COVER SHEET

Title: Finite Element Safety Analyses of a Geosynthetic-Reinforced Dam under Seismic Impact

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In geotechnical practice the analysis of safety against failure of embankments and dams exposed to earthquakes is usually performed by conventional slip circle analyses or other analytical "rigid body" methods using equivalent quasi-static forces. In contrast e.g. the German code DIN 19700 „Dam plants - Part 11: Dams" demands dynamic calculations for dams higher than 40 m. However, no indications are given how to perform such dynamic analyses. The issue can be of interest for smaller but sensitive dams as well. The paper presents a FEM based procedure for such cases.
The FE analyses enable a realistic modeling of the dam, the subsoil and the seismic excitation.
An example of a geosynthetic-reinforced reservoir dam with a waterproof geomembrane is given based on a real project.
Geometries, soils and geosynthetic reinforcement parameters, loads, constitutive models, and specific assumptions are described. Relevant results are presented and discussed together with specific issues concerning the geosynthetics and recommendations and conclusions are given.

INTRODUCTION

In practice the geotechnical engineer consistently faces the challenge, that relevant codes demand numerical analyses, which are not further specified, e.g. in the framework of serviceability and ultimate limit state safety analyses for offshore wind mill foundations or for earth dams. The latter is discussed in this paper.

Conventional approaches (e.g. slip circles "Bishop") with quasi-static horizontal "equivalent" loads generally do not represent realist mechanisms, and should therefore be accompanied by more comprehensive numerical analyses, using e.g. the finite element or finite differences method.

A novel procedure [5], the "dynamic phi-c-reduction" for a quantitative assessment of the safety of earth dams with a water face sealing against failure during seismic excitation in geotechnical practice is presented.

In the following chapter the procedure is explained, followed by an application example. Finally, a summary and an outlook are given.

DYNAMIC PHI-C-REDUCTION

The basic idea is similar to a conventional phi-c-reduction, i.e. the shear strength parameters are linearly decreased until a fully developed failure mechanism is found due to the dynamic excitation.

Starting with the original set, the shear parameters, i.e. the coefficient of internal friction tan(φ') and the cohesion c' are linearly reduced by means of a reduction factor (R.F.), starting with steps of 10% w.r.t. the initial values. Close to failure the step size is reduced to 5%.

For each set of parameters a complete simulation of the relevant seismic event is carried out by means of a finite element analysis using an advanced constitutive model allowing e.g. for deformation dependent shear modulus of the subsoil and therewith material damping (hardening soil small strain model, cf. below). Next an animation of the calculation results is generated and examined for failure mechanisms.

For this purpose (a) the deviatoric strain invariant and (b) plastic and tension cut-off points are evaluated. The first evaluation gives a good insight w.r.t. to developing shear bands, i.e. potential failure mechanisms and the latter is examined for actually developed failure mechanisms. For each analysis the relevant time is identified, where the system is closest to failure.

With the relevant analysis no. #*n* found, where a complete failure mechanism is found for the first time, the safety against slope failure due to earthquake loading is defined by

$$F.O.S. = 1 / R.F. = c'_0 / c'_n = \tan(\varphi'_0)/\tan(\varphi'_n), \tag{1}$$

where the subscript "0" denotes the original parameters and "*n*" the respective number of the iteration step (cf. conventional phi-c-reduction).

APPLICATION EXAMPLE

In the following example the procedure described above was used for a real earth dam construction project. The dynamic finite element analyses were carried out with the commercial FE code Plaxis® 2D, version 2011.02.

Project Outline & Subsoil Conditions

The investigations at hand were carried out in the course of the completion of tender documents for a water reservoir project. For this purpose an earth dam (height at the investigated cross-section 17.6 m) with a geomembrane sealing at the water face shall be constructed on relatively soft clay. The local upper clay stratum is considered to be homogeneous down to the depths, relevant for the numerical modeling. This material shall also be used for the construction of the earth dam.

