Seismic stability of Eastern Canada slopes: a spectral 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 at the centroid of the unstable mass by a constant coefficient, k_h. This method has been proven to be ineffective, especially for clayey soils, as the estimation of the seismic coefficient is made using Peak Ground Acceleration (PGA), which, as proven in the literature, is not a suitable parameter to estimate the earthquake effect. Although the pseudo-static method is not based on dynamic properties (plasticity index, natural period, etc.) or regional seismicity, it continues to be used within popular limit-equilibrium softwares (LE) without further consideration of dynamic conditions, mainly because it is simple to use and requires low computation time. More complicated nonlinear methods such as finite elements (FE) and finite difference (FD) methods are available, but their application is more complex, and they require important computation time. With the need to perform efficient but simple analysis as a tool intended for practical engineers, 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 proposed approach first implies determination of the natural period, the key parameter needed to carry out analysis, making it first possible to estimate the spectral pseudo-static coefficient at the bedrock, k_{h0}.Choice of $k_{h(z)}$ is afterwards possible when using a hyperbolic variation of the seismic coefficient, therefore resulting in accurate estimation of the earthquake effect in a deposit. 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, as a useful tool ultimately intended for field engineers. Throughout a case study of two slope geomechanical configuration, the nearly perfect match between the spectral pseudo-static method inside limit-equilibrium software SVSLOPE and the Finite Difference (FD) dynamic analysis factor of safety is exemplified in this paper. Quantification of the factor of safety is made using limit-equilibrium methods, clearly showing that the spectral pseudo-static method presents accurate results, throughout a numerical procedure that requires to the user less experience than finite difference methods.

Keywords: seismic slope stability, spectral pseudo-static, cohesive soil.

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 [1] 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 behaviour during past earthquakes. Seed [2] 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 [2]. The most important advantage of the method is its simplicity since one of the only required input parameters is seismic coefficient k_h. Another advantage is its similarity with conventional static analysis since based on limit equilibrium (LE).

In 1950, Terzaghi [1] 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 [3] 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 [4] 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 [4], [5]. The 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, which may not be the case. 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 [6].

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 [7]. The approach has been developed to take into consideration 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 [8]. The work presented in this paper aims to show the convenience of the proposed approach when using LE computation methods.

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. [9] 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. [10]. 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. [9]:

