

A useful tool to evaluate the seismic stability of clayey slopes: the spectral pseudo-static approach

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ABSTRACT

The pseudo-static method is the most widely used for slopes seismic stability evaluation. It consists to replace the earthquake effect by a constant coefficient, k_h . Although the pseudo-static method is not based on dynamic properties or regional seismicity, it continues to be used within popular limit-equilibrium softwares. With the urgent need to perform simple but efficient analysis, the spectral pseudo-static method, developed at the University of Sherbrooke, proposes to overcome the gaps of the conventional pseudo-static method by keeping its simplicity and low calculation time, while taking into consideration dynamic properties and regional seismicity. The herein study aims to show the convenience of the spectral pseudo-static method in the context of regional landslide risk management for Eastern Canada. Quantification of the factor of safety is made using limit-equilibrium methods versus finite difference methods, clearly showing that the spectral pseudo-static method presents accurate results.

RÉSUMÉ

La méthode pseudo-statique est la plus largement utilisée pour l'évaluation de la stabilité sismique des pentes. Elle consiste à remplacer la force sismique par un coefficient constant, k_h . Bien que cette méthode ne soit pas basée sur les propriétés dynamiques du dépôt ou sur la sismicité régionale, elle continue à être utilisée dans les logiciels d'évaluation à l'équilibre-limite. Face aux besoins urgents de développer une méthode basée sur ces aspects, la méthode pseudo-statique spectrale, développée à l'Université de Sherbrooke, propose de combler les lacunes de la méthode pseudo-statique conventionnelle en conservant sa simplicité et un temps de calcul réduit, tout en tenant en compte les propriétés dynamiques et la sismicité régionale. La présente étude vise à démontrer l'utilité de la méthode pseudo-statique spectrale dans le contexte de la gestion des risques de glissements de terrain pour l'Est du Canada. La détermination du facteur de sécurité est comparée à l'aide de méthodes d'évaluation à l'équilibre-limite et les méthodes par différence finies, démontrant clairement que la méthode spectrale pseudo-statique présente des résultats compatibles avec les analyses dynamiques complètes.

1 INTRODUCTION

The pseudo-static approach is one of the first procedures used for examining the seismic stability of slopes, where the vertical component of the seismic acceleration is neglected and only the horizontal component is considered. Since 1950, Terzaghi (Terzaghi, 1950) has been widely regarded as the first to explicitly apply it to the analysis of seismic slope stability. The application of the pseudo-static force to the center of gravity of the potentially unstable soil mass as proposed by Terzaghi would be true only if the accelerations were constant over the entire soil mass, which is not probably not the case. In addition, the selection of the pseudo-static coefficient, k_h , is based on the judgment and experience of the slope behavior during past earthquakes. Seed (Seed, 1979) gave some examples where pseudo-static analysis was used giving a safety factor greater than one, although partial or complete failure occurred, i.e. the total rupture of the Sheffield Dam ($k_h = 0.1$ and the calculated safety factor = 1.2). The occurrence of such fractures confirms the inadequacy of the concept of constant pseudo-static coefficient for predicting seismic stability. The most important advantage of the method is its simplicity since one of the only required

input parameters is the seismic coefficient k_h . Another advantage is its similarity with conventional static analysis since based on limit equilibrium (LE).

In 1950, Terzaghi proposed approximate values for k_h : 0.1 for a large earthquake, IX on the Rossi-Forel scale (partial or total destruction of buildings); 0.25 for a violent and destructive earthquake, X on the Rossi-Forel scale (large-scale disaster, ruins, stratum disturbance, soil cracks, mountain rockfall); and 0.5 for catastrophic earthquakes. Marcuson and Franklin (1984) have proposed, based on their experience, that k_h varies from one third to one half of the maximum acceleration to which an embankment could be subjected, including any amplification of acceleration at rock by the foundation or embankment to ensure a safety factor greater than 1. Hynes-Griffin and Franklin (1984) proposed that the value of k_h is between 0.05 and 0.20. They also proposed using pseudo-static analysis to distinguish between dams where there is evidence of seismic stability and dams that require further analysis. However, the pseudo-static coefficient k_h as proposed by these authors supposes constant earthquake force along the deposit. The assumption of a constant horizontal acceleration is a crude approximation, especially in slopes with relatively great heights as both field and laboratory