Due to the weak subsoil conditions a specific proposal with 7 layers of geosynthetic reinforcement was foreseen in the design of the consultant, which is aimed at reducing displacements of the dam due to self weight (spreading of the dam base, settlement of the crown) and increasing safety against failure of the slopes and base failure under static and especially seismic excitation.

The system had been already analysed using conventional procedures demonstrating sufficient safety for the ultimate limit state (ULS), i.e. global and local stability. The FE analyses were performed as a more precise cross-check providing not only a detailed view in terms of safety against failure (ULS) but in terms of corresponding total and local deformations as well (SLS).

Geometry & Finite Element Model

The decisive cross-section for the numerical investigations is depicted in Figure 1. The model dimensions are summarised in Table I. The spatial discretisation is shown in Figure 2, with the corresponding mesh properties given in Table II. At the model boundaries so-called absorbent boundary conditions are applied, which shall prevent reflections of the mechanical waves during dynamic excitation. As a consequence, minor displacements at these boundaries are generated. Thus they have to be far enough away to not influence the calculation domain of interest.

Loads

The water load of the filled reservoir is allowed for in terms of dead loads. Inertia forces of the water and therewith hydrodynamic pressures were neglected in the present study, because of the low inclination of the water face of only 13.9°. Figure 3 depicts the hydrodynamic pressure distribution curve according to [1] for the given geometry. The hydrodynamic pressure is very small and was therewith neglected here.

For the seismic excitation sets of real acceleration data were applied, after being scaled to fit the demanded maximum horizontal and vertical accelerations for the project (max $a_H/g = 0.233$, max $a_V/g = 0.070$). The accelerograms are depicted in Figure 4.

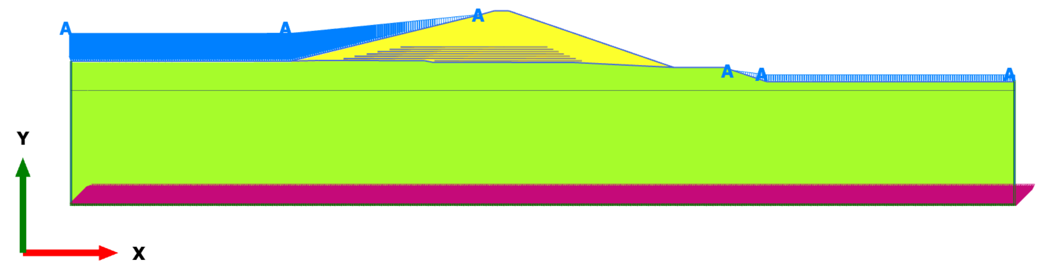

Figure 1. Model geometry.

TABLE I. Model Dimensions

	min. [m]	**max. [m]**
X	-150	150
Y	-150	-82.2

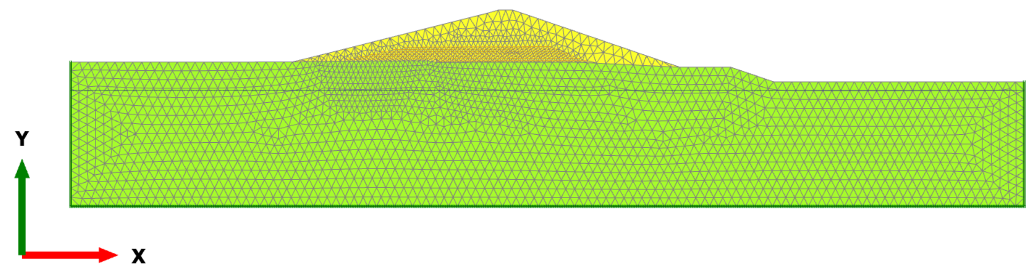

Figure 2. Finite element mesh.

