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Seismic Stability Analysis of an Urbanized Natural Slope

Ahmed Seddiki, Mohamed Khemissa
M'sila University, Faculty of Technology, Civil Engineering Department, Geomaterials Development Laboratory, M'sila, Algeria

Abstract. This paper presents the results of slope stability calculations carried out on an urbanized natural slope located in Aomar city (wilaya of Bouira, Algeria), of which rupture caused important damages in the slope itself and in the surrounding works. These calculations aim at analyzing the probable causes of rupture of the slope (seism, groundwater table, loading upstream, unloading downstream) in order to propose the adequate measurements of stabilization. Computation results obtained show that it is the combined action of several negative factors which started the slipping.

1 Introduction

Ground motions are among the most widespread and often serious geodynamic phenomena on surface of earth. They cause a natural and continual relief modification and occur or are reactivated generally in an unexpected way, notably during the earthquakes (seism, underground or marine explosions) or during the intense rainy periods with prolonged precipitations and combined action of various geological and geomorphologic factors. Seismic waves are an often catastrophic natural phenomenon. They produce slopes movements and cause damage to surrounding structures. This problem currently constitutes the major concern of engineers in charge of paraseismic design of works. Landslides are among the most spectacular and frequent slope movements, whose apparition causes deformations inside as outside of earth's crust. They develop in loosed soils or soft rocks mass and occur in very varied circumstances affecting all types of slopes, from small road embankments to massive landslides.

Seismic evaluation of slope stability is commonly based on the pseudo-static approach. The advantages of this approach are that it is easy to understand and apply, and it is applicable for both total and effective stresses slope stability analyses. The recent progress made in the data processing and numerical calculation domains leads to better a control problem of seismic slope stability. These methods agree however to define a total safety factor in function of which the stability of studied slope is regarded as ensured or compromised, or by partial safety factors affecting the stresses applied and soil mechanical properties [1].

This paper has the aim of analyzing the seismic slope stability of an urbanized natural slope located in Aomar city (wilaya of Bouira, Algeria). It deals with analysis probable causes of the slipping of slope starting from geotechnical data resulting from reconnaissance carried out on the site. The calculations were performed in accordance with the Algerian paraseismic rules [2]. A brief description of geotechnical properties of the soils, of seismic characteristics of the studied zone and its hydraulic regime is presented. The conditions retained for the stability calculations and their implementation are also exposed. Independent factors of instability of the slope related to mechanical properties of soils and to climatic conditions combined to probable seismic effects are then analyzed.

2 Brief description of the site

2.1 Geological and geomorphological context

Algeria is divided into two tectonic units separated by the fault of south Atlas. North of Algeria is characterized by an intense seismic activity. It was the seat of many earthquakes mainly in reverse fault in agreement with general movement of compression at border of the Eurasian and African tectonic plates. The May 21, 2003 Zemmouri-Boumerdès earthquake occurred with a magnitude M=6.8 is a typical example. Table 1 gives range of variation of the peak ground acceleration a_{max} recorded in this earthquake and its mean values [3]. The significant damage to infrastructures because of seismic slope instabilities are located in the mountainous areas with stiff slopes.

Table 1. Ground acceleration a_{max} (xg) recorded in Zemmouri-Boumerdès earthquake [3].

Direction of seismic waves	Range of variation	Mean values
East-West	0.05-0.58	0.32
North-South	0.04-0.46	0.21
Vertical	0.03-0.35	0.16

Aomar city is located at the junction of two national roads, RN5 and RN25, at about 100km at south-east from Algiers. It is extended on a surface of 6970ha and composed approximately of 50% of mountains, 35% of hills and 15% of plains. Instabilities of ground appeared in this city caused serious damages on a slope located close to the RN25 national road and in a college founded at its upstream (spacing of expansion joints of blocks, apparition of cracks in the court and in the surrounding wall, rupture of the oil storage tank base close to crown, escarpment and apparition of toe downstream from slope, apparition of cracks and light depression of the pavement, overturning of existent gabions). Aomar slope is located at the center of a formed basin of high reliefs of Djurdjura mountainous chains in north and Tellian Atlas in south. Fig. 1 presents a plan view of the site and position of the borings realized.