observations have demonstrated that the seismic response varies with the height according to various authors such as Hynes-Griffin and Franklin (1984) and Duncan (2014). The pseudo-static method also assumes that the shear strength of the soil within a slope remains essentially constant and the slope deformations are caused only by the inertial forces induced by the earthquake shaking (it does not account for the potential reduction of shear strength and stiffness of the slope material due to the development of shear strains during the earthquake shaking). Hence, the use of the pseudo-static method is problematic as the method typically indicates failure for clayey slopes (i.e. produces factors of safety fewer than 1) regardless of the actual stability of the slope and the resulting slip surface is determined by the thickness of the clayey layer within the slope of foundation. Moreover, the results of the pseudo-static analyses are dependent on the selected value of the pseudo-static coefficient, k_h , which is used to apply a constant horizontal acceleration to the model. The representation of earthquake effects by constant acceleration is therefore a crude approximation and is overly conservative: it assumes that the resulting earthquake-induced forces are constant and act only in the direction of instability (Jibson, 2011).

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 du Québec, Québec, Canada for the analyses of seismic stability of clayey slopes. The development of the spectral pseudo-static method was primarily based on detailed static, dynamic, and conventional pseudo-static analyses using the two-dimensional (2D) computation code, FLAC 7 (Itasca, 2009). The approach has been developed to take into consideration the variation of dynamic properties such as plasticity index, as well as the seismic zone as defined by the Centre d'expertise hydrique du Québec where the deposit under study is located (Karray et al. 2018a). The work presented in this paper aims to show the convenience of the proposed approach when using LE computation methods.

2 DEVELOPMENT OF SPECTRAL PSEUDO-STATIC APPROACH

By quantifying the variation of spectral acceleration at different locations in a clay soil deposit and consequently with the natural period, Karray et al. (2018b) 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. This ascertainment 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 with a constant force applies.

Spectral pseudo-static analyses (with a variable k_h coefficient) were performed in order to develop a formula for a variable seismic coefficient leading to the same factor of safety and nearly 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 $k_h(z)$ requires the comparison between the results of the dynamic analyses and those of the pseudo-static analyses. The analyses have been carried on, following the framework proposed by Karray et al. 2018b. The shear strength reduction procedure is adopted, in which the factor of safety is given by a systematic search for the value of the reduction factor that will cause the slope to fail. Static analysis, dynamic analysis, and conventional pseudo-static analysis were performed, resulting with the ascertainment that the conventional pseudo-static analysis failed to predict the slip surface obtained by the dynamic analysis, where the factor of safety and slip surfaces using pseudo-static method strongly disagree with those of dynamic analysis, as shown in Figure 1. The values of the factor of safety, given in Figure 1a and Figure 1d show the strong contrast between the two numerical simulations within a given slope. As shown, for 3H:1V slope, slope height of 10 m and deposit thickness of 20 m, the factor of safety using dynamic analysis is of 1.35. As for pseudo-static analysis, the corresponding factor of safety is 0.955, which corresponds to an error difference of 29%. Following the examinations of the spectral acceleration functions, a spectral pseudo-static approach has been developed. The function of seismic coefficient is therefore proposed by Karray et al. (2018b) as shown in Eq. 1:

$$k_{h(z)} = k_{h0} \left(1 + a \left(\frac{z}{H(t)} \right)^b \right) \quad (1)$$

Where k_{h0} is the seismic coefficient on rock (initial value); H_t 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. For 1.75H:1V slope angle, the corresponding function is illustrated in Figure 2 in dark line, where the different spectral acceleration profiles were determined at natural period of five different sections in a 1.75H:1V slope. It can be seen in this figure that the proposed function presents conservative estimation of spectral acceleration at bottom and top positions of the slope, with regards to the different established profiles.

