DC.

Dickenson, S. E. (1995). Dynamic response of soft and deep cohesive soils during the Loma Prieta Earthquake of October 17, 1989.

EM 1110-2-6050 (1999), Response Spectra and Seismic Analysis for Concrete Hydraulic Structures. U.S. Army Corps of Engineers - Engineer Manual.

Iwan, W. D. (1967, September). On a class of models for the yielding behavior of continuous and composite systems. ASME.

Mroz, Z. (1967). On the description of anisotropic workhardening. Journal of the Mechanics and Physics of Solids, 15(3), 163-175.

Schnabel, P. B. (1972). SHAKE a computer program for earthquake response analysis of horizontally layered sites. EERC Report, Univ. of California, Berkeley.

Skaftfeld, K. (2014). Experience as a guide to geotechnical practice in Winnipeg. M.Sc. Thesis, University of Manitoba.

Sun, J. I., Golesorkhi, R., & Seed, H. B. (1988). Dynamic moduli and damping ratios for cohesive soils. Berkeley: Earthquake Engineering Research Center, University of California.

Wair, B. R., DeJong, J. T., & Shantz, T. (2012). Guidelines for estimation of shear wave velocity profiles. Pacific Earthquake Engineering Research Center.