Effects of frequency content on dynamic slopes stability for Eastern Canada clays

Jonathan Mole, Mourad Karray and Mahmoud N. Hussien
Department of Civil Engineering, Faculty of Engineering, Sherbrooke University, Sherbrooke, Qc, Canada

Marie-Christine Delisle, Pascal Locat, Rémi Mompin and Catherine Ledoux
Ministère des Transports, de la Mobilité durable et de l'Électrification des transports du Québec, Qc, Canada

ABSTRACT
The pseudo-static approach consists in the replacement of the earthquake's action by a constant inertial force applied to the potentially unstable mass. This method is widely criticized since it ignores the dynamic aspect of the problem and more particularly the earthquake effect on the shear strength of the slope material. The spectral pseudo-static method, more suitable for the seismic analysis of clay slopes, has been developed at the Université de Sherbrooke in collaboration with Ministère des Transports, de la Mobilité durable et de l'Électrification des transports du Québec (MTMDET) between 2011 and 2017. Within this method, the action of the earthquake is replaced by an inertial force that varies with depth kh(z). An extensive parametric study has been performed to define the main features of the developed approach by taking into account the effect of the slope geometry, the dynamic soil properties, the natural period of the deposit, and the seismicity of the region as defined by NBCC. The method has been implemented into the limit-equilibrium software SVSVLOPE from Soil Vision © and thus it has become available for the everyday practice. In this study, the spectral pseudo-static approach is extended with the consideration of the earthquake's frequency content variation for proposition of kh(z) coefficients compatible with the regional seismicity of different seismic zones as defined by the Quebec Hydrique Expertise Center (CHEQ).

RÉSUMÉ
L'approche pseudo-statique consiste à remplacer l'action du séisme par une force d'inertie constante appliquée au centre de gravité de la masse potentiellement instable. Cette méthode est largement critiquée car elle ignore l'aspect dynamique du problème et plus particulièrement l'effet sismique sur la résistance au cisaillement du matériau de la pente. La méthode pseudo-statique spectrale, plus adaptée à l'analyse sismique des pentes argileuses, a été développée à l'Université de Sherbrooke en collaboration avec le Ministère des Transports, de la Mobilité durable et de l'Électrification des transports du Québec entre 2011 et 2017. Dans laquelle, l'action du tremblement de terre est remplacée par un force d'inertie variable avec la profondeur kh (z). Une vaste étude paramétrique a également été réalisée pour définir les principales caractéristiques de l'approche développée en tenant compte de l'effet de la géométrie de la pente, des propriétés dynamiques du sol, de la période naturelle du dépôt et de la sismicité de la région tel que défini par le CNBC. La méthode a été implémentée dans le logiciel d'équilibre limite SVSVLOPE de Soil Vision © et devient ainsi disponible pour utilisation dans la pratique. Dans cette étude, l'approche pseudo-statique spectrale est élargie avec la prise en compte de la variation du contenu fréquentiel du séisme pour la proposition de coefficients kh (z) compatibles avec la sismicité régionale des différentes zones sismiques définies par le Centre d'Expertise Hydrique du Québec (CHEQ).

1 INTRODUCTION

The pseudo-static approach is one of the first procedures used to examine the seismic stability of slopes, where the earthquake effects are replaced by a constant horizontal force applied at center of gravity of the potentially unstable soil mass (Terzaghi 1950). The use of the pseudo-static approach would be quite justified if the accelerations are constant over the entire soil mass. However, careful examination of the spectral acceleration ratios at different points within a given slope through rigorous numerical analysis showed that the assumptions made in the pseudo-static procedure are superficial approximations and overly conservative (Karray et al. 2017a) and thus lead, in many cases, to underestimation of factor of safety. In addition, the selection of the pseudo-static coefficient, *kh*, is based on the judgment and the accumulated experience from slope behavior during past earthquakes. This approach therefore does not have a rational basis for seismic coefficient selection and does not take into account the possible loss of shear strength and the degradation of the soil rigidity during earthquake events. However, the pseudo-static method provides a useful way to study the stability of slopes under seismic loads, especially for soils that do not lose a significant part of their resistance. The most important advantage of the method is its simplicity as well as its similarity to conventional static limit-equilibrium analyses.