TABLE II. Mesh properties

Model	2D plane strain
Elements	15 node triangular elements
No. of Elements	4,643
No. of Nodes	37,635

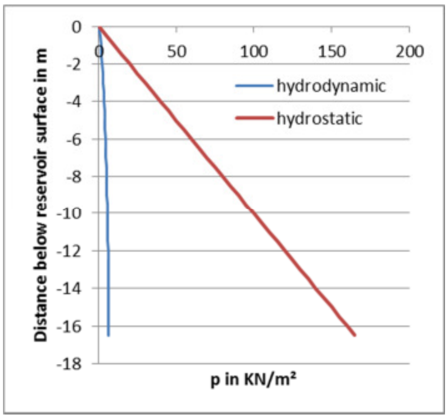

Figure 3. Hydrodynamic and hydrostatic pressure distribution (max $a_H/g = 0.233$, $\Theta = 75°$, h = 16,5 m).

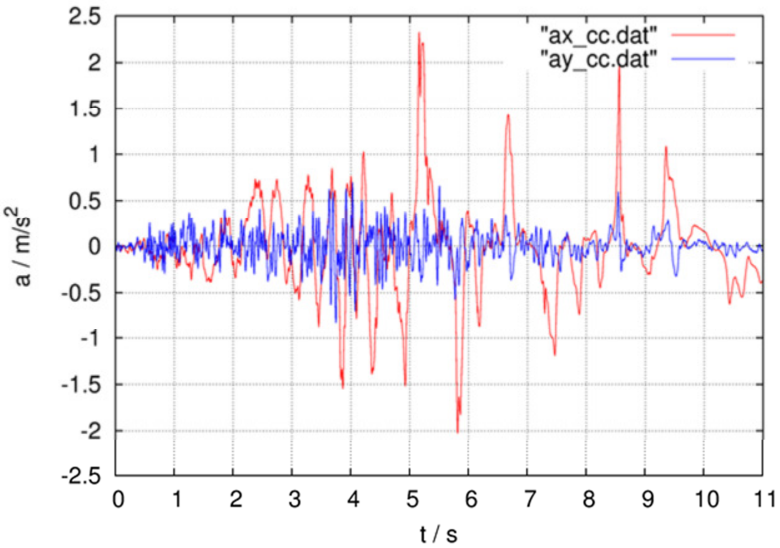

Figure 4. Acceleration of the lower model boundary.

Constitutive Models

SOILS

For the dynamic FE analyses the elasto-plastic "hardening soil small strain model" (HSsmall) [2] was used. It is the most advanced soil model included in the used FE code and allows for the following main features and advantages:

1. Pressure dependent material stiffness
2. Hysteric shear behavior, as a result of the shear deformation dependent shear stiffness, thus allowing for material damping under dynamic excitation.
3. Broad base of experience w.r.t. to material parameters, which makes possible realistic estimates in the absence of comprehensive field and laboratory data.

The material parameters for the given example are summarized in Table III.

TABLE III. Material Parameters of the HSsmall Constitutive Model

HS Small		1 Natural Subsoil	2 Embankment Fill
E_{50}^{ref}	[kN/m²]	3,500	15,000
E_{oed}^{ref}	[kN/m²]	3,400	14,440
E_{ur}^{ref}	[kN/m²]	10,500	45,000
exponent m	[-]	1	1
γ_{unsat}	[kN/m³]	18	18
γ_{sat}	[kN/m³]	20	20
c'	[kN/m²]	8	15
φ'	[°]	19	19
ψ	[°]	0	0
p^{ref}	[kN/m²]	100	100
$\gamma_{0.7}$	[-]	0.0005	0.0005
G_0^{ref}	[kN/m²]	24,000	85,000

The first three parameters are stiffness values, m controls the pressure dependence of the stiffness, $\gamma_{unsat/sat}$ is the volumetric weight of the soil under unsaturated/saturated conditions, φ' and c' are the conventional shear parameters friction angle and cohesion of the Mohr-Coulomb failure criterion, ψ is the dilatency angle, p^{ref} is the referential effective mean stress for which the stiffness values are given, G_0^{ref} is the so-called "dynamic" shear modulus and $\gamma_{0.7}$ is the shear strain for which after a reversal in shear strain direction by 180° (e.g. in direct shear tests or resonant column test) the actual shear modulus $G(\gamma_{0.7}) = 0.7\ G_0^{ref}$ [2].