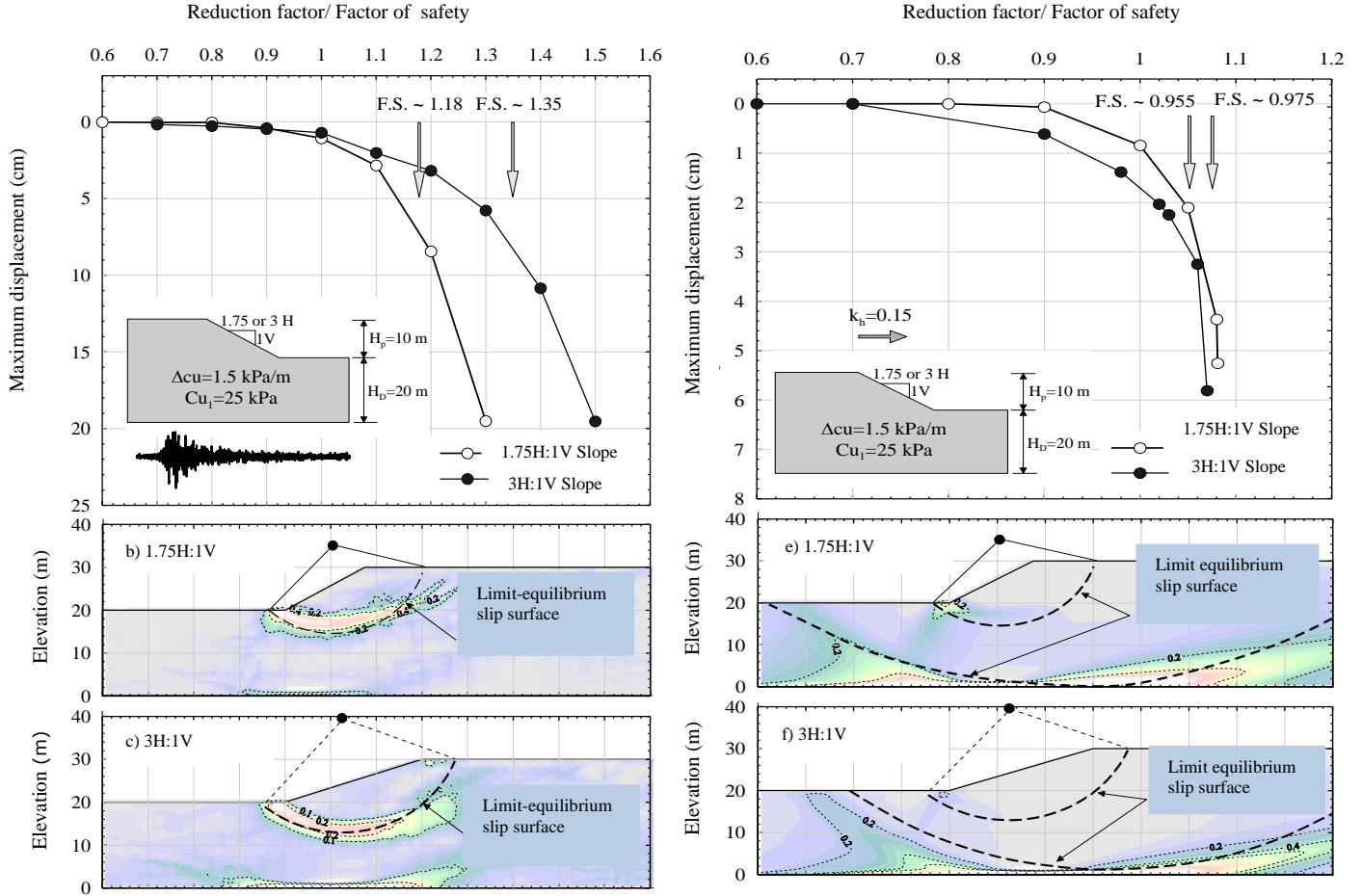


Figure 1: Comparison between dynamic analysis and failure surface obtained using constant seismic coefficient $k_h=0.15$ as proposed by the Centre d'expertise hydrique (CEHQ) for seismic Zone 4. Dynamic analysis: a) relative displacement-factor of safety curves; slip surface of slope angles: (b) 1.75H: 1V and (c) 3H: 1V. Pseudo-static analysis: (d) relative displacement-factor of safety curves; slip surfaces of slope angles: (e) 1.75H: 1V and (f) 3H: 1V. Adapted from Karray et al. (2017)

