

# Development of methods for the stability assessment of slopes subjected to seismic loading based on dynamic FE analyses

**Christoph Schmüdderich, Torsten Wichtmann**

*Chair of Soil Mechanics, Foundation Engineering and Environmental Geotechnics, Ruhr-University Bochum, Germany*

**Jan Machaček**

*Institute of Geotechnics, Technische Universität Darmstadt, Germany*

**Luis Felipe Prada-Sarmiento**

*Department of Civil and Environmental Engineering, Aarhus University, Denmark*

**Patrick Staubach**

*Chair of Geotechnics, Bauhaus-Universität Weimar, Germany*

**ABSTRACT:** Stability analyses are used to evaluate the level of safety for natural or man-made slopes or other geotechnical structures. Considering slopes subjected to seismic loading, many simplifications are required when adopting common stability approaches. An accurate incorporation of effective stresses, excess pore water pressures or accelerations is mostly not possible. The present work was dedicated to the development of approaches for the assessment of seismic slope stability based on results of dynamic finite-element analyses (DFEA). The latter can provide realistic spatial and temporal distributions of stresses, excess pore water pressures and accelerations during a seismic event that should be accounted for in the stability analyses. Three approaches were presented, allowing for a more rigorous assessment of the seismic slope stability. These approaches are based on extensions of the limit equilibrium method (LEM), strength reduction finite-element analysis (SRFEA) and strain-dependent slope stability (SDSS). In contrast to conventional approaches, the proposed methods enabled to investigate the evolution of the Factor of Safety (FoS) during dynamic loading while accounting for the influence of potential excess pore water pressures. The stability analyses were carried out using geoSlice (LEM) and pySDSS software packages and the FE software package numgeo. The applicability of the approaches was shown for a well-known centrifuge model test subjected to seismic loading, where DFEA and subsequent stability analyses were conducted. The study showed the importance of advanced approaches for slope stability assessment, especially for analyzing the evolution of slope stability during seismic loading. In addition, the critical failure surface associated with the least factor of safety changed rapidly during a seismic event because of spatially and temporally varying accelerations and excess pore water pressures. Lastly, LEM and SRFEA showed an earlier and more significant impact of the seismic loading on the predicted FoS.

**KEYWORDS:** Dynamic finite element analysis, Earthquake, Factor of safety, Slope stability

## 1 INTRODUCTION

The stability assessment of slopes enclosing residual lakes formed in decommissioned opencast pit mines poses significant challenges, particularly under seismic loading. These slopes are often constructed from uncompacted materials deposited by spreaders, making them prone to densification during earthquakes. This tendency to densification leads to an increase of excess pore water pressures under undrained or partially drained conditions, consequently resulting in a decrease of effective stress and shear resistance, heightening the risk of slope failure or liquefaction. Even when full liquefaction is avoided, the temporary reduction in shear strength during seismic events can lead to significant instabilities. To improve safety assessments under such conditions, advanced numerical models that can simulate the dynamic behavior of soils, such as strain accumulation, pore pressure build-up, and stress history effects, are essential.

Various methods exist for static slope stability analysis. Traditional approaches include the limit equilibrium method (LEM) (Janbu, 1954; Bishop, 1955; Morgenstern and Price, 1965; Spencer, 1967), limit analysis (LA) (Chen et al., 1969; Michalowski, 1995), strength reduction finite element analysis (SRFEA) (Matsui and San, 1992; Griffiths and Lane, 1999; Tschuchnigg et al., 2015), and finite element limit analysis (FELA) (Sloan, 2013; Krabbenhoft and Lyamin, 2015; Mahmoudi et al., 2020; Schmüdderich et al., 2025), as well as stress-based approaches (Zou et al., 1995; Farias and Naylor, 1998). While many methods rely on simple elastoplastic models or only account for a failure criterion, more advanced work has