Terzaghi (1950) proposed values for the pseudo-static coefficient, *kh*: 0.1 for severe earthquake event, using to Rossi-Forel scale IX (Partial or total destruction of buildings); 0.25 for violent, destructive earthquake, Rossi-Forel scale X (Great disaster, ruins, disturbance of the strata, fissures in the ground, rock falls from mountains); and 0.5 for catastrophic earthquakes. The coefficient ranges between 0.1 and 0.15 as proposed by Makdisi and

Seed (1978). Selection of *kh* is afterwards done quantitively. Ambraseys (1960) pointed out that earth dams are neither rigid nor perfectly elastic bodies. As a result, their seismic response increases with elevation as confirmed by field observations and laboratory tests. For this particular reason, the USSR code of 1957 proposed a variable coefficient according to the geometry of earth dams, critical damping and spectral intensity. In addition, Makdisi and Seed (1979) proposed a coefficient between 0.1 and 0.15, calculated on the basis of acceleration multipliers of 0.5 and 0.2, and reference accelerations of 0, 2 *g* and 0.75 *g*, respectively. They also recommend a reduction in the used soil shear strength by 20%. Based on the early US Four-Zone Seismic Map, according to Algermissen (1969), the pseudo-static coefficient varies between 0 and 0.27 within these zones. In 1970, the US Army Corps of Engineers published another map dividing the United States and Puerto Rico into five zones based on the probability of damage; The pseudo-static coefficient, in the new map, varies between 0 and 0.15. Seed (1979) reported that in the United States the coefficient values are typically between 0.05 and 0.15 and in Japan its values are generally less than 0.2. He has also provided the design seismic coefficient used in many earth dams around the world; these coefficients varied between 0.1 and 0.15 except in Chile where its maximum value reached 0.2 and the resulting factor of safety was between 1.0 and 1.5. Marcuson III and Franklin (1983) have proposed, based on their experience, that *kh* varies from one-third to one-half of the maximum acceleration to which the embankment could be subjected, including any amplification of acceleration at rock by the foundation or embankment to ensure a factor of safety greater than 1. Hynes-Griffin and Franklin (1984), based on permanent displacement analyses, provided a rather rational basis for choosing the value of the seismic coefficient, and they proposed that the value of *kh* is between 0.05 and 0.20.

In an effort to propose an alternative to the conventional pseudo-static approach, the concept of the spectral pseudo-static procedure has been developed at the Université de Sherbrooke in collaboration with the Ministère des Transports, de la Mobilité durable et de l'Électrification des transports du Québec, Québec, Canada for the analyses of seismic stability of clayey slopes. The development of the spectral pseudo-static procedure was primarily based on detailed static, dynamic, and conventional pseudo-static analyses using the two-dimensional (2D) computation code, FLAC 7 (Itasca, 2007). The approach has been developed to take into account variation of dynamic properties such as plasticity index, as well as consideration of the seismic zone where the deposit under study is located (Karray et al. 2018a). The work presented in this paper aims to extend the proposed approach with consideration of frequency content with different signal spectrums, from earthquakes compatible with seismicity of Eastern Canada.

2 DEVELOPMENT OF SPECTRAL PSEUDO-STATIC APPROACH

By quantifying the variation of spectral acceleration at different locations in a deposit, Ghobrial et al. (2017) agreed that spectral acceleration follows more or less a transcendental function. In practice, the maximum acceleration at the base of the deposit and at the surface can be similar. However, these values are not representative of the global movement of the deposit, since the acceleration at its base can be transported by a frequency very different from that at the surface. The accelerations must be compared for the same frequency which represents the propagation of a wave of a certain length having a movement in one direction or the other on the height of the deposit. The ground motions that belong to the potentially unstable surface are synchronized for waves that propagate at frequencies close to the natural frequency of deposition. This generally implies that the movements of the soil layers within the potentially unstable volume are within the same direction and that the hypothesis of replacing the seismic action by a constant force applies. This constitutes the principle of the spectral pseudo-static approach.