3 ASSESSMENT OF FACTOR OF SAFETY (FOS) USING SPECTRAL PSEUDO-STATIC APPROACH WITHIN LIMIT-EQUILIBRIUM ANALYSIS (LE)

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 Eq. 1, implementation of the spectral pseudo-static method into limit-equilibrium software SVSLOPE from Soil Vision (Fredlund and Thone, 2011) has been performed. The dynamic factor can, therefore, be estimated with the soil discretization using a simplified slice method (which ignores the internal forces in-between the slices). This leads to account of seismic force for determination of the factor of safety using Eq. 2:

$$F.S._d = r \frac{\sum C_u l_i}{\sum W_j \sin(\alpha_i) + \sum k_h(z) W_j \cos(\alpha_j)} \quad (2)$$

Where C_u is the shear strength, l_i is the length of the slip surface, W_i the weight of the potentially unstable mass, a_i the horizontal distance between the center of gravity and rotary center, $k_h(z)$ the pseudo-static coefficient at corresponding height of the deposit and $F.S._d$ the estimated dynamic factor of safety. 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 horizontal 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 inertial seismic forces. The program 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.

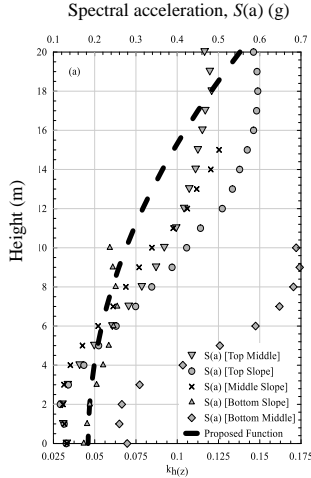


Figure 2: Spectral Acceleration Profiles at five Sections versus variation of proposed spectral pseudo-static coefficient for 1.75H:1V slope angle. The spectral acceleration profiles are determined at the natural period of each section. From Karray et al. (2017).

3 NUMERICAL RESULTS AND DISCUSSION

As suggested by Mole et al. (2018), consideration of frequency content is primordial in order to properly assess the of the dynamic factor of safety of a given seismic slope. The study examined the results of six dynamic analysis for a homogeneous clayey slope of 1.75H:1V slope angle, with increasing shear strength of ΔSu of 1.5 kPa/m from the surface to the bedrock, where initial shear strength is of 25 kPa, from a slope of slope height H_s of 10 m and deposit thickness H_D of 25 m for seismic Zone 4 in Quebec City. The pertaining results of the obtained factor of safety for different Eastern Canada compatible earthquakes are summarized in Table 1. It has been suggested to use the average \bar{x} and standard deviation σ in order to propose a conservative value of the factor of safety represented by $\bar{x} - \sigma$ for the pertaining analysis, as shown in Table 2.

The pertaining results presented in Table 2 show that for the same geometrical and geotechnical configurations, different realistic earthquake solicitations submitted to a homogeneous clayey slope may induce different response of the soil. In fact, the study used six different earthquake motions compatible with Eastern Canada seismicity to show that the maximum displacement observed at the toe of slope differs from one numerical FD simulation to another. The methodology, explained within the framework by Karray et al. (2018b), proposes to quantify the factor of safety according to maximum displacement at the toe of slope, i.e. the area where soil plastification occurs. The proposed approach suggests to reduce systematically the shear strength resistance of the soil and calculate maximum displacement, which is normalized according to total height of slope geometry, corresponding to the reduction factor. Hence, the reduction factor corresponding to failure (i.e. the factor of safety) is of 0.2% of relative

displacement of the slope within this area, since it has been observed by Karray et al. (2018b) that this corresponds to plastification of tested slopes. Table 1 shows that when using this approach for the tested slope configuration, the dynamic factor of safety differs from 1.23 to 1.33, which corresponds to a difference of the value of factor of safety of 0.1. Therefore, using statistical parameters $\bar{x} - \sigma$ allows to propose a value of factor of safety which is conservative concerning possible earthquake solicitations for a given region, in occurrence 1.25. This is shown through Table 2. Therefore, using the same proposed approach, it is possible to observe the response of the soil deposit for different geometrical and geomechanical configurations, using the six different compatible earthquake solicitations for seismic zone 4 region of Quebec City that have been used in Mole et al. 2018 study.