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

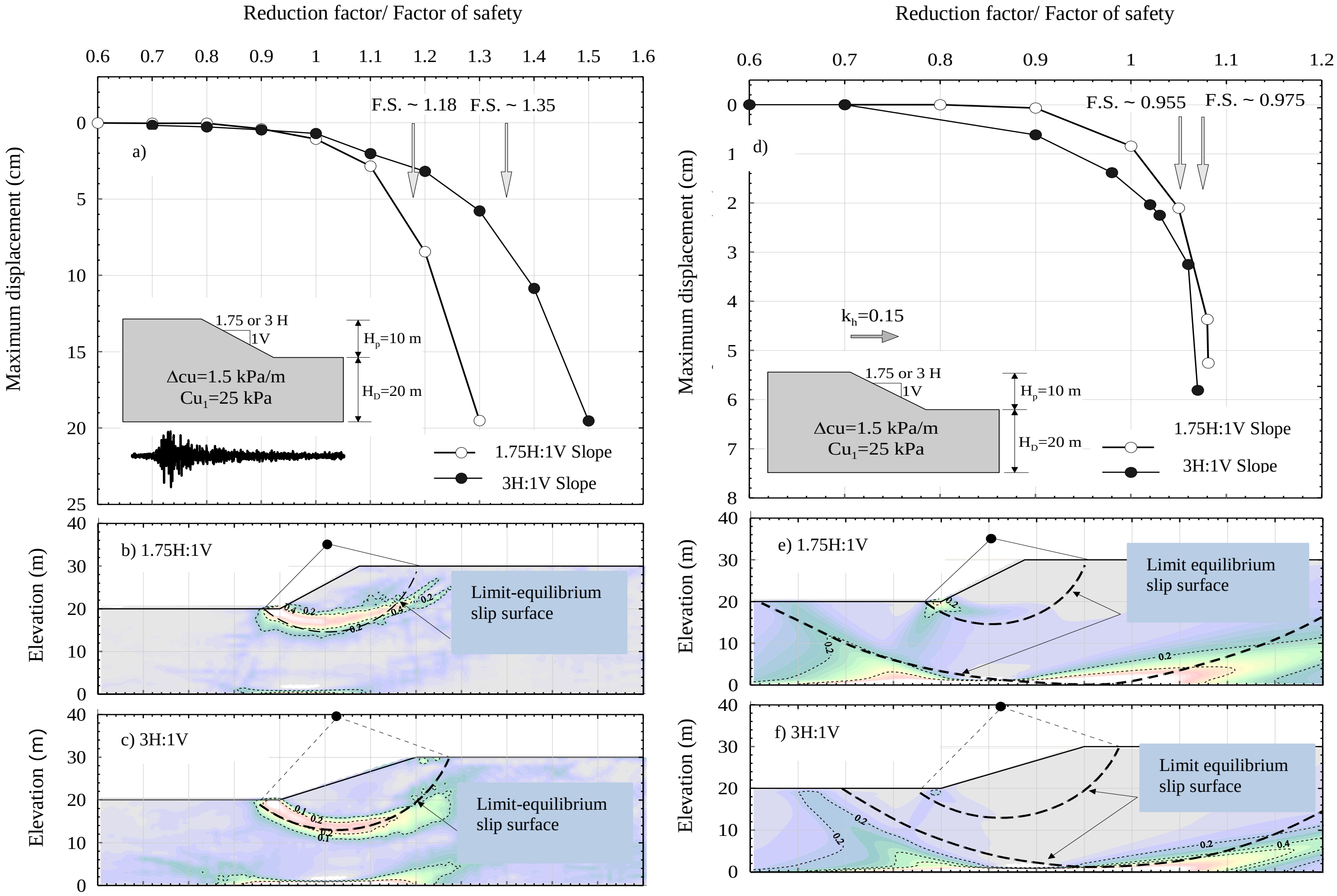

Figure 1: Comparison between dynamic analysis and failure surface obtained using constant seismic coefficient k_h=0.15 as proposed by the Centre d'expertise Hydrique [12] for seismic Zone 4. Dynamic analysis: a) relative displacement-factor of safety curves; slip surface of slope angles: (b) 1.75H: 1V 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. [9]

Where k_{ho} 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.

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

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 [11] has been performed as described in Karray et al. [9]. 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 the following formula:

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

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

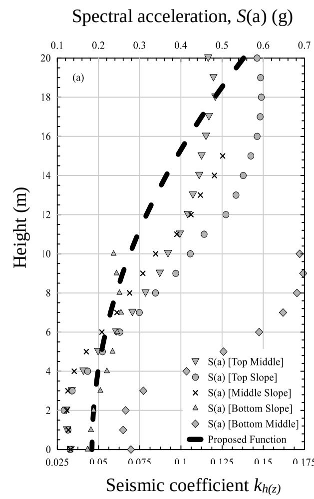

Figure 2: Spectral Acceleration Profiles at five Sections versus variation of proposed spectral pseudo-static coefficient for 1.75H:1V slope angle. The spectral acceleration profiles are determined at the natural period of each section. From [9].

deposit makes it possible to calculate the moment of the driving forces for each of the slices, discriminated horizontally and vertically. The vertical 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.

NUMERICAL RESULTS AND DISCUSSION

As suggested by Mole et al. [13], consideration of frequency content is important in order to properly assess the value of the factor of safety of 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 ΔS_u 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 $\bar{x}$ - σ for the pertaining analysis, as shown in Table 2.