explored the use of more complex constitutive models such as barodesy (Schneider-Muntau et al., 2018) and clay hypoplasticity (Kadlíček and Masín, 2020). Recently, the concept of strain-dependent slope stability (SDSS) proposed by Nitsche and Herle (2020), which allows the use of arbitrary constitutive model for slope stability analysis, has been extended for circular slip surfaces and applied to slopes subjected to earthquake loading (Schmüdderich et al., 2022; Schmüdderich, 2024; Shakya et al., 2024). When seismic effects are considered, methods are typically classified into three categories (Jibson, 1993). The Pseudo-Static Analysis (PSA) simplifies seismic forces as constant static loads applied to a potential sliding mass. This method is widely used with LEM, LA, SRFEA, and FELA but is limited by its assumptions of constant force and often neglects excess pore water pressures. The Pseudo-Dynamic Approach (PDA) improves upon PSA by allowing the seismic load to vary with time and location, although it still requires assumptions about the nature of ground motion and often ignores excess pore water pressures. The Permanent Displacement Method, based on Newmark's sliding block theory (Newmark, 1965; Kramer, 1996), evaluates displacement by integrating the difference between ground acceleration and yield acceleration over time. While widely used, it requires predefined acceptable displacements or velocities and assumes a rigid sliding mass. Over the decades, the method has been extended to consider factors like soil deformability and excess pore water pressure build-up. Dynamic Finite Element Analysis (DFEA) is the most comprehensive method, as it can model the spatial and temporal evolution of stresses, strains, accelerations, and excess pore

water pressures during seismic events, especially when sophisticated constitutive models and coupled displacement-pore water pressure element formulations (u-p) are used. Although DFEA provides detailed insights, assessing the factor of safety (FoS) still requires additional analysis. A common practice is to run multiple DFEA simulations with varied strength and stiffness parameters to detect instability indicators, such as rapid displacement increases or numerical non-convergence. However, this approach is computationally expensive.

To balance accuracy and efficiency, hybrid or two-step approaches are being explored. These involve using DFEA results, such as distributions of excess pore water pressure and accelerations, as inputs for follow-up stability analyses via LEM, LA, SRFEA or FELA. Despite their promise, such coupled frameworks are still under development, and only a few studies have fully implemented them. Nevertheless, due to regulatory requirements demanding quantifiable safety metrics like FoS, the development of reliable and computationally efficient seismic slope stability analysis tools remains a high priority in geotechnical engineering (Dahmen, 2019).

In this study, three hybrid approaches based on DFEA coupled with LEM, SRFEA and SDSS are presented. The applicability of the approaches is demonstrated for a centrifuge model test of an earth dam subjected to seismic loading.

## 2 METHODS

### 2.1 Limit Equilibrium Method (LEM)

The Limit Equilibrium Method (LEM) is a collective term encompassing a variety of approaches that share common assumptions regarding the shape of the slip surface, the method for identifying the critical slip surface, the distribution of stresses, and the definition of yield strength along the slip surface. A fundamental characteristic of all LEM techniques is that slope stability is analyzed based on a multitude of predefined slip surfaces, from which the critical slip surface - defined as the one with the lowest safety against loss of stability - is determined using optimization algorithms. In this study, LEM specifically refers to Bishop's method of slices (Bishop, 1955), with the factor of safety (FoS) defined as shown in Equation (1).

$$\text{FoS} = \frac{\sum_i R_i \cdot (c'_i l_i + N'_i \tan \phi'_i)}{\sum R_i \cdot W_i \sin \alpha_i} \quad (1)$$

In this equation,  $[ ]_i$  refers to the number of the slice,  $R$  denotes the radius,  $l$  and  $\alpha$  the base length and inclination of a slice,  $\phi'$  and  $c'$  the friction angle and cohesion of the soil,  $W$  the total weight of the slice, and  $N'$  the effective normal force at the slice base. The latter one can be expressed via

$$N'_i = \frac{W_i - l_i \left( u_i \cos \alpha_i + \frac{c'_i}{\text{FoS}} \sin \alpha_i \right)}{\cos \alpha_i + \frac{\tan \phi'_i \sin \alpha_i}{\text{FoS}}} \quad (2)$$

where  $u$  denotes the hydrostatic pore water pressure. Note that the FoS must be determined in an iterative manner as it is both the output in Eq. (1) and an input for  $N'$  in Eq. (2) that again contributes to Eq. (1).