Field investigations reveal existence of three soil layers with variable thicknesses from one boring to another (Fig. 2). At the site of borings, the nature of the soil massif comprises from top to bottom:

– a layer of muddy clay between 0 and 3m of depth;
– a layer of marly clay between 3 and 7m of depth;
– a layer of blue marl starting from 7m of depth.

It will be noted moreover that the in-situ observations seem to locate the critical slip surface in the altered part of marl layer.

2.2 Geotechnical characteristics of soils

Fig. 3 presents the evolution of geotechnical characteristics of soils with depth. Table 2 gives the values of mechanical parameters considered in the slope stability calculations.

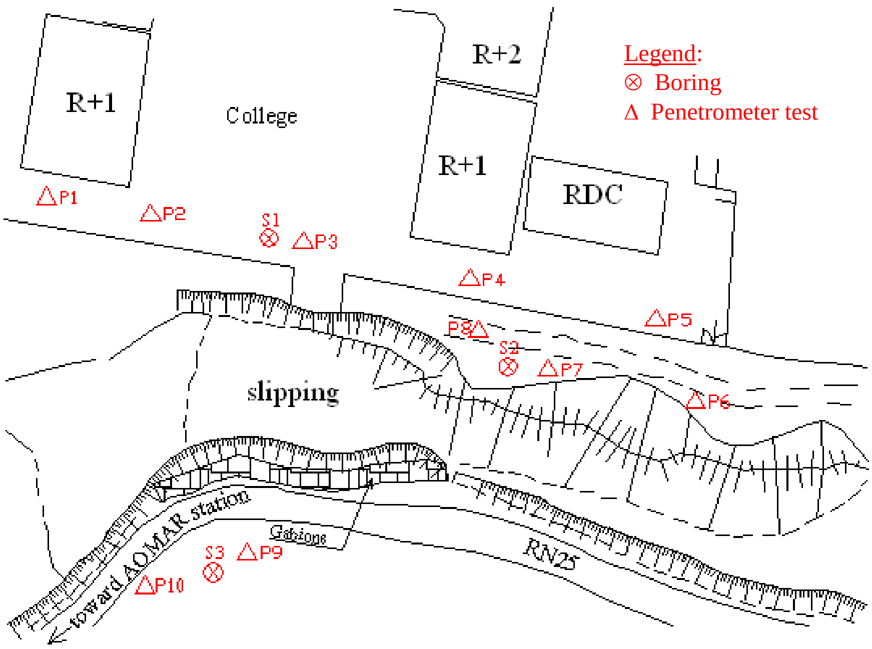

Fig. 1. Plan view of the site and position of the borings realized.

