SLOPE STABILITY UNDER DYNAMIC LOADING

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Summary

It takes a great effort to estimate the slope stability behavior under dynamic loading. As the classical (limit equilibrium methods are more appropriate for solving static problems, the use of deformation criteria is a better choice for the dynamic loading cases. This research gives comparison between the methods for dynamic slope stability analysis based on given basic geometry and typical soil type for the region of Sofia. Seismic loading corresponding to the one of the Balkan region is used to perform static, pseudo-static, pseudo-dynamic as well as 2D deformation analysis. Some input data for GeoSlope and Plaxis 2D are discussed. Results for safety factors and deformations are shown and compared.

.

Key words

Slope stability, seismic loading.

1. INTRODUCTION AND METHODS FOR STUDYING SLOPE STABILITY

The analyses of seismic stability of slopes are divided in two types: (I) Inertia vulnerability due to seismic inertia forces – it is applied to soils, which do not change their shear strength during an earthquake. (II) Vulnerability due to a weakened soil shear strength during a quake.

The first type of analysis is suitable for hard soils that do not show quick clays behavior, well-sealed noncohesive soils as well as soils above soil water level. The second type of analysis is suitable for sensitive clays, which reduce their shear strength, for soft clays and organic soils and non-sealed soils under soil water level that show signs of liquefying or generating a substantial pore water pressure. [1]

1.1 Short description of the methods

1.1.1 Pseudo static methods

The main feature of these methods is that the seismic loading is represented by pseudo static inertia forces, given in horizontal and vertical direction (Fh, Fv) They are applied in the center of mass of the slipping object and are defined thus:

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$$F_h = k_h \cdot W; \quad F_v = k_v \cdot W,$$

where: $k_h = a_h/g$ and $k_v = a_v/g$ are dimensionless seismic coefficients; a_h, a_v – horizontal and vertical seismic acceleration of the earth; g = 9,81 m/s^2 – earth's acceleration; W – unit weight of the sliding mass. [2]

1.1.2 Lamella and block methods based on limit equilibrium

Lamella and block methods of limit equilibrium are usually applied in 2D solutions. These methods do not account the deformations in the soil body. The sliding mass is a solid object. The static equilibriums and the Mohr-Coulomb criteria are applied. Determining the shear strength and the resisting and active forces along the slip surface allows the safety factor ratio (Fs) definition.

1.1.3 Pseudo static analysis using FEM

The horizontal seismic factor k_h which corresponds to the safety factor Fs=1 is called critical seismic factor k_c. The critical ground acceleration is determined so that $a_c = k_c.g$. With values of the horizontal acceleration greater than a_c destruction of the slope will occur. The ratio between the critical factor k_c and the seismic factor k_h defines the potential loss of stability. Analysis using FEM has the advantages of modeling the soil as a deformable environment and traces the slip surface trough the areas with highest incremental shear deformations. [1]

1.1.4 Permanent displacement methods

These methods define the accumulated displacements in the soil object during the earthquake period, The stability is estimated according to the regulations for serviceability of the construction.

The main features for these methods are introduced by Newmark. The potential sliding mass is modeled as a rigid block, which slides onto a plane base of soil in limit state. The resistance of shearing between the block and base is estimated through the critical acceleration factor $a_c=k_c.g$ which corresponds to the safety factor in the pseudo static analysis Fs=1. When the accelerations in the rigid block (soil mass) exceed the critical acceleration, displacements are accumulated. [1]

1.1.5 Dynamic analysis of slopes

Through 1D, 2D and 3D numerical models a dynamic analysis is being applied to the soil mass, where the seismic loading is given as an accelerograms or response spectrum. The evaluation for slope stability is done by displacement criteria which takes into account the displacements time function. The determinations allow the usage of complex constructive soil models and including the different geotechnical conditions. The analysis is performed with an appropriate software using FEM.

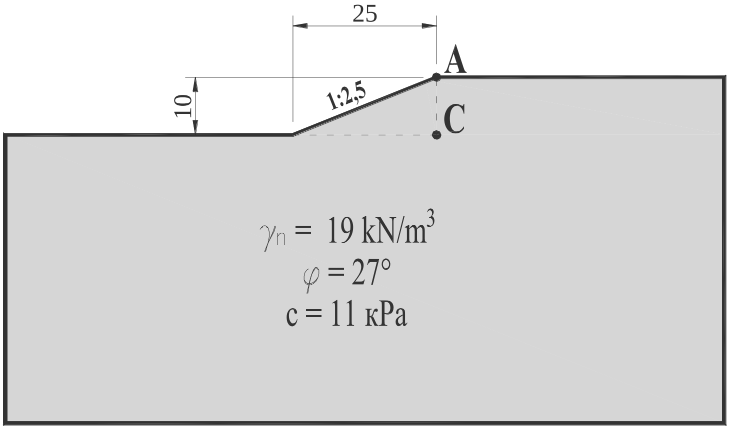
1.1.6 Purpose of the study

The purpose of the study is to compare the different methods of slope stability based on the given geometry and material parameters. It should be evaluated which of the two main criteria (safety factor or displacements/deformations) is more prevail for the given case.