### 2.2 Strength Reduction Finite-Element Analysis (SRFEA)

To quantify the level of safety for a slope using the strength reduction finite element analysis (SRFEA), the shear strength parameters of the soil ( $\tan \phi'$  and  $c'$ ) are gradually reduced until failure is obtained. The FoS can then be expressed as the ratio of the shear strength at current and failure state, expressed

according to Eq. (3) with  $\phi_{\text{red}}$  and  $c_{\text{red}}$  referring to the reduced friction angle and the reduced cohesion at failure, respectively.

$$\text{FoS} = \frac{\tan \phi}{\tan \phi_{\text{red}}} = \frac{c}{c_{\text{red}}} \quad (3)$$

According to literature, different concepts can be followed to detect failure, for instance 1) bulging of the slope expressed in terms of large nodal displacements or shear strains, 2) a continuous plastic zone extending from the top to the bottom of the slope and 3) non-convergence of the solution indicated by large, unbalanced forces. In this study, a displacement-based criterion proposed in Schmüdderich (2024) is used.

Main advantages of the SRFEA include that no a-priori assumptions on the shape or location of the failure mechanism are required. The critical slip surface is found automatically as slope failure occurs naturally through the zones of insufficient shear strength. SRFEA can be performed in software like numgeo using different linear-elastic perfectly plastic constitutive models, such as Mohr-Coulomb, Drucker-Prager and Matsuoka-Nakai.

### 2.3 Strain-dependent Slope Stability (SDSS)

To evaluate slope stability while accounting for the current stress state, stress history, soil density, and realistic stress-strain behavior, the strain-dependent slope stability (SDSS) concept can be applied. This approach determines the factor of safety (FoS) for a predefined slip surface, which is discretized by a user-defined number of points. A pre-calculated stress field (e.g., from finite element analyses) is used to determine the stress state at each of these points, which are then rotated to align with the slip surface. The FoS is calculated based on shear stress mobilization, integrating the soil's stress-strain response. Simple shear element tests are simulated at each point along the slip surface to assess shear stress mobilization as shear strain increases. For a slip surface of length  $L$ , the global mobilized shear resistance ratio  $T(\gamma)$  is computed using Eq. (4), integrating the mobilized shear stresses  $\tau_{\text{mob}}$  over shear strain  $\gamma$  for segments  $i$  of length  $L_i$ , and normalizing by the initial shear stresses  $\tau_0$  integrated over the same segments. Based on  $T(\gamma)$ , the maximum value  $T_{\text{max}}$  and the corresponding shear strain  $\gamma_{\text{max}}$  is determined. Slope stability is evaluated as  $\text{FoS}(\gamma) = T_{\text{max}}$  for  $\gamma \leq \gamma_{\text{max}}$  and  $\text{FoS}(\gamma) = T(\gamma)$  for  $\gamma > \gamma_{\text{max}}$ .

$$T(\gamma) = \frac{\sum_i \tau_{\text{mob},i}(\gamma) \cdot L_i}{\sum_i \tau_0 \cdot L_i} \quad (4)$$

A key advantage of SDSS over conventional slope stability approaches is its ability to integrate advanced constitutive models for FoS estimation. This allows the same model to be employed both in the simulation of the large boundary value problem (BVP) and in the SDSS-based stability analysis. In addition to the stress state, other state variables from the constitutive model (e.g., void ratio) can also be transferred from the BVP to the element-level tests. This facilitates a more realistic representation of complex soil mechanical behavior in slope stability assessments.

## 3 APPROACHES FOR SEISMIC SLOPE STABILITY ASSESSMENT

### 3.1 Introduction

To assess the behavior of slopes subjected to seismic loading, dynamic finite element analyses (DFEA) should be performed using advanced constitutive models capable of capturing key aspects such as strain accumulation and the development of excess pore water pressures. DFEA yields information on

displacements and potential soil liquefaction, which can serve as an initial estimate of seismic slope stability. For a quantitative evaluation based on DFEA results, engineers typically rely on project-specific displacement or strain thresholds, which require substantial professional experience. As these thresholds can vary between practitioners, such assessments are inherently subjective.

To address this limitation, the objective of this work is to present alternative methods for an objective evaluation of seismic slope stability. These methods are based on three different approaches: LEM, SRFEA, and SDSS. A common feature of all three methods is that they are applied after the DFEA, ensuring that the dynamic simulation remains unaffected by the choice of stability assessment method. For the sake of completeness, it should be noted that Schmüdderich (2024) and Schmüdderich et al. (2025) also proposed an approach combining DFEA and FELA for assessing seismic slope stability.