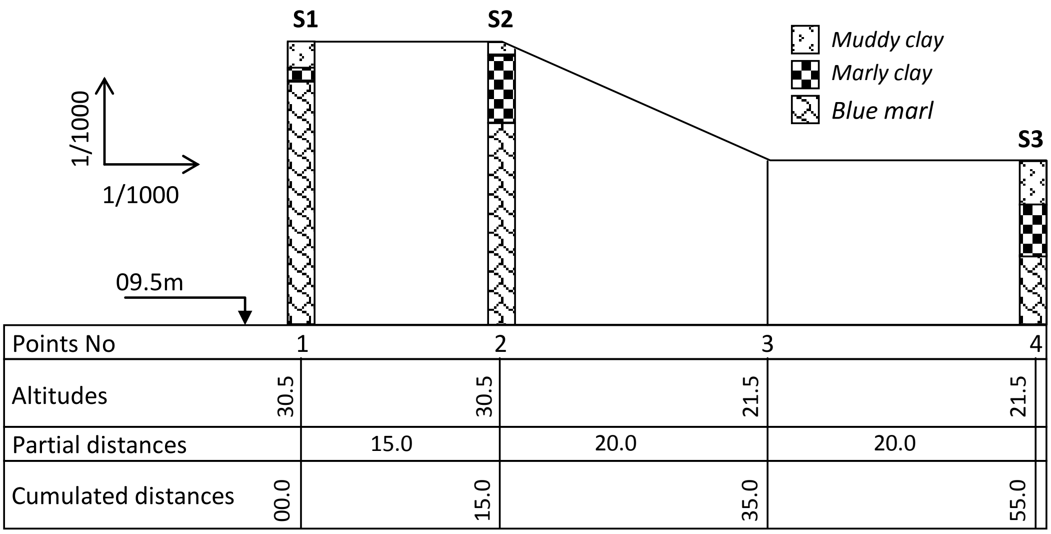

Fig. 2. Geotechnical profile of the slope in axis of slipping.

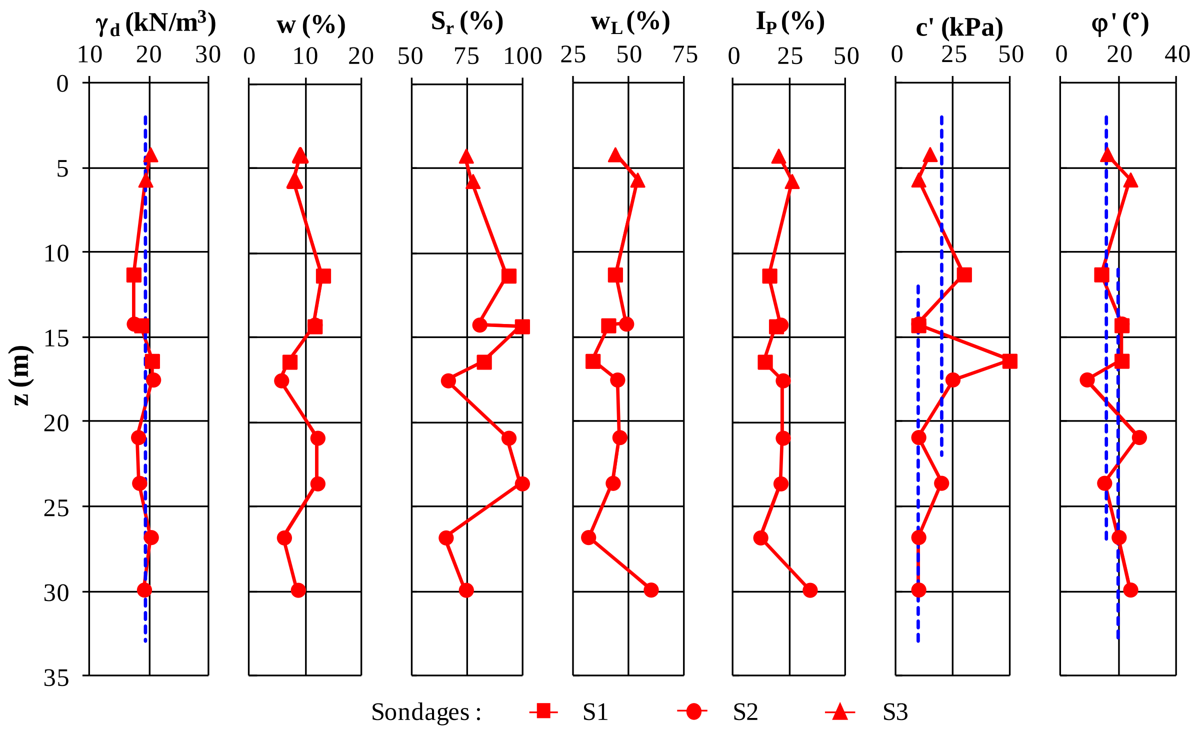

Fig. 3. Evolution of the geotechnical characteristics of soils with depth.

Table 2. Values of the calculation parameters considered.