2. GEOMETRY AND IMPACT

2.1 Geometry of the model

The geometry of the model is build according to minimum positive (stable) safety factors for dynamic and static analysis. The geometry is given in Picture 1. .



Picture 1. Geometry of the slope

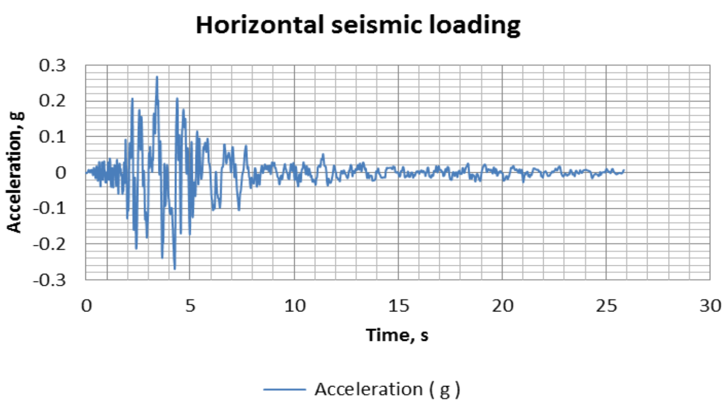
1.1 Impact

The static loading on the slopes are presented only by the unit weight of the soil. More interesting for the study is the dynamic loading. In this case two types of seismic load are considered – quasi-static and dynamic. Quasi-static impact is revealed according to [5] item 1.1.1:

$$k_h = \frac{a}{g}.0,5.S \quad ,$$

where *S = 1* is the soil factor according to EC.

The PGA takes the value of 0.27, in old Bulgarian standards, $k_h = 0.135$. [5] The dynamic loading is presented by accelerograms with PGA = 0.21 in southern Greece (Kalamata). The graph is scaled to PGA = 0.27. Horizontal seismic loading accelerogram can be seen on Picture 2.



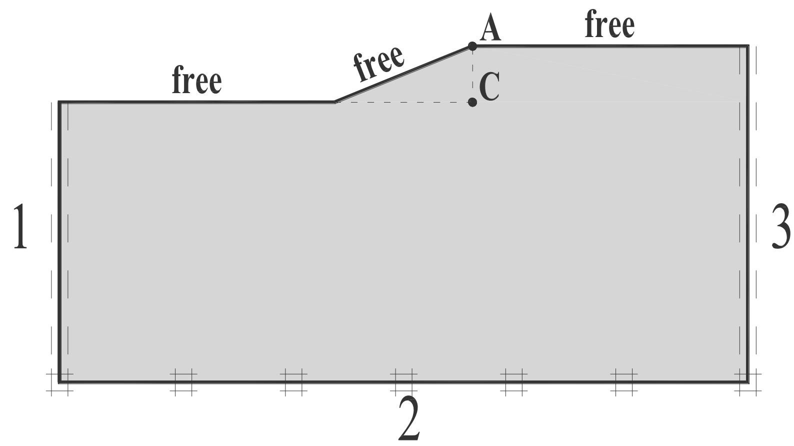
Picture 2.Horisontal seismic loading

The calculated pseudo-static coefficient is used for the pseudo-static analysis with both Plaxis and Geostudio. The dynamic analyses were performed with the scaled accelerogram already given in Picture 2.

3. BOUNDARY CONDITIONS AND PARAMETERS ON THE USED MATERIAL MODELS

3.1 Boundary conditions

The boundary conditions for the classic method solutions are related only to keeping the relevant equilibrium conditions. When the stresses on the slip surface are calculated using FEM relevant restrains are needed. The dynamic solution is also dependent on the boundary condition.. Picture 3 indicates the relevant fixities. The quasi-static models are fixed on axis X of 1 and 3 and on Y of 2. Dynamic models in Plaxis and Geostudio are completely different. Because of the linear character of the solution, Geostudio has standard fixities. In this case, 1 and 3 cannot move according to Y and 2 - according to X and Y. The loading is applied on the bottom boundary (2). Plaxis supports fully dynamic (elasto-plastic dynamic solution) and has built in absorbent boundaries – 1 and 3. The loading is also given on the bottom (2).