Spectral pseudo-static analyses (with a variable *kh* coefficient) were performed in order to develop a formula for a variable seismic coefficient leading to the same factor of safety and practically the same slip surface as that of the dynamic analysis. This formula must take into account the geometry of the slope as well as the dynamic properties of the seismic movement and the ground. Examination of the variation of the spectral acceleration inside the deposit shows that the inertial force varies with the depth so that it is minimal at bedrock level and gradually increases to its maximum at the surface. The optimization of the function *kh (z)* requires the comparison between the results of the dynamic analyses and those of the pseudo-static analyses. Static analysis, dynamic analysis and conventional pseudo-static analysis were performed. Proving that the conventional pseudo-static analysis failed to predict the failure surface obtained by the dynamic analysis, where factor of safety and slip surfaces using pseudo-static method strongly disagree with those of dynamic analysis (**Error! Reference source not found.**). Based on these result, a spectral pseudo-static approach was developed. Variable seismic coefficient was proposed using this formula:

$$k_h(z) = k_{ho}\left[1 + a(z/H_t)^b\right] \quad [1]$$

Where *kho* is the seismic coefficient on rock (initial value); *Ht* is the total height of the deposit, *a* and *b* are two coefficients that affect the shape and position of the slip surface, and *z* represents the variation of the height measured from the bedrock level. It was found that *a* and are *b* generally equal to 2, except for slope heights equal to 5 m, where these coefficients may vary.

2.1 Incorporation of spectral pseudo-static method in SVSLOPE software

In this section, the principles in which the spectral pseudo-static analysis can be performed using limit-equilibrium methods is explained. Using the hyperbolic function in Equation 1, implementation into limit-equilibrium software SVSLOPE from Soil Vision (Fredlund and Thode 2011) has been performed as described in Karray et al. (2017 b.)

The method has been validated for numerous configurations. The dynamic factor of safety can therefore be estimated with the soil discretization using a simplified slice method (which ignores the internal forces in-between the slices), as proposed by Karray et al.2017b.

This lead to account of seismic force for determination of factor of safety using the following formula:

$$F.S._{d} = r\frac{\sum C_{ui}l_i}{\sum W_j \sin(\alpha_i)+\sum k_{hz}W_j\cos(\alpha_j)} \quad [2]$$

The introduction of a variable seismic force according to the position in the deposit makes it possible to calculate the moment of the driving forces for each of the slices, discriminated horizontally and vertically. The vertically discrimination of the slices is to consider the variable seismic force with the depth as well as the variable undrained shear strength. The program first calculates the critical factor of safety under static conditions. Then the analysis is conducted using the seismic inertial forces. The program therefore calculates the radius of the circle and center of the circle to assess critical slip surface. It also presents the variation of the static and the pseudo-static safety coefficient as a function of the variation of the coordinates of the center of the slip surface.