Soil layer	γ_d (kN/m^3)	c′ (kPa)	φ′ (°)
Muddy clay	19.5	20	16
Marly clay	19.5	20	16
Blue marl	19.5	10	20

2.3 Seismic characteristics of the studied zone

Aomar city is classified by the Algerian paraseismic rules [2] like a zone of mean seismicity (zone IIa). The horizontal and vertical seismic coefficients, k_h and k_v, taken into account in seismic slope stability calculations are:

$$k_h = 0.5Ag \qquad k_v = 0.3k_h \qquad (1)$$

where A indicates the acceleration coefficient of zone and g=9.81m/s^2 the earth gravity acceleration. Table 3 gives the values of k_h and k_v defined by the Algerian paraseismic rules [2] according to the group of use considered for zone of mean seismicity (zone IIa).

Table 3. Values of the seismic coefficients adopted [2].

Zone	Group of use	A	k_h (xg)	k_v (xg)
IIa	1A	0.25	0.1250	0.0375
	1B	0.20	0.1000	0.0300
	2	0.15	0.0750	0.0225
	3	0.10	0.0500	0.0150

Classification of works:
1A – works of vital importance (safety, hospitals)
1B – works of great importance (schools, mosques)
2 – current works (dwellings, offices)
3 – works of low importance (hangars)

3 Slope stability calculations

Slope stability calculations were performed with the PETAL-LCPC program for slope stability calculations in limit equilibrium method for a circular and not circular slip surfaces by method of slices (Bishop, Fellenius) [4]. Slope stability calculations performed with PETAL-LCPC program directly give the safety factor of slipping of slope.

Seismic action is taken into account using pseudo-static approach. The principle of this approach consists to replace the seismic action by an equivalent static action which takes account of the probable reaction of sloped soil mass. The pseudo-static efforts are represented by the two seismic coefficients k_h and k_v. These two parameters characterize the horizontal and vertical components of forces brought by sloped soil mass (Fig. 4).

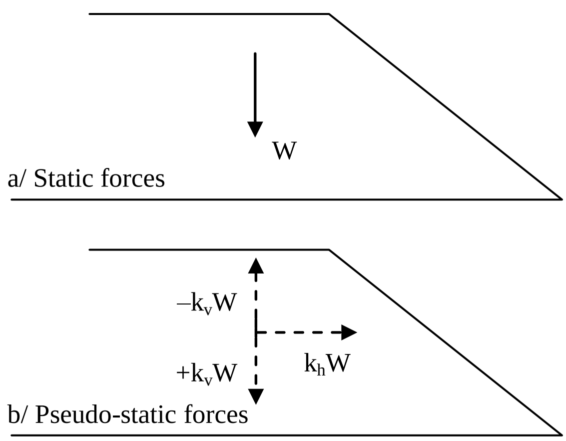

Fig. 4. Forces brought by a sloped soil mass.

In-situ observations and laboratory test results make it possible to note that it is about a rotational slipping because of a swing of the slipped soil massif along an appreciably circular surface and of presence of toe downstream of slope and of an escarpment along the crown. Slope stability calculations performed with PETAL-LCPC program show that the rupture is localized in the altered part of marl layer (Fig. 5). Stability calculations performed under only effect of the gravity loading (without seism: k_h=0 and without groundwater table: h_w=0) show that the Aomar slope is stable (FS=1.74). Also, other causes having led to the rupture of slope must be sought.