Picture 3 Boundary conditions

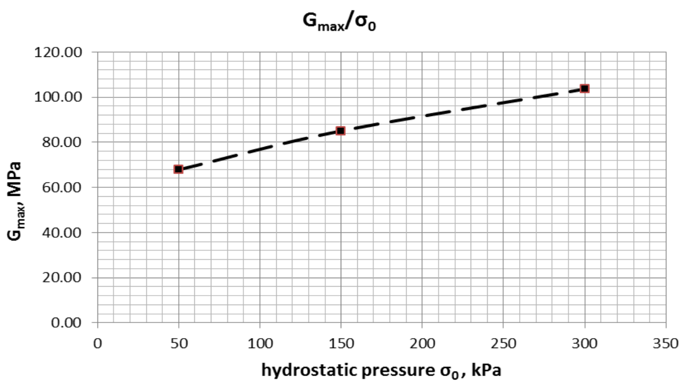
3.2 Materials, models and parameters

Except for the classical lamella methods which are represented with the parameters of the Mohr-Coulomb model, in the solution there are extra models considered. Plaxis supports HSM (Hardening Soil Model) and HS small (Hardening soil model with small strain stiffness). The parameters of the materials are given in table 1.

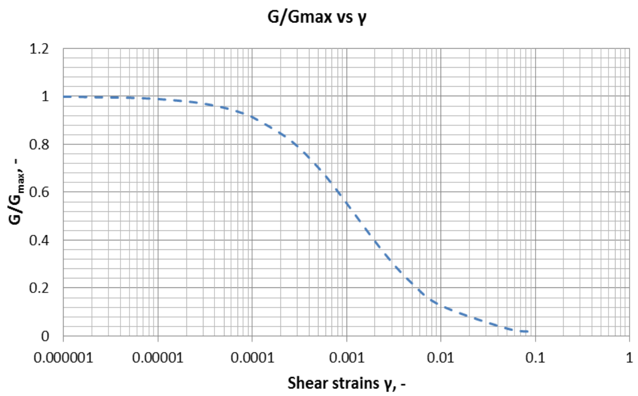
Table 1. Model Parameters

Parameters			Model			
		dimension	LE	MC	HSM	HS small
Unit weight	γ	[kN/m^3]	19	19	19	19
Youngs modulus	E´	kPa	28000	20800		
Poisson ratio	ν	-	0.2	0.2		
Reference modulus	E50,ref	kPa			5000	5000
Odometer modulus	Eoed,ref	kPa			5000	5000
Unloading modulus	Eur,ref	kPa			25000	25000
Maximal shear modulus	G0,ref	kPa				80000
Reference shtear strain	γ0,7	-				0.003
Unloading poisson ratio	ν'ur	-			0.2	0.2
Refference pressure	pref	kPa			100	100
Parameter	K0,nc	-			1-sin(φ)	1-sin(φ)
Parameter	Rf	-			0.95	0.95
Cohesion	c'ref	kPa	11	11	11	11
Effective angle of friction	ϕ´	°	27	27	27	27

Geostudio gives an opportunity to change the shear module depending on the hydrostatic pressure. With the equivalent linear model the reduction of the maximum shear module with the growth of the shear strains can be taken into account. The two curves are shown respectively on Picture 4 and Picture 5



Picture 4 Stress dependent shear modulus - based on resonant column tests [6]



Picture 5 Reduction curve for shear modulus - based on resonant column tests and extrapolation [6]

4. RESULTS FROM THE STUDY

4.1 Static and pseudo-static safety factors.

In the static models, the only comparable parameter is the safety factor. The comparison between safety factors with different static and pseudo-static models are given in table 2.