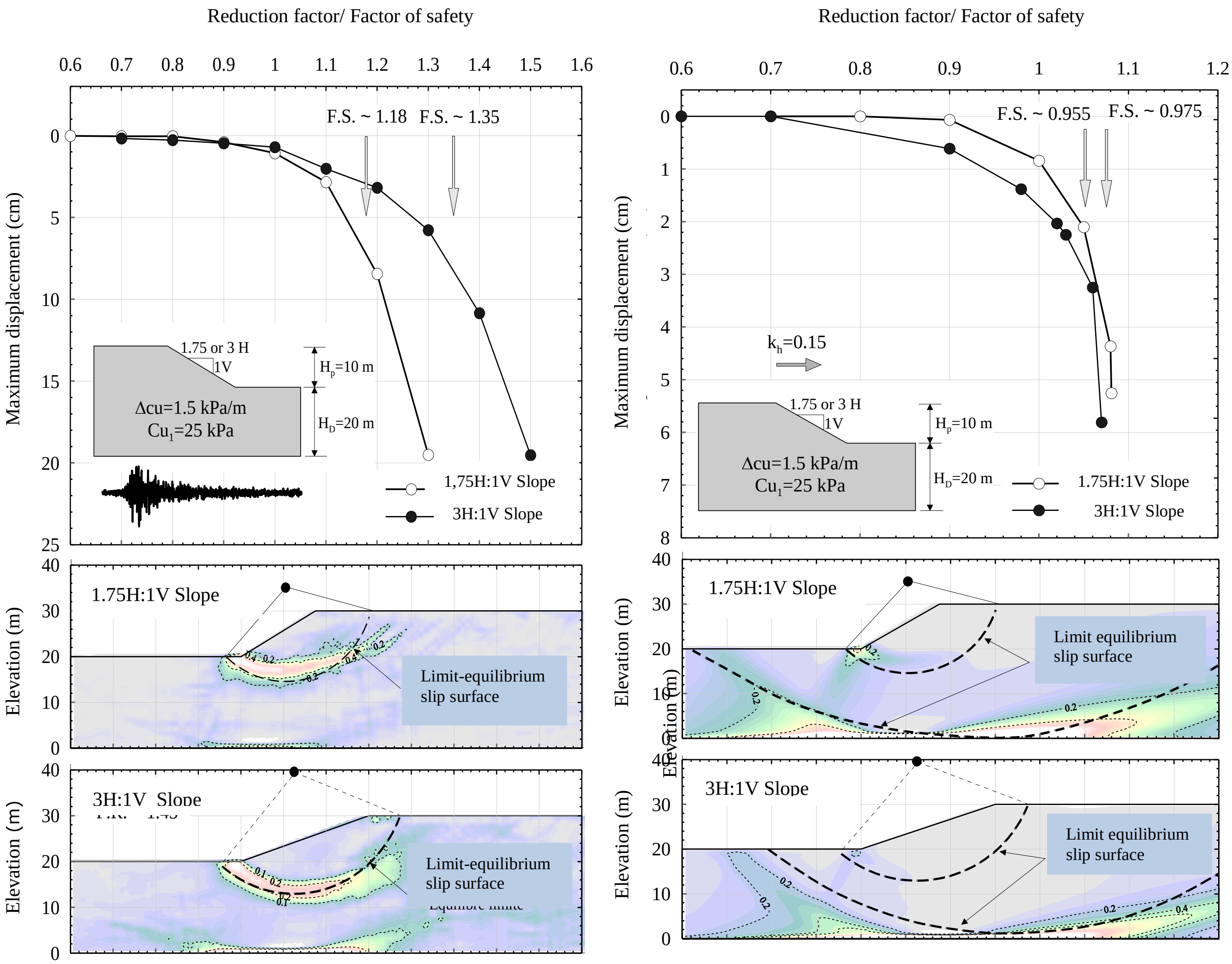

Figure 1: Comparison between dynamic analysis and failure surface obtained using a constant seismic coefficient *kh*=0,15 proposed by NBCC (National Building Code of Canada) for seismic zone 4. Adapted from Karray et al. (2017c).

In the following sections, the effect of different earthquake synthetic signals is studied, as a quantitative effort to relate spectral pseudo-static coefficient with the regional seismicity of Eastern Canada.

3 CONSIDERATION OF FREQUENCY CONTENT ON DYNAMIC SLOPE STABILITY

The seismic coefficient depends on the natural period of the slope that depends on the total height of the slope and the deposit, as well as the slope angle. In Karray et al. 2017c work, it has been shown that the plasticity index has an effect on the value of the seismic coefficient. Another factor that may have an effect on the seismic coefficient is