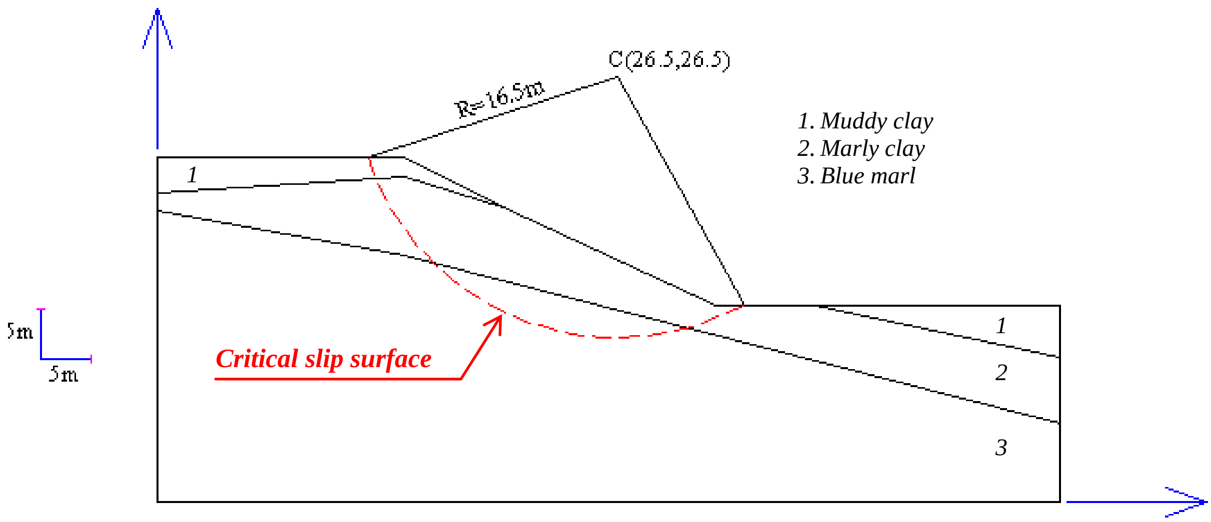

Fig. 5. Localization of the critical slip surface of Aomar slope using PETAL-LCPC program.

4 Probable causes of slope's rupture

To justify the Aomar slope's rupture, we thus will examine, for various possible horizontal seismic coefficients ranging between k_h=0 (without seism) and k_h=0.125g (seismic characteristic of the site according to the Algerian paraseismic rules [2], the real effects of a resistance fall of soils, of a possible variation of the groundwater table, of an excessive loading upstream of the slope and of its possible unloading downstream.

4.1 Effect of a soil resistance loss

The variation of effective cohesion of ±25% varies the safety factor value from 10 to 11% (Fig. 6). The variation of effective internal friction angle of ±25% varies the safety factor value from 15 to 16% (Fig. 7). The slope remains quasi stable, even for a maximum value of the horizontal seismic coefficient characterizing the site.

4.2 Effect of a probable interstitial overpressures

Extensive geotechnical investigations carried out after landslide indicates that the soils were saturated with water. However, no piezometric measurement was carried out to locate the phreatic level. However, because of the seasonal variations due to surface phenomena of evapo-transpiration and to a drainage by infiltration towards the slope's toe, slope stability calculations were performed on the assumption of fluctuations of groundwater table between the dry state (h_w=0) and the saturated state parallel with the slope (Fig. 8), and also on the assumption of a variation of seismic coefficient for a given phreatic level (Fig. 9). At dry state, the slope is stable even in the event of seism. At wet state, it becomes unstable and collapses when phreatic level exceeds 19.5m altitude under a horizontal seismic coefficient k_h=0.050g.

4.3 Effect of an excessive loading upstream

Side upstream, Aomar slope is located near a college. The weight of this building or quite simply that of tanker which supplies the oil storage tank would have contributed to slipping of slope. In general, the overloads applied on slope upstream have a negative influence on its stability. But, in this case, it can be noted that the slope remains quasi stable under a uniform load q=100kPa, even for a maximum value of the horizontal seismic coefficient characterizing the site (Fig. 10).

4.4 Effect of a possible unloading downstream

Side downstream, Aomar slope is limited by the RN25 national road. The possible digging of a ditch, or an unspecified excavation at this place, constitutes a sufficient unloading to destabilize the slope. But, in this case, it can be noted that the slope remains stable after the digging of a ditch, even for a maximum value of the horizontal seismic coefficient characterizing the site (Fig. 11).