The national building codes of 2005 and 2010 (NBCC, 2005 and NBCC, 2010) define the seismic loading in the form of a response spectrum. The spectrums used in Mole et al. 2018 and for the herein study are presented in Figure 3. The spectrums, used for a damping of 5 %, have been scaled using multiplication factors to take into account local site conditions, i.e. amplification of the signal inside the soil deposit as suggested by Finn (2003), therefore showing the relatively high energy located at high frequencies, characteristic of Eastern Canada earthquakes motions. Nevertheless, the perceived frequency content for these

Table 1: Dynamic factor of safety for six compatible earthquakes of Quebec City seismic Zone 4, performed on 1.75H:1V clay slopes of 10 m slope height, 15 m deposit thickness with shear strength of 1.5 kPa/m. From Mole et al. (2018).

Earthquake	Factor of safety
Synthetic Atkinson-1 (2009)	1.28
Synthetic Atkinson-2 (2009)	1.23
Synthetic Atkinson-3 (2009)	1.28
Synthetic SIMQKE (Vanmarcke, 1976)	1.28
1988 Saguenay Earthquake (Boore, 1989)	1.33
measured at Quebec City	
1985 Nahanni Earthquake (Boore, 1992)	1.30

Table 2: Statistical parameters for six compatible earthquakes of Quebec City seismic Zone 4, performed on 1.75H:1V clay slope of 10 m slope height, 15 m deposit thickness with shear strength of 1.5 kPa/m. From Mole et al. (2018).

Statistical parameter	Factor of safety
\bar{x}	1.28
σ	0.03
$\bar{x} - \sigma$	1.25

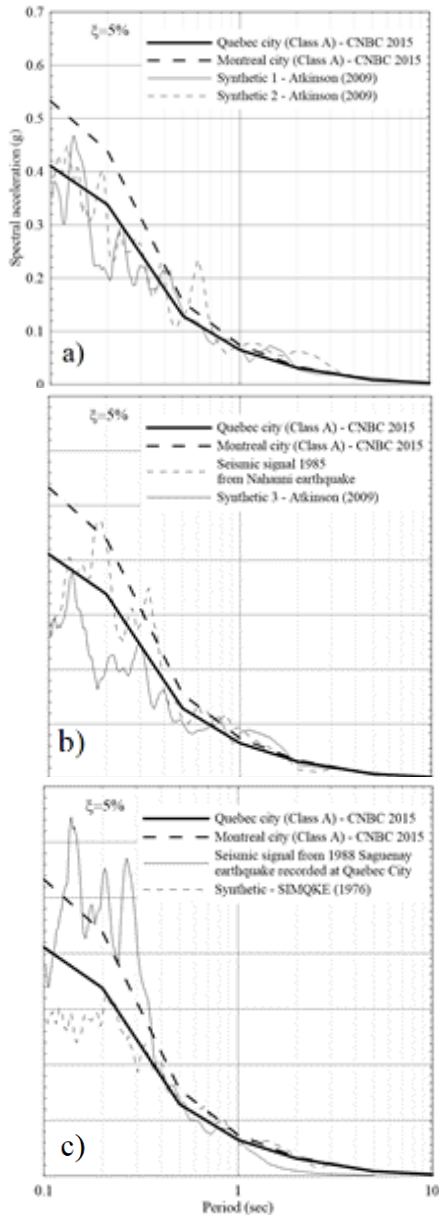


Figure 3: Acceleration spectrums for synthetic and real earthquakes spectrums compatible with Quebec seismic zone 4 used in this study: a) Atkinson-1 (2009) and Atkinson-2 (2009), b) Atkinson-3 (2009) and 1985 Nahanni earthquake and c) 1988 Saguenay earthquake and SIMQKE (1976)

six accelerogram spectrums shows that there is variation of the energy of the seismic earthquake solicitation for the presented periods. The Quebec City design spectrum is shown in Figure 3, as well as the Montreal City design spectrum.