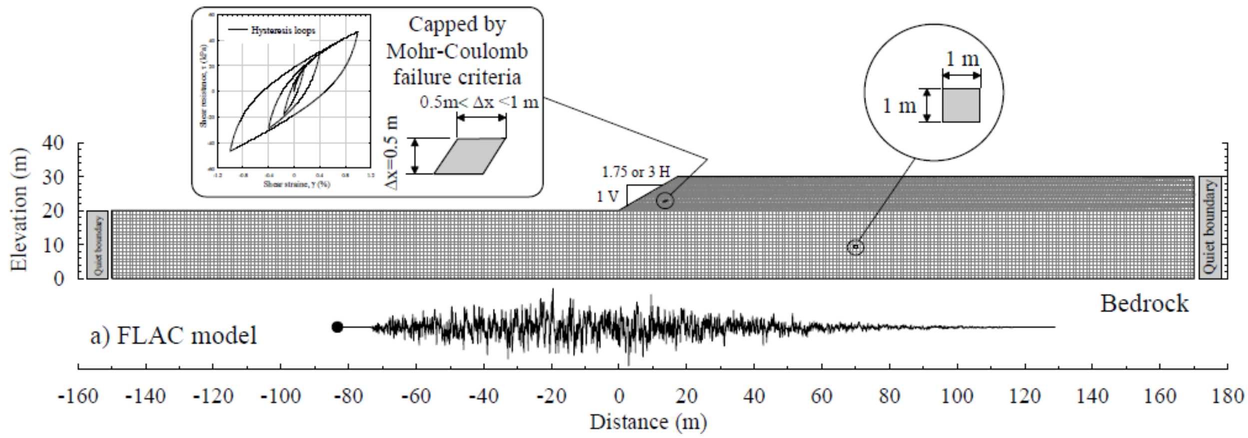

Figure 2*:* Basic characteristics of the slope, meshing, and associated boundary conditions. Model shown for geometry of H_S=10 m and deposit height of H_D=20 m*. (*Karray et al. 2018a).

the frequency content of the earthquake, which is one of the components of the seismic solicitation of the earthquake.

In the province of Quebec, the “centre d’expertise hydrique du Québec” (CEHQ) has provided a map for the seismic zones that can be used in the seismic design of high-capacity dams. The map published in 2002 provided the seismic coefficients to be used, while the map published in 2013 provided the peak bedrock acceleration. Comparing both maps, the value of the seismic coefficient is half the peak bedrock acceleration. The peak bedrock acceleration in these five zones varies between 0.05 and 0.5, hence the seismic coefficient varies between 0.025 and 0.25. This peak acceleration does not actually reflect the frequency content of an earthquake that may lead to underestimation or overestimation of the pseudo-static coefficient. Consequently, the pseudo-static coefficient varies not only with the frequency content, but also with the natural period and the seismic zone of the seismic event. To examine the effect of the seismic characteristics on the variation of the seismic coefficient, dynamic analyses were performed using five signal spectrums, compatible with the regional seismicity of different seismic zones. For space limitations, the results pertaining to Zone 4, in Quebec City, will be presented. The analyses are performed on the slopes 1.75H:1V and 3H:1V. Where the results presented here are for H_S=10 m for deposit height of H_D=20 m, using I_p of 30%.

The national building codes of 2005 and 2010 define the seismic loading in the form of a response spectrum. The values of the response spectrum given in the appendix C of the second volume are for a soil class C (very dense soil and soft rock) and they can be converted to soil class A (hard rock) by multiplying these values by acceleration- and velocity-based site coefficients provided in the first volume. This can afterwards be used to perform dynamic analysis.

3.1 Dynamic analysis

In this study, the slope and the underlying deposit are divided into 1m thick sub-layers. The properties of each sub-layer are constant and the Mohr-Coulomb failure criterion has been adopted to describe the behavior of the cohesive soil under different loadings. The parameters of the Mohr-Coulomb model are: the density, ρ, the cohesion, c, the friction angle, φ = 0, the Poisson's ratio, v and the elastic modulus, E. The latter two can be replaced by the bulk modulus, K, and the shear modulus, G. The cohesion of the first sub-layer is 25 kPa and it gradually increases downward with an increase rate (ΔSu) of 1.5 kPa. The value of soil unit weight is selected at 1.65 t/m^3. The maximum shear modulus, G_0 of the soil is evaluated according to the value of the undrained shear strength, Su following the correlation suggested by Locat and Beauséjour (1987):

$$G_0 = 0.379 \times S_u^{1.05} \quad [3]$$

The shear wave velocity profile is then derived using the elastic relationship between G_0 and V_s: $G_o=\rho V_s^2$.