As shown in Table 2, a conservative value of the factor of safety should be of 1.25 for this geometry. This means that a method that provides an accurate of the factor of safety through LE analysis should give a factor of safety very similar to 1.25, which corresponds to the dynamic analysis for to the same geometrical and geomechanical configuration. As suggested by Mole et al. [13], the natural period is 1.03 s as shown in Figure 3. This natural period corresponds to a value of the spectral pseudo-static coefficient ($k_{h(z)}$) on the surface of 0.101. In order to verify the efficiency of the proposed approach for LE analysis, the numerical simulation is carried out in LE software SVSLOPE from Soil Vision [11]. The contours of the factor of safety, slope information at failure, spectral pseudo-static coefficient value to the bedrock (k_{h0}) and corresponding slip surface for this geometry is shown in Figure 4. The search method used is Grid and Tangent as the calculation method is General Limit Equilibrium (GLE) proposed by Fredlund et al. [14]. By using Eq. (1), the proposed value of spectral pseudo-static coefficient value to the bedrock (k_{h0}) is 0.305. Coefficients *a* and *b* are 2 and 2. When using the values of k_{h0}, *a* and *b* in LE software SVSLOPE, the obtained factor of safety is 1.30. While comparing with reference value of 1.25 of Table 2, obtained using FD simulations, the difference between the latest and the LE simulation performed in SVSLOPE software is of 4 %.

As suggested by Karray et al. [10] and can be verified in Karray et al. [8], the correct position of beginning of slip surface for seismic analysis of clayey slopes corresponds to the toe of the slope, where plastification occurs. Throughout extensive parametric study, the various geometrical and geomechanical configuration carried out through FD computer code FLAC 7 verify this ascertainment as careful examination of the slip surface of the carried out numerical simulation follow this behaviour. The stability of the slope is then evaluated using the method of slices and limit equilibrium to determine critical slip surface and the factor of safety. The toe of slip surface corresponds to the toe of the slope, and development of slip surface is made upward through the toe of the slope. This is verified through FD and LE analysis, where the corresponding slip surface is found to be similar [10]. With the conventional pseudo-static approach, beginning of the position of the toe of the slip surface does not correspond to the position of the toe of the slope as can be perceived in Figure 1e and Figure 1f [9].

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. [13].

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) measured at Quebec City	1.33
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. [13].