### 3.2 Spatial pseudo-static analysis using LEM

A common approach to evaluate the stability of slopes subjected to seismic loading is the pseudo-static analysis (PSA), as discussed in Section 1, where inertial forces are explicitly included in the slope stability analysis. These inertial forces are calculated based on the soil unit weight and pseudo-static (or seismic) coefficients  $k_h$  and  $k_v$ , which represent horizontal and vertical accelerations normalized by gravitational acceleration. When PSA is combined with the Limit Equilibrium Method (LEM), seismic effects are incorporated into the analysis by applying inertial forces to each slice. PSA can be carried out using either constant or spatially varying pseudo-static coefficients across the domain. However, spatial distributions of pseudo-static coefficients are not always available for every boundary value problem and many commercial LEM programs, such as GGU-Stability (2021), only support the use of constant pseudo-static coefficients for the entire domain, without the ability to import external spatial distributions. Other programs, such as Quake/W (GeoStudio, 2020), offer the capability to perform DFEA with a limited range of constitutive models to approximate spatial variations in seismic coefficients and excess pore water pressures. It is important to note that excess pore water pressures can have a significant influence on slope stability and should therefore be considered in PSA.

geoSlice (an inhouse-LEM code developed by the first author, Schmüdderich, 2024) enables users to define a constant value or import a spatial distribution of pseudo-static coefficients. The implementation of constant coefficients has been verified through comparative analyses with GGU-Stability. Contrary to other available software, geoSlice supports the import of spatially varying fields. This functionality allows for seismic slope stability assessments to be performed using spatially varying acceleration and pore pressure data, such as those derived from a dynamic finite element analysis (DFEA).

### 3.3 Spatial pseudo-static analysis using SRFEA

The spatial pseudo-static analysis using Strength Reduction Finite Element Analysis (SRFEA) aims to perform both the DFEA and SRFEA within the same software environment. The numgeo software package (Machaček, 2020; Staubach, 2022) was selected for this purpose, as it already includes key capabilities such as dynamic finite element analysis (DFEA) and advanced constitutive models, which were implemented and verified prior to this study. Additional features, including elastoplastic constitutive models (e.g., Mohr-Coulomb and Matsuoka-Nakai) and the strength reduction method, were introduced to numgeo in Schmüdderich (2024).

A significant advantage of conducting both DFEA and SRFEA within the same software package is the consistent use of interpolation schemes, element types, and spatial discretization across both analyses. This consistency simplifies the transfer of stress states, excess pore water pressures, and state variables between the two steps. Furthermore, using a single software platform facilitates the automation of the sequential analyses, offering efficiency and reliability. It is important to recognize that during a seismic event, the system is in a state of dynamic equilibrium. However, slope stability analyses are typically based on static equilibrium. To incorporate dynamic effects into the stability analysis, inertial forces must be accounted for. In this approach, the global nodal inertial force vector, obtained as the product of the mass matrix and acceleration vector, is stored during the dynamic simulation along with relevant nodal and element data. In the SRFEA, this nodal inertial force vector is imported and applied as an additional external force vector, preserving the influence of dynamic loading within the static framework of the slope stability analysis.

SRFEA is performed using a so-called Restart analysis, which allows changes to the material model and boundary conditions by restarting a previously completed simulation. While robust and easy to use, this method is computationally expensive, as multiple DFEAs must be run to track the evolution of the FoS during a seismic event. Assuming constant frequency over the DFEA duration, approximately  $n/2$  DFEAs are required for  $n$  SRFEA evaluations. A more efficient alternative is the so-called Submodel analysis available in numgeo. Here, the main DFEA simulation is paused while an SRFEA is executed on a copied instance of the FE model at a selected moment during the dynamic loading. Once the SRFEA is completed, the DFEA resumes. This approach significantly reduces computational costs while still capturing the effects of seismic loading on slope stability.