In the context of developing a method which takes into consideration dynamic properties of deposit and compatible earthquake motion, the consideration of the frequency content is primordial. So, when analyzing a

slope that presents the same dynamic properties inside a given seismic region, a limit-equilibrium (LE) simulation must give as an output a value of factor of safety which stays conservative with the different possible earthquake solicitations as enumerated in Table 2. This is shown through an exhaustive example for a 2H:1V slope angle, ΔSu of 2.5 kPa/m, slope height H_s of 5 m and deposit thickness H_D of a 25 m homogenous clay slope. For the herein geometrical and geotechnical configurations, the FD analysis are shown in Figure 5 and Table 3. The results show the variability of the value of factor of safety with variation of frequency content. For a first synthetic earthquake from Atkinson database, i.e. *Atkinson-1* earthquake in Figure 5a (Atkinson, 2009), obtained factor of safety is of 2.3.

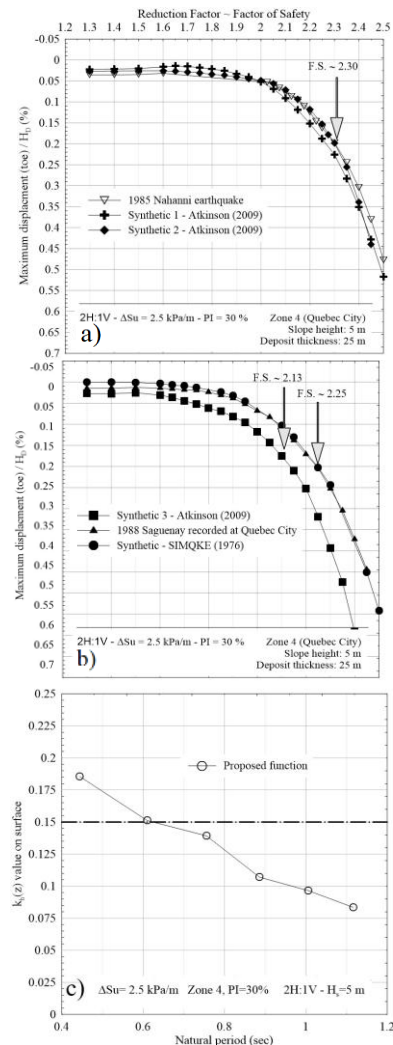


Figure 5: FD numerical simulations for 2H:1V slope angle, ΔSu of 2.5 kPa/m, H_s of 5 m and H_D of 25 m clay slope: a) reduction factor vs maximum displacement at toe for dynamic simulations and b) proposed spectral pseudo-static function for corresponding natural periods for a slope height H_s of 5 m.

As for another synthetic earthquake from Atkinson database, i.e. *Atkinson-3* earthquake in Figure 5b, the value of the factor of safety is of 2.13, which provides a difference of 0.17. Nevertheless, it is possible to calculate a conservative value of the factor of safety, shown in Table 4. This means that an analysis performed inside a LE software should, in principle, give the same factor of safety

as the one in Table 4 (i.e. $\bar{x} - \sigma$) in order to stay conservative with the different possible earthquake solicitations for Eastern Canada regions, when using proposed value of $k_h(z)$ at the surface provided in Figure 5c. In occurrence, the natural period of the slope under study is of 0.99 s, which gives value of $k_h(z)$ at the surface of 0.096. Using Eq. 1 therefore allows to obtain the value of k_{h0} , the spectral pseudo-static coefficient at the bedrock, which is of 0.032. Using LE software SVSLOPE, it is then possible to perform the analysis using the same coefficient k_{h0} . As shown in Figure 6a, the spectral pseudo-static LE simulation using this coefficient provides a value of factor of safety 2.32. This means that, by comparison with FD dynamic analysis, the error difference using spectral pseudo-static approach is of 4.3 %. As for a conventional pseudo-static LE numerical simulation, carried out using Centre d'expertise hydrique du Québec proposed coefficient of 0.15, the obtained value of factor of safety is of 1.43 as shown in Figure 6b. Using the conventional pseudo-static approach therefore provides an error difference of 38.4 %. The position of grid and tangent are for pseudo-static analysis is shown in Figure 6c for illustration purposes.

Table 3: Dynamic factor of safety for six compatible earthquakes of Quebec City seismic Zone 4, performed on 2H:1V clay slope of 5 m slope height, 25 m deposit thickness with increasing shear strength of 2.5 kPa/m.