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

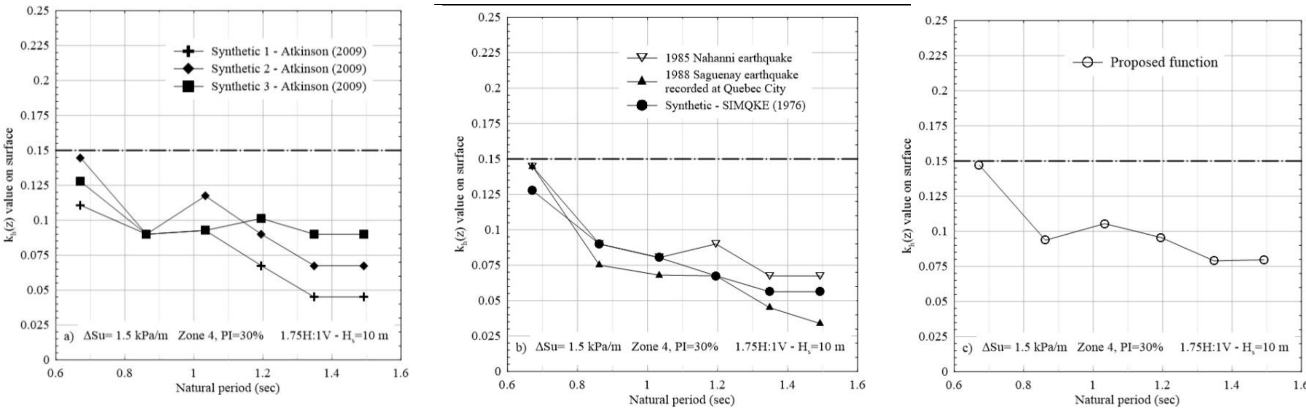

Figure 3: Variation of the proposed spectral pseudo-static coefficient with consideration of frequency content (a) Synthetic-1 – Atkinson [15], Synthetic-2 – Atkinson [15], Synthetic-3 - Atkinson [15] b) 1985 Nahanni earthquake,1988 [16] Saguenay earthquake recorded at Quebec City [17] and Synthetic – SIMQKE [18] c) proposed function. From Mole et al. [13]

Hence, the slip surface from LE simulation presented in Figure 4, respects the listed conditions concerning position of the toe of the slip surface. Using the spectral pseudo-static function listed in Eq. (1) therefore provides accurate estimation of the slip surface for the corresponding geometry, as error difference is of 4 % for the factor of safety with dynamic analysis obtained using FD numerical methods.

Furthermore, in order to assert the efficiency of the proposed approach, it is adequate to perform comparison between the spectral pseudo-static procedure for LE analysis and FD analysis for a new slope angle (i.e. 2H:1V), different slope height (i.e. 10 m) and different deposit thickness (i.e. 30 m) for seismic Zone 4 in Quebec City. Pertaining results are presented in Figure 5. In principle, variation of deposit thickness, slope height and slope angle should not alter the proposed approach. Hence, the FD analysis must be performed for the corresponding geometry with design spectrum for Québec City. Dynamic simulation are performed using FD FLAC 7 software using shear strength reduction procedure as proposed by Karray et al. [10] and are shown in Figure 5b. The 6 compatible Eastern Canada accelerograms in Mole et al. [13] are used since they are representative of Eastern Canada ground solicitations for Quebec City Zone 4 site. The corresponding spectrums are presented in Figure 5a with their proper amplification factor to capture the amplification effects of local soil conditions on ground motions, therefore fitting 2015 NBCC conception spectra. The results of FD dynamic simulations allow to obtain Figure 5c, which proposes a conservative value of pseudo-static coefficient on the surface for different values of natural periods. The currently proposed constant value of 0.15 for Quebec City seismic Zone 4 is also illustrated in this figure to show the constant seismic force for different ranges of natural periods possible for this geometry. The proposed approach suggests that reduction factor corresponding to failure (i.e. the factor of safety) is of 0.2% of relative displacement of the slope as shown in Figure 5b [10]. Therefore, results are summarized in Table 3 and statistical parameters are enumerated in Table 4. The results of FD simulations show that for this geomechanical and geometrical configuration, a conservative value of the factor of safety for different compatible earthquake solicitations is of 1.28. Hence, Figure 5c shows that for corresponding value of natural period, the value