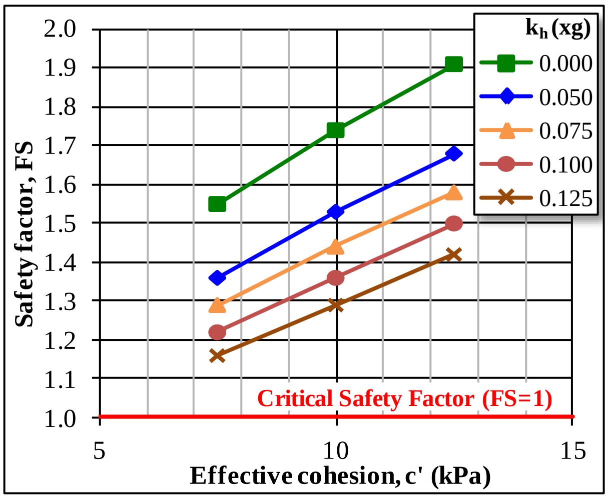

Fig. 6. Influence of effective cohesion on the safety factor

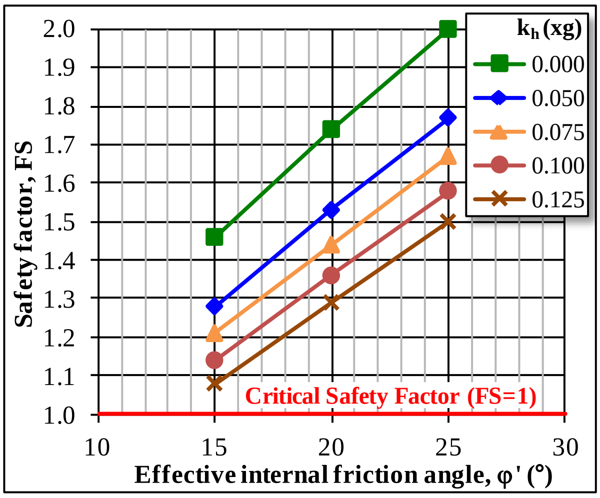

Fig. 7. Influence of effective internal friction angle on the safety factor

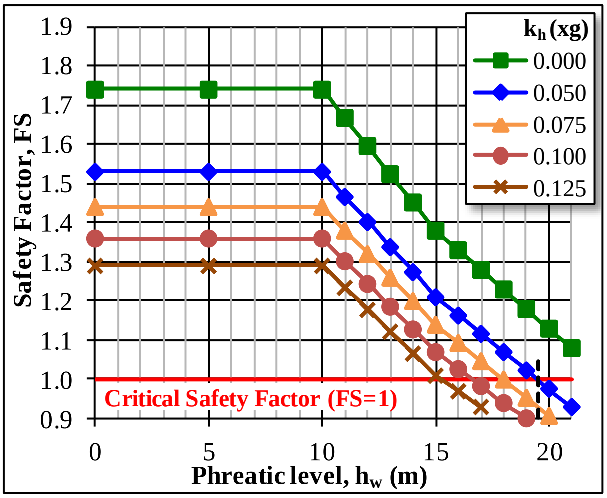

Fig. 8. Influence of phreatic level on the safety factor

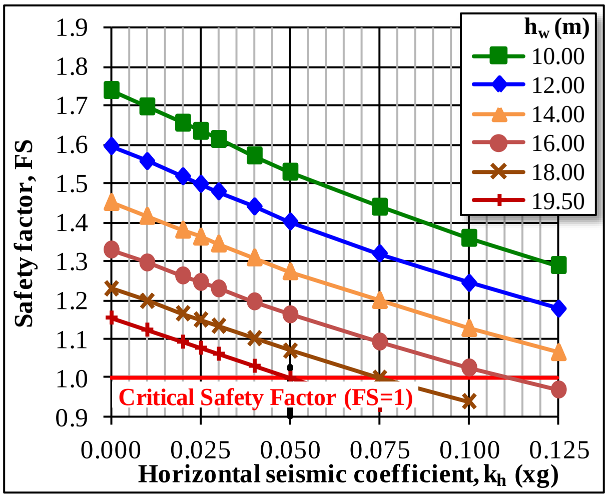

Fig. 9. Influence of seismic coefficient on the safety factor

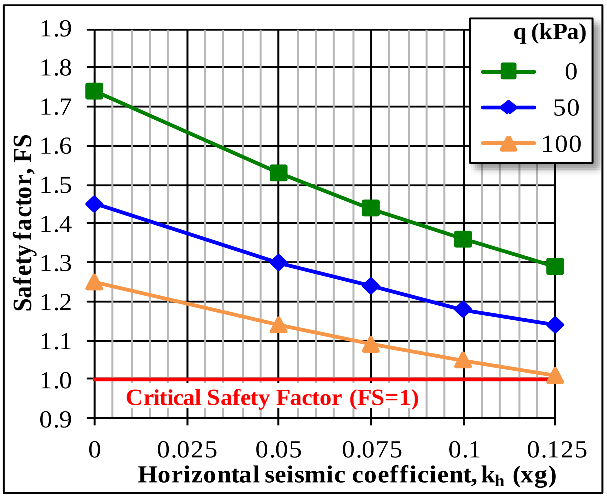

Fig. 10. Effect of loading upstream from the slope on the safety factor

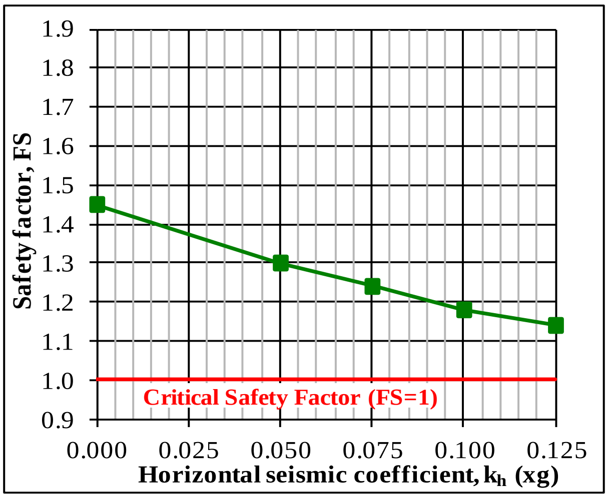

Fig. 11. Effect of unloading downstream from the slope on the safety factor

5 Summary and conclusions

Slope stability analysis carried out on Aomar slope (wilaya of Bouira, Algeria) shows that the rupture occurred in the altered part of marl layer; this having been confirmed by in situ observations and analysis of borings which located the critical slip surface at this level.

Table 4 summarizes the results of stability calculations carried out for the possible actions combinations considered in this study, in accordance with the Algerian paraseismic rules [2]. The safety factor values obtained show that an alone action is not sufficient to destabilize the slope. In addition, it can be noted that, for certain combinations, the safety factor calculus shows that the slope is unstable.

Table 4. Safety factor values for the possible actions combinations.