As suggested by Karray et al. 2018b, the numerical model is of 30 times larger than the slope height. This configuration ensures that the reflections at the limits of the model do not affect the result of the numerical simulation. An example of numerical model for H_S*=10 m* for deposit heights of H_D*=5 m* is shown in Figure 2. Different accelerograms compatible with seismicity of Eastern Canada are afterwards included in dynamic analysis, according to multiplying factors used to calibrate acceleration spectra with those proposed by NBCC Class A for the corresponding seismic zone. The Atkinson-1 (2009), Atkinson-2 (2009), Atkinson-3 (2009), 1985 Nahanni earthquake and 1988 Saguenay earthquake are utilized herein as they are rich in high frequency components, a condition that is consist with the seismicity of Eastern Canada (Harpin et al. 2017). More specifically, the utilized accelorgrams such as those proposed by Atkinson (Atkinson, 2009) and the 1988 Saguenay earthquake shown in Fig. 3 show the development of high acceleration amplitudes at short durations. In the seismic

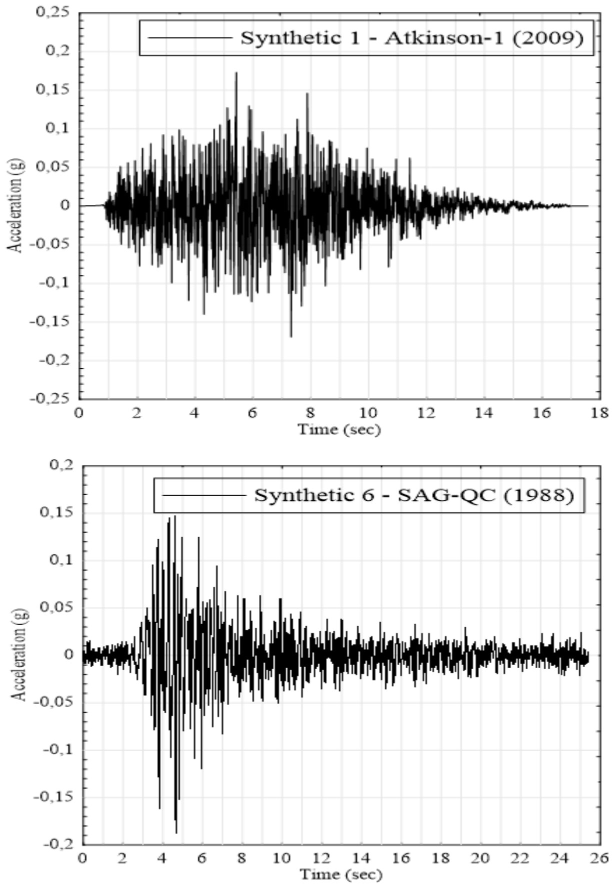

Figure 3: The Atkinson-1 (2009) and the 1988 Saguenay earthquake used in the current dynamic analyses.

design of clayey slopes to withstand different earthquakes, the consideration of the earthquake's frequency content variation should be taken in account in the proposed values of *kh(z).*

In this study, the design spectrum corresponding to the different earthquakes considered are adjusted to fit the 2015 NBCC design spectrum for Québec City, showing that the different spectrums vary with the period. This, in fact, would induce a difference in the spectral acceleration, for a given natural period, as shown in Fig. 4. In Fig. 4, the Montreal City design spectrum is also provided to illustrate the effect of the frequency content for different seismic zones. Dynamic analyses were performed using the five suggested accelerograms compatible with seismicity of Eastern Canada. Fig. 5 shows that the factor of safety is variable with the frequency content of the earthquake. Indeed, for the case of slope 1.75H: 1V, where H_s = 10 m for H_D = 5 m, the factor of safety obtained varies between 1.14 and 1.31 depending on the different earthquake characterizations.