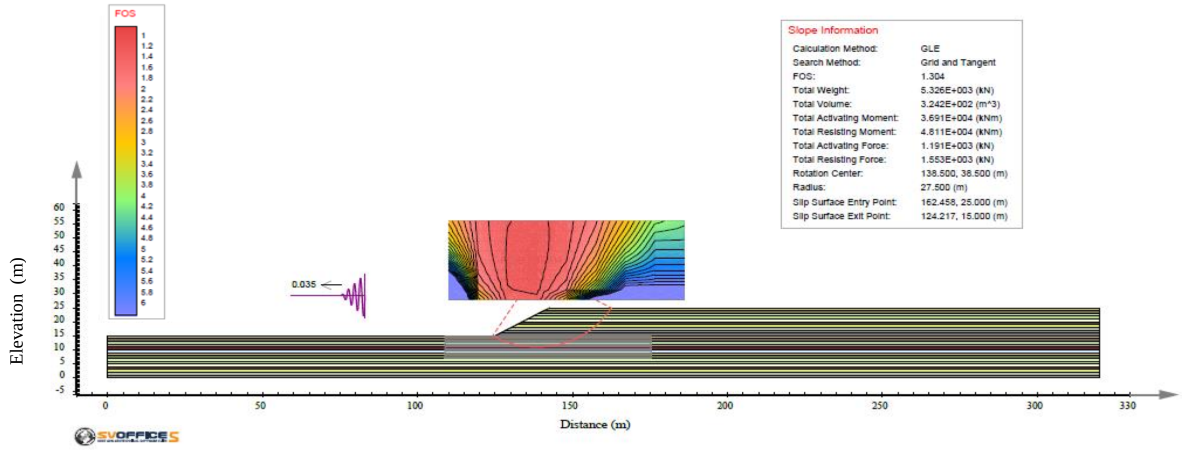

Figure 4: Slip surface for homogeneous clayey slope of 1.75H:1V slope angle, with increasing shear strength of of 1.5 kPa/m from the surface to the bedrock. Initial shear strength is of 25 kPa. Slope height is 10 m and deposit thickness is of 15 m.

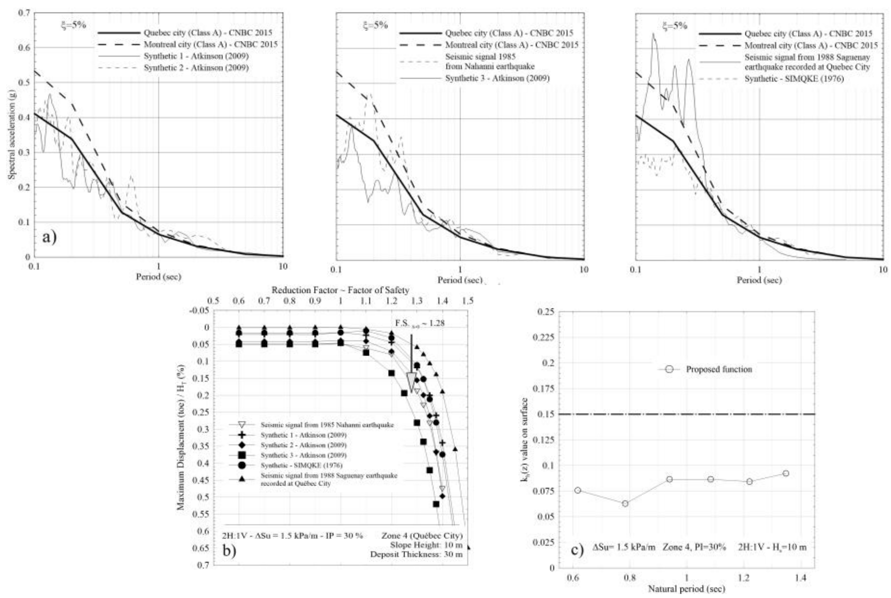

Figure 5: FD numerical simulations for 2H:1V slope angle, ΔS_u of 1.5 kPa/m,. H_S of 10 m and H_D of 30 m clay slope: a) seismic Zone 4 Quebec City compatible spectrum Synthetic-1 [15], Synthetic-2 [15], Synthetic-3 [15], 1985 Nahanni earthquake [16], 1988 Saguenay earthquake recorded at Quebec City [17] and Synthetic – SIMQKE [18] b) reduction factor vs maximum displacement at toe for dynamic simulations and c) proposed spectral pseudo-static function for corresponding natural periods of 2H:1V slope height H_S of 10 m.

of the seismic coefficient on surface is 0.092. This means that when using hyperbolic function of Eq. (1) where *a* and *b* are 2 and 2, the value of the seismic coefficient at bedrock k_{h0} is 0.031. To summarize, for a 2H:1V clay slope of 10 m slope height, 30 m deposit thickness with increasing shear strength of horizontal layers of 1.5 kPa/m and shear strength on the surface of 25 kPa, a numerical simulation using LE analysis with a 0.031 seismic coefficient using *a* and *b* of 2 and 2 should provide a factor of safety of 1.28.