Earthquake	Factor of safety
Synthetic Atkinson-1 (2009)	2.25
Synthetic Atkinson-2 (2009)	2.30
Synthetic Atkinson-3 (2009)	2.13
Synthetic SIMQKE (Vanmarcke, 1976)	2.25
1988 Saguenay Earthquake (Boore, 1989) measured at Quebec City	2.25
1985 Nahanni Earthquake (Boore, 1992)	2.30

Table 4: Statistical parameters for six compatible earthquakes of Quebec City seismic Zone 4, performed on 2H:1V clay slope of 5 m slope height, 25 m deposit thickness with increasing shear strength of 2.5 kPa/m.

Statistical parameter	Factor of safety
\bar{x}	2.27
σ	0.05
$\bar{x} - \sigma$	2.22

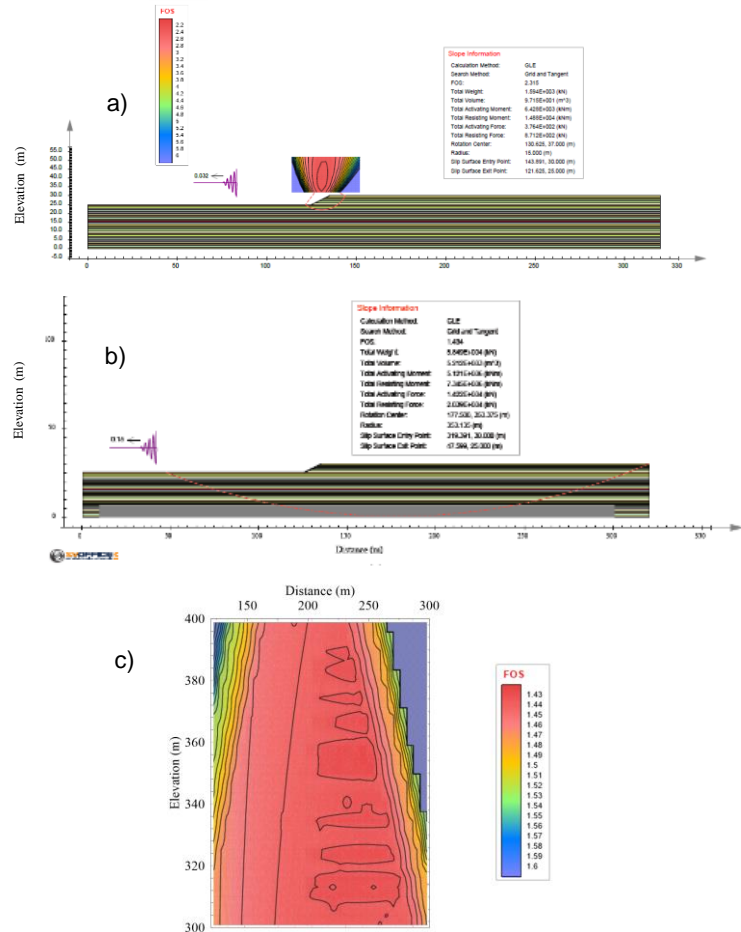


Figure 6: LE simulations carried out for 2H:1V slope angle, slope height of 5 m, deposit thickness of 25 m and increasing shear strength of 2.5 kPa/m a) spectral pseudo-static approach b) conventional pseudo-static approach c) corresponding grid

4 CONCLUSION

This paper corroborates the accuracy of the spectral pseudo-static approach developed at Sherbrooke University for LE analysis when compared with FD dynamic numerical simulations. The coherence of the spectral pseudo-static approach regarding position of the toe of the slip surface and value of the factor of safety at failure shows that the proposed approach is accurate when compared with FD numerical methods. The proposed hyperbolic variation of the seismic coefficient proposed in Eq. (1), therefore simulating the earthquake effect, can be used with confidence within LE analysis. The numerical simulations performed herein show conservative factor of safety when comparing when 6 different accelerograms used for FD analysis. As the hyperbolic variation of the seismic force presents consistent agreements with FD analysis, use of a constant force regardless of natural period as proposed using conventional pseudo-static method is overly conservative for LE analysis as expressed in the literature. The proposed approach can be used with certainty inside LE software SVSLOPE for conception purposes.