### 3.4 SDSS for earthquake loading

Following Nitzsche and Herle (2020), the global mobilized shear resistance ratio  $T(\gamma)$ , presented in Eq. (4), is constrained to begin at  $T(\gamma = 0.0) = 1.0$  for any slip surface, regardless of boundary conditions or constitutive models. This results from the chosen normalization, where division by the sum of initial shear stresses ensures unity at the start of the  $T(\gamma)$  curve. Since  $\text{FoS}_{\max} \geq 1.0$  is always ensured, slope failure cannot be identified based on the original approach with  $\text{FoS}_{\max}$  as indicator for safety at low strain levels. In static FE simulations with advanced constitutive models (e.g., multi-surface bounding plasticity, hypoplasticity), this constraint may be secondary, as equilibrium should not be found for unstable slopes. However, in dynamic analyses including damping and inertial effects, failure does not necessarily cause non-convergence. Inertial forces can maintain equilibrium, allowing the simulation to continue far beyond the point of momentary failure. To enable the classification of unstable slopes with FoS smaller than 1.0, the SDSS approach is modified to include dynamic time  $t_{\text{dyn}}$  during seismic loading and a reference time  $t_0$  representing static conditions. The revised approach for the determination of  $T(\gamma)$  in DFEA is shown in Eq. (5).

$$T(\gamma) = \frac{\sum_i \tau_{\text{mob},i}(\gamma, t_{\text{dyn}}) \cdot L_i}{\sum_i \tau_0(t_0) \cdot L_i} \quad (5)$$

Note that the FoS curve is evaluated in the same way as in the original approach: thus,  $\text{FoS}(\gamma)$  is equal to the maximum global mobilized shear resistance ratio  $T_{\max}$  for shear strains less than the one associated with  $T_{\max}$ . Otherwise, the  $\text{FoS}(\gamma)$  curve is identical to the  $T(\gamma)$  curve.

Table 1. Parameters of the Hypoplastic model ( $\varphi_c - \beta$ ) with intergranular strain (IGS,  $m_T - \chi$ ) for Nevada sand (Triantafyllidis et al., 2022)

$\varphi_c$ in $^\circ$	$\nu$	$h_s$ in MPa	$n$	$e_{d0}$	$e_{c0}$	$e_{i0}$	$\alpha$	$\beta$	$m_T$	$m_R$	$R$	$\beta_R$	$\chi$
31.0	0.24	755	0.328	0.511	0.883	1.05	0.34	0.9	4.5	9.0	$10^{-4}$	1.4	0.48

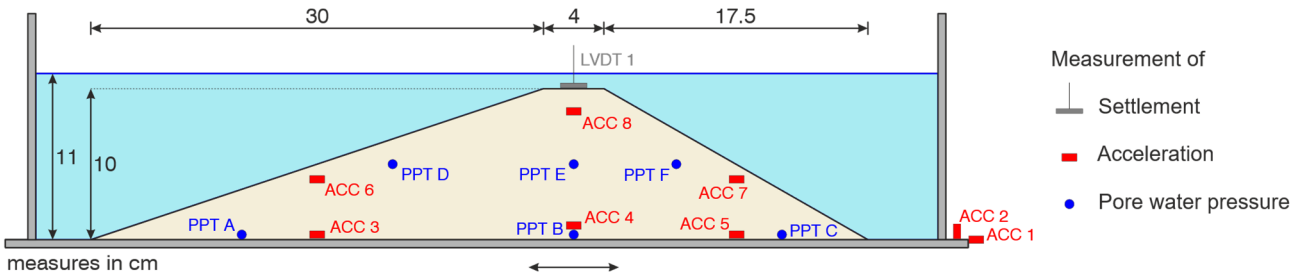


Figure 1. Geometry and dimensions of the VELACS dam model in centrifuge model scale, modified after Muraleetharan et al. (2004)

## 4 CENTRIFUGE MODEL TEST

### 4.1 Introduction

Centrifuge model tests were performed at Rensselaer Polytechnic Institute as part of the Verification of Liquefaction Analyses by Centrifuge Studies (VELACS). These tests, including the one examined in this study, were documented by Arumoli et al. (1992) and Muraleetharan et al. (2004). The geometry and dimensions of the model, in centrifuge scale, are schematically illustrated in Figure 1. The tests were conducted at a centrifugal acceleration of 50 g. Accordingly, the dam had approximate dimensions of 51.5 cm in width and 10 cm in height in model scale. The water table was at a height of 11 cm. To construct the model, oven-dried Nevada Sand was pluviated into the container to form the dam, achieving a relative density of  $D_r = 43\%$ . Once the dam was formed, the water level was raised to its final elevation, and the centrifuge was accelerated to 50 g. Dynamic loading was applied by subjecting the base of the model to lateral acceleration in accordance with the input motion shown in Figure 2. Note that the time axis in Figure 2 also corresponds to the centrifuge model scale.