All these values are more or less common quantities in geotechnical engineering and can be determined or estimated without much effort.

GEOSYNTHETIC REINFORCEMENT

As geosynthetic reinforcement geogrids from the geogrid family Fortrac® M consisting of polyvinyl alcohol (PVA) were chosen for the project because of their low tendency to creep, high short- and long-term tensile stiffness (tensile modulus J), resistance against a wide range of environmental stresses and high coefficient of interaction (bond) also to cohesive and partially cohesive soils as in this case. Due to the latter no interfaces between the geogrids and the soil are implemented in the FE model. The tensile modulus assumed herein is $J = 6.555$ kN/m to model the linear elastic behaviour.

Results

Figure 5 depicts the shear strain invariant (measure for amount of shear deformation) for the decisive time t ≈ 9,7 s during the earthquake excitation. The result suggests a slope failure mechanism at the air face of the dam. The "slide body/slip circle" passes directly at the end of the geosynthetic reinforcement, which apparently influences the location of the potential failure mechanism. In the course of the project, this finding led to an improvement of the geogrid layout: The geosynthetic reinforment was extended toward the air face of the dam, which yielded a higher safety against failure due to seismic excitation according to the procedure presented here.

In Figures 6 to 9 the plastic and tension cut-off points are shown for all simulations carried out in the course of the dynamic phi-c-reduction.

The first complete failure mechanism is found for R.F. = 0.8 (Fig. 9), which yields a F.O.S. ≈ 1 / 0,8 = 1,25 against slope failure due to earthquake excitation.

It should be noted that the F.O.S. given here cannot be compared to the ones obtained by conventional slope analyses. It should rather be seen as an indicative value. The mechanism found here should be used in conventional slope failure analyses, e.g. after Bishop or Janbu to fulfill the requirements of relevant codes.

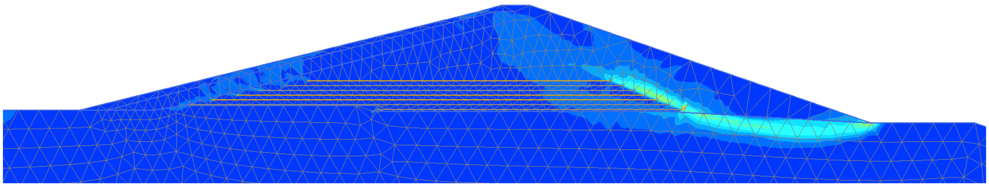

Figure 5. Shear strain invariant (R.F. = 1,00).

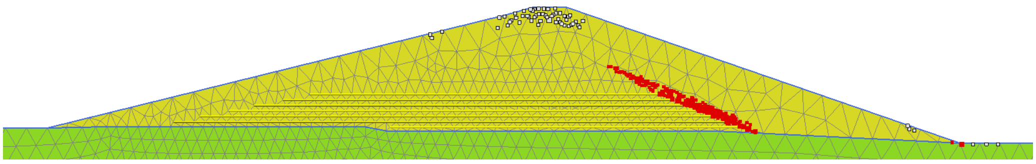

Figure 6. Plastic points (red) and tension cut off points (white/grey) – R.F. = 1,00 (#1).

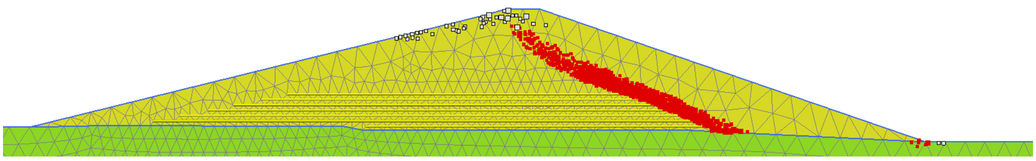

Figure 7. Plastic points (red) and tension cut off points (white/grey) – R.F. = 0,90 (#2).