Following this ascertainment, numerical simulation using LE method has been performed in SVSLOPE for the corresponding geometry. The model has been built to constitute the same as the one proposed for dynamic analysis, i.e. horizontal layers of 1 m with increasing shear strength of 1.5 kPa/m with initial value of 25 kPa on surface. The results are presented in Figure 6 and have been executed using the proposed seismic coefficient at the bedrock k_{h0} of 0.031, and coefficients *a* and *b* are 2 and 2 to simulate the earthquake effect. The slip surface agrees with the observations performed by Karray et al. [9] for clayey slopes since located at the toe of the slope. Therefore, comparison can be made between the resulting factor of safety of 1.30 and results of FD dynamic simulations of Figure 5a and Table 4, which suggest that a conservative value of the factor of safety is 1.28 for the current analysis. Hence, the error between LE simulation in SVSLOPE and reference FD dynamic simulations is

Table 3: Dynamic factor of safety for six compatible earthquakes of Quebec City seismic Zone 4, performed on 2H:1V clay slope of 10 m slope height, 30 m deposit thickness with increasing shear strength of 1.5 kPa/m.

Earthquake	Factor of safety
Synthetic Atkinson-1 (2009)	1.35
Synthetic Atkinson-2 (2009)	1.33
Synthetic Atkinson-3 (2009)	1.25
Synthetic SIMQKE (Vanmarcke, 1976)	1.35
1988 Saguenay Earthquake (Boore, 1989) measured at Quebec City	1.40
1985 Nahanni Earthquake (Boore, 1992)	1.30

Table 4: Statistical parameters for six compatible earthquakes of Quebec City seismic Zone 4, performed on 2H:1V clay slope of 10 m slope height, 30 m deposit thickness with increasing shear strength of 1.5 kPa/m.

Statistical parameter	Factor of safety
$\bar{x}$	1.33
σ	0.05
$\bar{x} - \sigma$	1.28

of 1.3 % for this numerical simulation. This shows the efficiency of the proposed hyperbolic function of the seismic force of Eq. (1) for predicting factor of safety as well as the slip surface in LE software SVSLOPE.

In order to visualize the difference in terms of earthquake effect on the slope, the pseudo-static approach as proposed by Terzaghi [1] is applied to the slope. As suggested by the Centre d'expertise hydrique du Québec [12] for Quebec City seismic Zone 4, a constant pseudo-static coefficient of 0.15 is applied in the model. This means that inside a same seismic zone, slopes which have different natural period or different dynamic properties are to be applied the same constant seismic coefficient, as for the current analysis. As remarked by Karray et al. [9], the pseudo-static method produces very deep slip surfaces, that go often to the bedrock for clays, which can also be seen in Figure 6b. One of the reasons of this is the constant seismic force applied through the deposit, as well as the low shear strength of clays. The position of the toe of the slip surface is nevertheless far from the toe of slope, which means the pseudo-static method fails to predict correction of slip surface. In the case of this 2H:1V clay slope with increasing shear strength of 1.5 kPa/m, the LE simulation produces slip surface which hits the bedrock and is wide of roughly 240 m large. Since the LE position of the grid to calculate factor of safety is extremely high in elevation due to deep slip surface, the grid is shown in Figure 6c for visual presentation needs. It should nevertheless be noted that position of the center of the grid is at 230 m on elevation in the model to adequately calculate contours of the factor of safety. The resulting factor of safety for the carried out simulation is of 0.90, meaning failure occurs. The error difference of the factor of safety between FD simulations for this geometry shown at Table 4 and pseudo-static simulation is therefore of 29.6 %. For comparison, it should also be mentioned that difference of factors or safety of the proposed spectral pseudo-static approach, which proposes hyperbolic variation of seismic force with height, and pseudo-static approach as proposed by Terzaghi [1], where seismic force is constant along the deposit, procure a difference of 30.3 %. The results of the carried out simulations therefore show the superiority of the spectral pseudo-static approach for clayey slopes in comparison with the pseudo-static approach: the use of hyperbolic variation of seismic force as proposed by Eq. (1) provides realistic slip surface and factors of safety, as constant seismic force along deposit provides factor of safety greatly different from that of FD dynamic analysis.