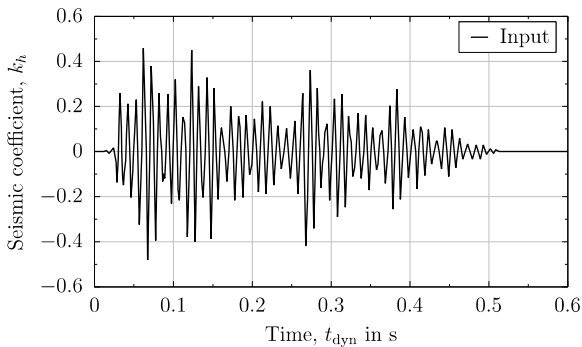


Figure 2. Input motion at the bottom of the VELACS model

### 4.2 Dynamic Finite-Element Analysis

The finite element software numgeo was used for the analysis of the dynamic excitation of the VELACS centrifuge model test. The simulation was performed in model scale, including the spin-up of the centrifuge (increase of gravity to 50 g). The mechanical behavior of Nevada sand is modeled using Hypoplasticity with Intergranular Strain (IGS) with the parameters provided in Table 1. A bulk modulus of  $K^w = 5$  MPa and a hydraulic conductivity of  $K = 6.6 \cdot 10^{-5}$  m/s were used. The FE model consists of 1089 elements and 3417 nodes. To account for changes in the pore water pressure and

consolidation effects during and after the earthquake loading, so-called u-p elements are used, discretizing the solid displacements  $\mathbf{u}$  and the pore water pressure  $p^w$  at the nodes. The simulations are performed in an updated Lagrangian framework, using the Zaremba-Jaumann objective stress rate. The simulation was performed in the following steps:

1. Application of gravity (1 g) while displacements of the bottom boundary were constrained in both directions. The pore water pressure was prescribed at each node according to a hydrostatic distribution, considering the phreatic level depicted in Figure 1.
2. Gravity is increased from 1 g to 50 g in small increments to approximate the spin-up phase. Note that the unit weight of the soil and the water are affected by the increased gravity.
3. Excitation of the model base in the horizontal direction in a dynamic step. The excitation is applied by a Dirichlet boundary condition, imposing the acceleration-time history depicted in Figure 2.

### 4.3 Results of the dynamic analysis

To assess whether the DFEA using Hypoplasticity by von Wolffersdorff (1996) with Intergranular Strain (Niemunis and Herle, 1997) is capable of reproducing the results of the centrifuge model test, vertical displacement, acceleration and excess pore water pressure time histories obtained from the experiment and the numerical simulation are compared for sensors LVDT 1, ACC 7 and PPT F in Figure 3.

In both the experiment and numerical simulation, no displacements occur up to  $t \approx 0.03$  s due to the initially low amplitudes of dynamic loading. As the loading amplitudes increase, displacements begin and show an almost linear growth until  $t \approx 0.4$  s. After this point, the rate of displacement slows down. For  $t > 0.45$  s, displacements in the experiment remain nearly constant, while the simulation still shows slight changes. Overall, there is good agreement between experimental and simulated displacements throughout the test. The FoS could be estimated based on a displacement threshold, though it should be noted that the final 1.5 cm displacement (15% vertical strain) clearly exceeds acceptable limits for design.

Analyzing the horizontal accelerations in terms of seismic coefficients from the experiment and the numerical simulation, slight deviations are seen for ACC 7. Comparing excess pore water pressures at PPT F, underestimation of  $\Delta p^w$  is observed in the simulation. Increased  $\Delta p^w$  of about 4.0 kPa remain in the experiment after the test, which may result from deformation of the soil and the transducers. Note that underestimation of  $\Delta p^w$  in the simulation results in larger effective stresses and larger shear resistance, potentially leading to a higher FoS prediction.