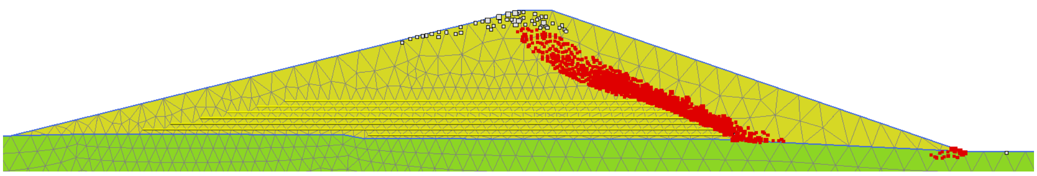

Figure 8. Plastic points (red) and tension cut off points (white/grey) – R.F. = 0,85 (#3).

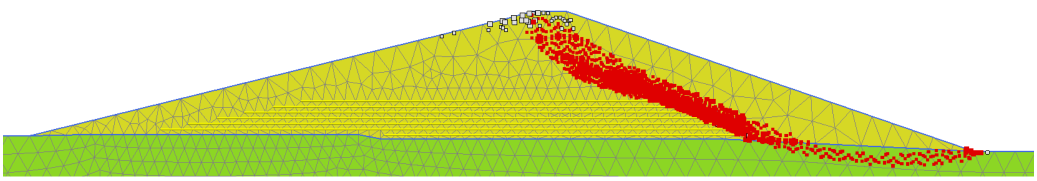

Figure 9. Plastic points (red) and tension cut off points (white/grey) – R.F. = 0,80 (#4).

CONCLUSIONS & OUTLOOK

A novel procedure for a quantitative assessment of a factor of safety against slope failure of an earth dam due to seismic excitation, the so-called "dynamic phi-c-reduction" is described in this paper. The applicability has been demonstrated by an example from a real project.

The analyses confirmed the sufficient global and local stability of the geo-reinforced dam and proved additionally the non-critical level of deformations of different types and strains even in the most critical phase of earthquake excitation.

Additionally, the FE analyses rendered possible an improvement of the layout of the geosynthetic reinforcement w.r.t. the safety against slope failure during earthquake. A further advantage of the FE analyses carried out is that one also obtains the time history of tensile stresses and strains of the different geogrid layers. These results can also be used for an optimization of the design of the geosynthetic reinforcement.

At present, hydrodynamic effects are not allowed for. In the framework of this study, they could be neglected due to the low inclination angle of the dam slopes. In general this effect should be taken into account. The interaction between the water and the dam could be modeled with lumped added masses on the water face [3] [4]. For this purpose a special finite element has to be implemented in the respective FE code. However, most codes common in practice today do not allow for this feature, yet.

In the given example modified acceleration data from a real earthquake was used for the dynamic excitation. The signals were scaled to meet the requirements for the peak accelerations demanded in the project. Besides the peak accelerations relevant earthquake codes demand specific frequency contents for design accelerations. For this purpose there are tools, allowing the engineer to generate random signals with the demanded characteristics.

REFERENCES

1. Zangar, C.N. 1952. *Hydrodynamic Pressures on Dams due to Horizontal Earthquake Effects.* Engineering Monographs No. 11, United States Department of the Interior, Bureau of Reclamation.
2. Benz, T. 2007. "Small-Strain Stiffness of Soils and its Numerical Consequences," PHD Thesis, Geotechnical Institute, University of Stuttgart, Germany, Publication No. 55.
3. Westergaard, H . M. 1933. "Water Pressures on Dams during Earthquakes," *Trans. ASCE,* Vol. 38.
4. Huang, J. 2011. "Seismic Response Evaluation of Concrete Gravity Dams Subjected to Spatially Varying Earthquake Ground Motions," PHD Thesis, Drexel University Philadelphia, Pennsylvania, USA.
5. Brötzmann, F. 2010. "Dynamische Finite-Elemente-Analysen von Dämmen unter Erdbebenbeanspruchung," Master Thesis, Institute of Geotechnical Engineering, Dresden University of Technology, Germany.