Table 2. Safety factor F_S

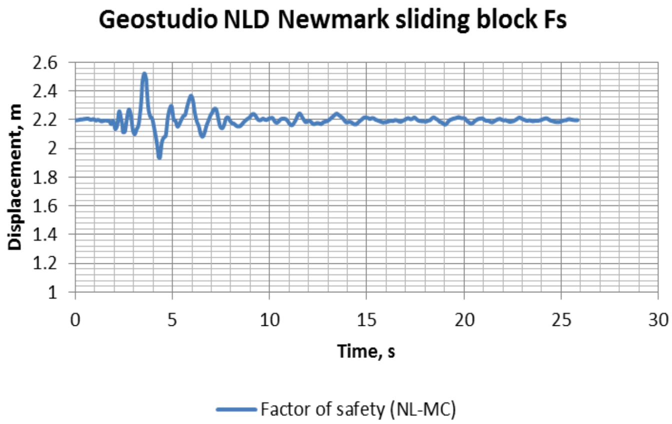
Plaxis 2D (phi-c reduction)	Material models			
solution	LE	MC	HSM	HS small
static	-	2.100	2.104	2.109
pseudostatic	-	1.495	1.496	1.502

Geoslope	Methods			
solution	Fellenius	Bishop	Janbu	M-P
static	1.972	2.134	1.976	2.075
pseudostatic	1.532	1.524	1.467	1.536

It can be concluded that for regular slopes there is no significant difference among all standard lamella and phi-c reduction methods. Slight differences for safety factors can be noticed among standard lamella methods for the static as well as the pseudo-static solution. Phi-c reduction method in Plaxis, gives also insignificant difference. The criterion for all models is Mohr Coulomb that’s why Plaxis 2D table shows only a slight increase of the safety factor with the increase of the constitutive model complexity.

4.2 Dynamic solution and assessment for the safety factor

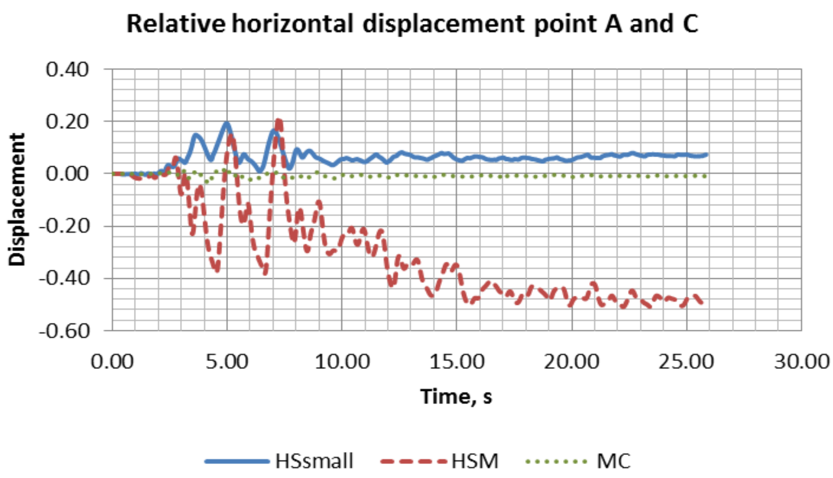
For the Geostudio dynamic solution we use a Non Linear Dynamic one based on the prerequisite described above. The MC material model parameters are applied. The plastic deformations with the slope are insignificant, less than 1 mm. After the Newmark sliding block solution there is no accumulation of permanent displacement. The graph of the safety factor over dynamic time is shown on Picture 6.



Picture 6. Geostudio NLD - Newmark

Based on the Geostudio version, it wasn´t possible to solve the Newmark sliding block method with Equivalent linear dynamic models.

Plaxis integrates the nonlinear material with time. These material models have complex interrelationship between the different parameters therefore the dynamic model is sensitive to every single one. Calibration of these models could bring up meaningful results and evaluation of the deformations. Picture 7 shows the difference between displacements of points A and C in time. It can be assumed that thanks to the increased module for MC, the model gives adequate displacements in the range of 2 cm. HSM accumulates unidirectional deformations because of the small loading and about 5 times bigger unloading module. Due to the extra parameters HS small, accumulates smaller plastic deformations but with difficult direction estimation.



Picture 7. Relative horizontal displacement for point A and C

5. CONCLUSION

Despite the various methods for estimating the seismic slope stability the problem has yet to be solved. Different methods give different results for the safety factors. Using relatively simple and distinguished slip surfaces the classical (lamella) methods solve the seismic stability with sufficient accuracy. With hard to determine slip surfaces or promiscuity in the layers, a FEM solution is recommended as the safety factors are directly connected to the stresses in the soil. The dynamic solutions are hazard for safety factor estimation but they are the only ones that can evaluate the displacements. Despite the accumulation of plastic deformations and the possibility for quantification, using HSM and HS small models should be done with special attention. It is recommended to perform more complex plastic solutions only where constructive elements are presented (the soil body is rigid enough) and/or small displacements are anticipated.

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