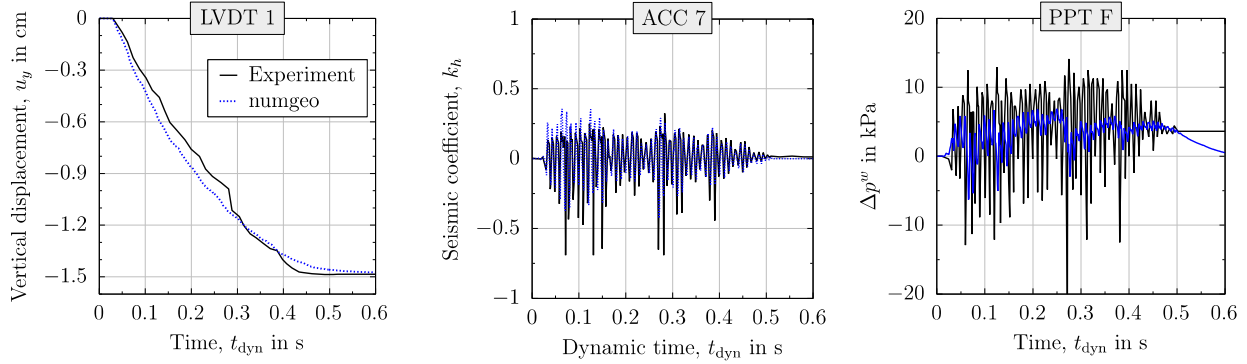


Figure 3. Comparison of vertical displacements (LVDT 1), horizontal seismic coefficients (ACC 7) and excess pore water pressures (PPT F) obtained from numgeo with measurement from the experiment (Muraleetharan et al., 2004)

#### 4.4 Slope stability assessment

To assess the evolution of the FoS during dynamic loading in the VELACS model, all three methods (LEM, SRFEA, SDSS) were used. To ensure consistency with the dynamic analysis, a stabilizing load of 1 kPa was applied for all stability analyses. In contrast to SRFEA, where the failure surface was identified automatically, in LEM and SDSS, many slip surfaces were evaluated to determine the most critical one associated with the least FoS. Additionally, LEM and SDSS required separate analyses for the left and right sides of the dam. Further details on each approach are provided in the following paragraph.

In LEM, spatial distributions of pseudo-static coefficients ( $k_h$  and  $k_v$ ) and excess pore water pressures  $\Delta p^w$  were transferred from the DFEA. While  $k_h$  values were always considered acting in the driving direction,  $k_v$  values were varied to determine the critical direction. Unit weights of the soil and the water were determined considering increased gravity. Unlike SDSS and SRFEA, which used the Matsuoka-Nakai (MN) surface as the yield or limit surface to guarantee consistency with the hypoplastic model used for the dynamic analysis, in LEM, the Mohr-Coulomb (MC) criterion was used. For plane strain problems, such as 2D slope stability, with Lode angles  $0^\circ \leq \theta \leq 10^\circ$ , MC yields lower shear strength, resulting in smaller FoS. To compensate for this, an equivalent friction angle according to Griffiths and Huang (2009) of  $\varphi_{MC} = 34.75^\circ$  was used. In SRFEA, the stress state, (excess) pore water pressures and inertial forces were transferred from the DFEA, where the latter two were kept constant throughout the stability analyses. The material behavior was modelled using the MN model with  $\varphi = \varphi_c$  (Table 1). SRFEA was performed considering an initial FoS of  $FoS_0 = 0.5$ . The critical FoS was obtained using a displacement-based criterion. Moreover, the

influence of inertial forces (NDF) was studied. In SDSS, the hypoplastic model was used in accordance with the DFEA. Note that intergranular strain (IGS) was deactivated in SDSS to avoid overestimation of the shear stresses and FoS. The stress tensor and the void ratio were transferred from the DFEA to the element test simulations. SDSS was conducted via direct simple shear (DSS) tests for 15 nodes along a potential slip surface. Evaluation of  $T(\gamma)$  was conducted in accordance with Eq. (5) and slope stability was assessed via  $FoS_{max}$ . As computational costs associated with SDSS are larger than for LEM and SRFEA, stability analyses were conducted for fewer time steps.