Horizontal seismic coefficient k_h (xg)	0.000	0.050	0.075	0.100	0.125
Gravity Loading (GL)	1.74	1.53	1.44	1.36	1.29
GL + Loading Upstream (LU)	1.45	1.30	1.24	1.18	1.14
GL + Unloading Downstream (UD)	1.53	1.35	1.28	1.21	1.15
GL + Phreatic Level (PL) (h_w=19.5m)	1.15	1.00			
GL + LU + PL (h_w=19.5m)	1.10				
GL + UD + PL (h_w=19.5m)	1.05	Unstable slope (FS<1)			
GL + LU + UD + PL (h_w=19.5m)					

Thus, causes of rupture can be multiple. However, we can think that they come from the one of the two following causes or from their combination:

– an increase in stresses by an excessive loading upstream or by suppression of the abutment downstream from the slope associated to a modification of soil hydraulic characteristics under a light seism (or under an unspecified source of vibration);
– a notable modification of the soil mechanical characteristics (shear strength loss of soils by disturbance effect).

However, it goes without saying, in all the cases, the rupture comes essentially from the mineralogical nature of alluvial formations. Marls being evolutionary rocks, their behavior changes in presence of water and become high plastic. Thus, rupture of the slope can be attributed to a shear strength loss of soils without forgetting of course hydraulic conditions combined probably to unfavorable seismic conditions.

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