It is important to mention that the procedure used to find the factor of safety in Karray et al. 2018b by using the shear strength reduction method, is still used in this paper: (1) plot the relative displacement between a point in the middle of the slope and a point at the bottom of the foundation soil as a function of the reduction factor; (2)

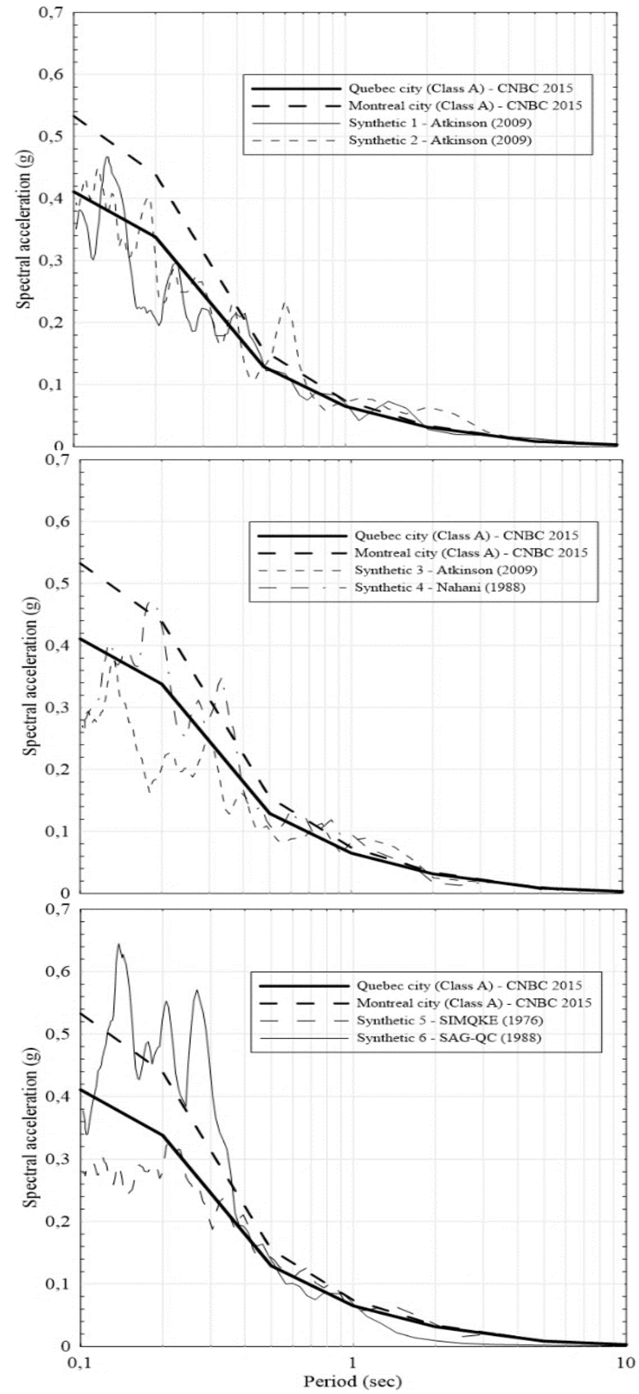

Figure 4: Acceleration spectra for earthquakes spectrums compatible with Quebec seismic zone 4 used in this study

determine the factor of safety corresponding to 0.2% of the maximum displacement, corresponding to plastification of the slope. Moreover, the development of the slip surface is examined throughout the same shear strength reduction analysis. However, the pertaining results are not presented here because the space limitation.

The current numerical results lead also to relate the spectral pseudo-static coefficient at the surface *kh(z)* with