The results of the slope stability analyses are depicted in Figure 4. Initially, the FoS is comparable across all approaches, with higher FoS for the left side of the dam due to a gentler slope. Once the seismic excitation starts (Figure 2), a significant drop in the FoS is seen. This drop is more pronounced for LEM and SRFEA as inertial forces are directly considered in the approaches. In SDSS, a less pronounced drop is seen and the FoS rather reduces as  $\Delta p^w$  increases. For all approaches, rapid fluctuations in FoS are apparent that can be explained by the high-frequency nature of the seismic input signal. As a result, the critical failure mechanism often switches between the left and right sides, a behavior seen in Figure 4 (LEM, SDSS) but also observed when evaluating the displacement patterns obtained from SRFEA. Between 0.4 and 0.5 seconds, as the seismic signal weakens, the magnitude of the fluctuations of FoS decreases accordingly. After 0.5 seconds, the FoS increases again, aligning well with the dissipation of  $\Delta p^w$  (Figure 3). Comparing LEM and SRFEA, both approaches classify the VELACS model as unstable for almost the entire test duration, while SDSS shows a little delay in this regard. Note that FoS estimates based on LEM should be considered conservative as inertial forces are always considered acting in driving direction.

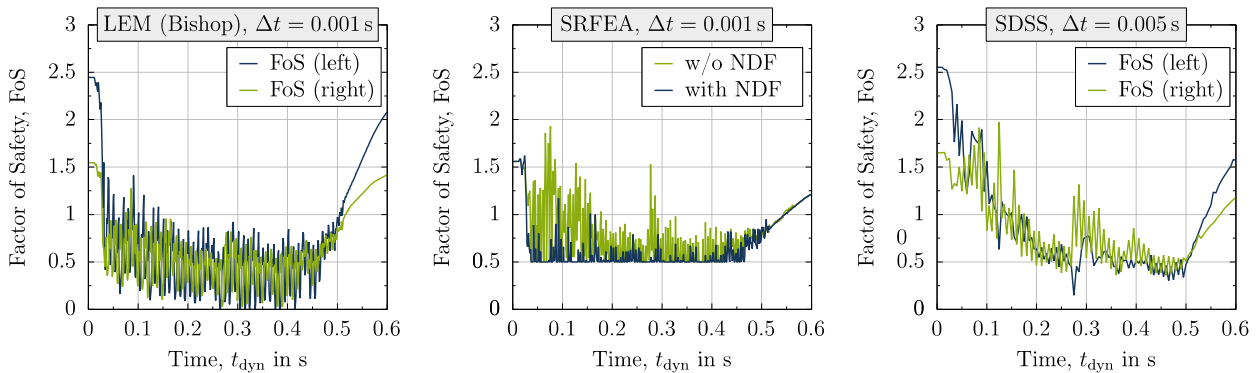


Figure 4. Evaluation of the FoS of the VELACS model dam based on LEM considering a slope failure to the left and right side, based on SRFEA with or without considering inertial forces (NDF), and based on SDSS considering a slope failure to the left and right side

## 5 SUMMARY, CONCLUSIONS AND OUTLOOK

This study was dedicated to the development of approaches for seismic slope stability assessment. Three approaches based on the limit equilibrium method (LEM), strength reduction finite-element analysis (SRFEA) and strain-dependent slope stability (SDSS) were presented. All three approaches were designed to be conducted after dynamic finite-element analyses (DFEA), which provided realistic estimates of spatial and temporal distributions of stresses, excess pore water pressures and accelerations during a seismic event. The applicability of the approaches was shown for the VELACS centrifuge model test, a model dam accelerated to 50 g and subjected to high-frequency seismic loading. Based on the analyses performed in this study, the following general conclusion can be drawn:

1. Final vertical displacements of 1.5 cm (15% strain) in the centrifuge test show seismic loading significantly affected dam stability, though the exact moment of failure is difficult to detect based on the evolution of displacements.
2. Accurate FoS assessment under seismic loading requires DFEA with advanced constitutive models for cyclic behavior, followed by proper stability analyses.
3. Stability analyses must account for spatial and temporal variations in inertial forces and excess pore pressures, which strongly influence FoS.
4. Stability analyses of the VELACS model revealed that the high-frequency seismic input signal causes the FoS to fluctuate rapidly, with the critical slip surface switching between the left and right slopes based on seismic intensity and distribution.

Further boundary value problems of slopes or dams subjected to seismic loading should be studied to improve the level of confidence working with the new approaches for seismic slope stability assessment. Also, other sophisticated constitutive models suitable for soil behavior under cyclic loading should be used with SDSS to study the influence of the constitutive model on the FoS. Lastly, the new approaches should be used to analyze the slope stability of transient problems, for instance slopes subjected to infiltration or rapid water level drawdown.

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