4 ACKNOWLEDGMENTS

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5 REFERENCES

- Atkinson, G.M., 2009. Earthquake time histories compatible with the 2005 National building code of Canada uniform hazard spectrum. *Canadian Journal of Civil Engineering*, 36(6), pp.991-1000.
- Boore, D.M. and Atkinson, G.M., 1992. Source spectra for the 1988 Saguenay, Quebec, earthquakes. *Bulletin of the Seismological Society of America*, 82(2), pp.683-719.
- Boore, D.M. and Atkinson, G.M., 1989. Spectral scaling of the 1985 to 1988 Nahanni, Northwest Territories, earthquakes. *Bulletin of the Seismological Society of America*, 79(6), pp.1736-1761.
- Duncan, J. M., Wright, S. G., and Brandon, T. L., 2014. *Soil strength and slope stability*. John Wiley and Sons.
- Finn, W.L. and Wightman, A., 2003. Ground motion amplification factors for the proposed 2005 edition of the National Building Code of Canada. *Canadian Journal of Civil Engineering*, 30(2), pp.272-278.
- Fredlund, M.D., and Thode, R. 2011. SVSLOPE theory manual. *Soil Vision Systems Inc.*, Saskatoon, Sask.
- Hynes-Griffin, M. E., & Franklin, A. G., 1984. Rationalizing the Seismic Coefficient Method. *Miscellaneous Paper No. GL-84-3*, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi.
- Itasca, F.L.A.C., 2009. Fast Lagrangian Analysis of Continua, Version 4.0. *User's manual*. Itasca Consulting Group, Inc. Minneapolis, Minnesota, USA.
- Jibson, R., 2011. Methods for assessing the stability of slopes during earthquakes. *Engineering Geology*, 122(1-2), 43-50.
- Karray, M., Hussien, M.N., Souilem, M., Locat, P. and Mompin, R., 2018a. Adjustment of the spectral pseudo-static approach to account for soil plasticity and seismic zone. *Canadian Geotechnical Journal*, (ja).
- Karray, M., Hussien, M.N., Delisle, M.C. and Ledoux, C., 2018b. Framework to assess the pseudo-static approach for the seismic stability of clayey slopes. *Canadian Geotechnical Journal*, (ja).
- Karray, M., Souilem, M., Ghobrial, F. and Hussien, M.N., 2017. Développement de la méthode pseudo-statique spectrale pour l'analyse de stabilité dynamique des talus argileux. *Report No. Geo-02-17*.
- Le Centre d'Expertise Hydrique du Québec. 2013. www.cehq.gouv.qc.ca/loisreglements/barrages/reglement/Seismiques_QC_150.pdf
- Marcuson III, W.F., Franklin, A.G. and Hadala, P.F., 1984. SOIL DYNAMICS—STATE OF THE ART, 1980. In *Wind and Seismic Effects: Proceedings of the 12th Joint Panel Conference of the US-Japan Cooperative Program in Natural Resources, May 19-23, 1980, National Bureau of Standards, Gaithersburg, MD* (Vol. 665, p. 213). US Department of Commerce, National Bureau of Standards.
- Makdisi, F.I. and Seed, H.B., 1979. Simplified procedure for evaluating embankment response. *Journal of Geotechnical and Geoenvironmental Engineering*, 105 (ASCE 15055).
- Mole, J., Karray, M., Hussien, M., Delisle, M. C., Locat, P., Mompin, R., and Ledoux, C., 2018. Effects of frequency content on dynamic slopes stability for Eastern Canada clays. In *71st Canadian Geotechnical Conference*, Edmonton, Alberta, Canada.
- National Research Council of Canada. Associate Committee on the National Building Code. (2005).
- National Research Council of Canada. Associate Committee on the National Building Code. (2010).
- Terzaghi, K., 1950. Mechanism of landslides. *Application of geology to engineering practice*, *Geol. Soc. Am*, pp.83-123.
- Vanmarcke, E.H., Cornell, C.A., Gasparini, D.A. and Hou, S., 1976. SIMQKE: A program for artificial motion generation. *Civil Engineering Department, Massachusetts Institute of Technology*