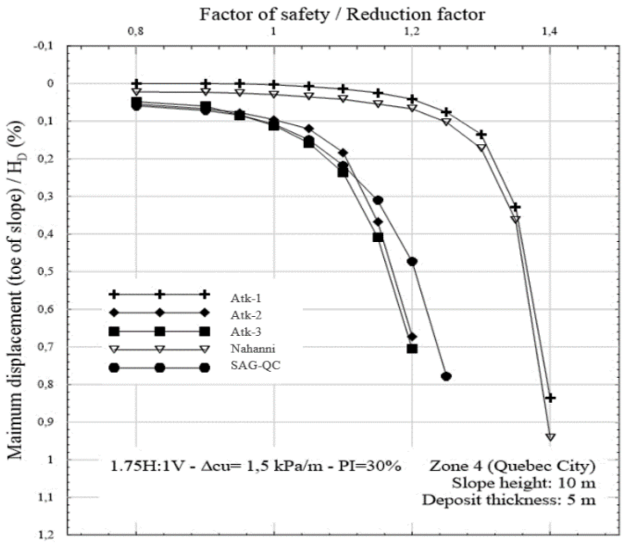

Figure 5: Relative displacement factor of safety curve for 1.75H:1V, H_S= 10 m and H_D= 5 m. The factor of safety varies between 1.32 and 1.14.

natural period of a given deposit, while choosing conservative coefficient with respect to different compatible earthquake motions. This is shown in **Error! Reference source not found.**6, which is elaborated for seismic zone 4, plasticity index of 30% and shear strength value that increases by 1.5 kPa / m. This figure shows that the *kh(z)* value is critically dependent on the slope geometry and dimensions. Other variations of shear strength were also studied but not presented in this paper, whereas increase of shear strength of ΔSu = 1.5, 2.0, and 2.5-kPa/sub-layer were considered.

4 CONCLUSION

Previous efforts concerning the spectral pseudo-static procedure allow seismic analysis of clayey slopes with consideration of dynamic properties, such as the plasticity index, as well as the seismic zone as proposed by NBCC. The spectral pseudo-static method has been incorporated and validated into limit-equilibrium software SVSLOPE, as shown in previous studies by Karray et al. 2017 b. The numerical simulations performed in this study aim to extend the spectral pseudo-static method to include wider range of synthetic earthquakes compatible with regional seismicity of Eastern Canada, in the calculation of the proposed coefficient *kh(z)* at the surface which is. As shown from the comparison of various relative displacement factor of safety curves, the factor of safety was found to be variable with different earthquake characteristics, and the spectral pseudo-static coefficient *kh(z)* must remain conservative with respect to different applied earthquakes. The use of hyperbolic variation proposed for spectral pseudo-static approach therefore follows this ascertainment. Allowing to obtain relations for the surface coefficient kh(*z*), function of the natural period of the deposit, conservative value of seismic coefficient different earthquake motions.

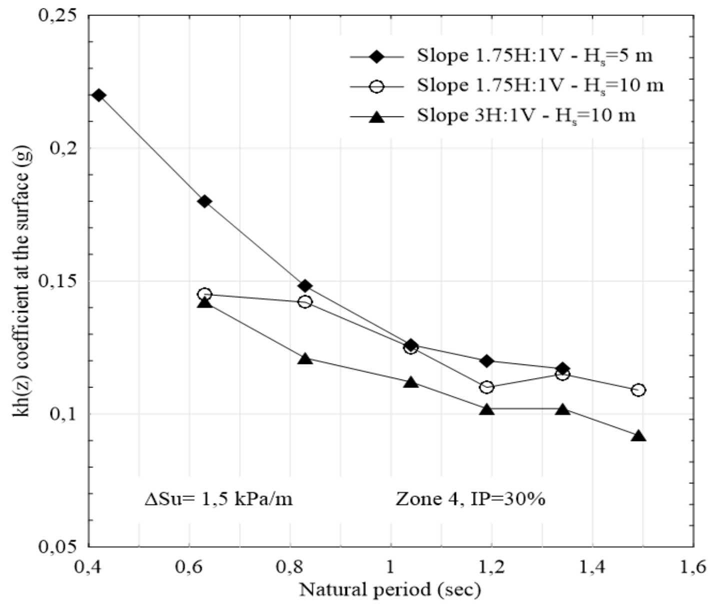

Figure 6: Proposed seismic coefficient as a function of natural period, with consideration of different earthquakes compatible with seismicity of Eastern Canada. Results shown for seismic zone 4, plasticity index of 30% and 1.5kPa\m shear strength profile.

5 AKNOWLEDGMENTS

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