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 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 [4], [5], [6], [8], [9] and [10]. The proposed approach can be used with certainty inside LE software SVSLOPE for conception purposes.

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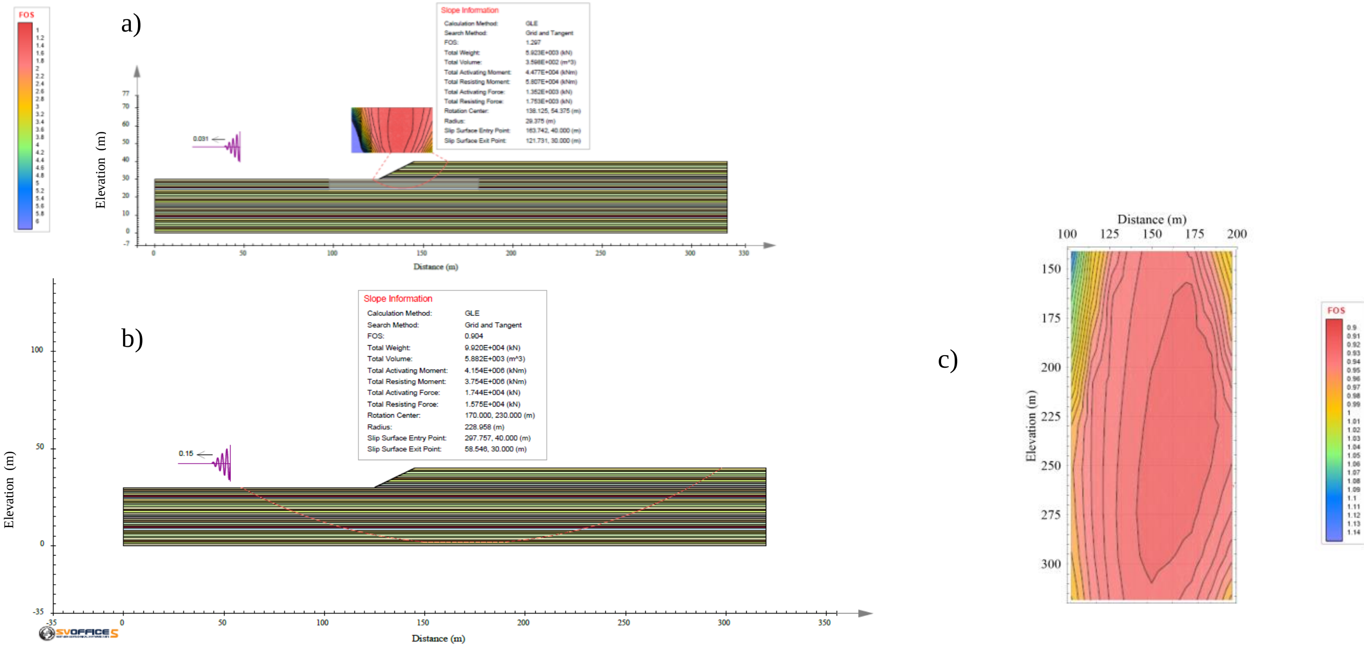

Figure 6:LE simulations carried out for 2H:1V slope angle, slope height of 10 m, deposit thickness of 30 m and increasing shear strength of 1.5 kPa/m a) spectral pseudo-static approach b) conventional pseudo-static approach c) corresponding grid

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