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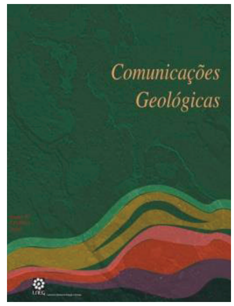
Stability analysis of El Molinar slide (Alcoy, SE Spain)



Análise de estabilidade de deslizamento de El Molinar (Alcoy, SE Espanha)

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Abstract: The El Molinar slide is a translational slide that affects Upper Miocene marls near the city of Alcoy (Alicante, SE Spain). In this study, the stability of this landslide is studied focusing on the effect of variations of the water table within slide body and the possible effect of maximum expected earthquake in a 475 year return period. The results obtained shown that the water table is the main variable in this problem. Its change may induce very large variations in safety factor (from 1.53 up to 0.69, corresponding to dry and complete saturation, respectively). The stability under dynamic conditions shows that this slide is not sensitive to waves with frequencies above 2 Hz, but it reduces significantly its safety factor when waves applied are characterized by low frequencies, especially when their characteristic frequency is below 0.6 Hz.

Keywords: landslide, earthquake, water table, safety factor, reactivation.

Resumo: O deslizamento do Molinar é um deslocamento translacional que afeta as margas miocénicas perto da cidade de Alcoy (Alicante, SE Espanha). Neste estudo, a estabilidade deste movimento foi estudada e focou-se no efeito das variações do nível freático no corpo do deslizamento e os possíveis efeitos do sismo com intensidade máxima esperada para um período de retorno de 475 anos. Os resultados obtidos mostram que o nível freático é a principal variável neste problema. A sua alteração pode induzir grandes variações no fator de segurança (de 1,53 a 0,69, correspondendo a estado seco e completamente saturado, respectivamente). A estabilidade em condições dinâmicas mostra que este deslizamento não é sensível a ondas com frequências superiores a 2 Hz, mas reduz significativamente o seu fator de segurança quando as ondas aplicadas têm frequências mais baixas, especialmente quando a sua frequência é inferior a 0,6 Hz.

Palavras chave: Desmoronamento, sismo, lençol freático, factor de segurança, reativação.

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1. Introduction

The stability of a slope can be regarded as a balance between resisting and driving forces that act on it. Under static conditions, this balance is usually broken when water infiltrates into the slope or when water table rises after periods of intense rainfall. As this cause is common in the nature, it constitutes the most effective way to trigger landslides (Wieczoreck, 1996). Moreover, when an earthquake occurs, seismic ground motion applies an additional driving force on the slope, thereby favoring its instability (Duncan and Wright, 2005).

In this paper, we present the results of an analysis of stability (safety factor) done for the El Molinar landslide (Alcoy, SE Spain). This slide has reactivated several times during the last centuries in relation with intense rainy periods and/or with a severe earthquake occurred in the area.

2. The study zone

The landslide is located just south of the city of Alcoy (Alicante, SE Spain, Fig. 1a). It corresponds to a translational slide *sensu* Cruden and Varnes (1996). It affects Upper Miocene marls and it is 400 m long (approx.) and 100 m wide (Fig. 2). Failure surface is located at about 10-14 m below ground surface at the central part of landslide body (IGME, 1985; Fig. 3).

This slide was first described after the December 2, 1620, Mw 5.5, earthquake (Dávila, 1990; Delgado *et al.*, 2011). During the 70's and early 80's of the XXth century, it reactivated several times. The Spanish Geological Survey studied this landslide for local authorities (IGME, 1985), suggesting controlling water infiltration and not to apply any overload at the crown area. Nevertheless, at the beginning of the 90's (XXth century), an earth-fill was done at this zone (Figs. 1b, 1c, 2 and 3).

As part of the study done by IGME (1985), geotechnical boreholes were drilled (Fig. 2) and undisturbed samples were tested. According to these tests, marls are characterized by a residual friction angle of 16º, a cohesion close to 0 kPa, and a density which varies between 1760 kg/m^3 (dry) and 2040 kg/m^3 (bulk density). More recently, Cantó (2017) measured shear wave velocity in the landslide (Fig. 2). It varies between 250 and 270 m/s.

3. Methodology of slope stability analysis

The stability of this slide was studied considering limit equilibrium methods (Janbu, 1973). Figure 3 presents the section considered,

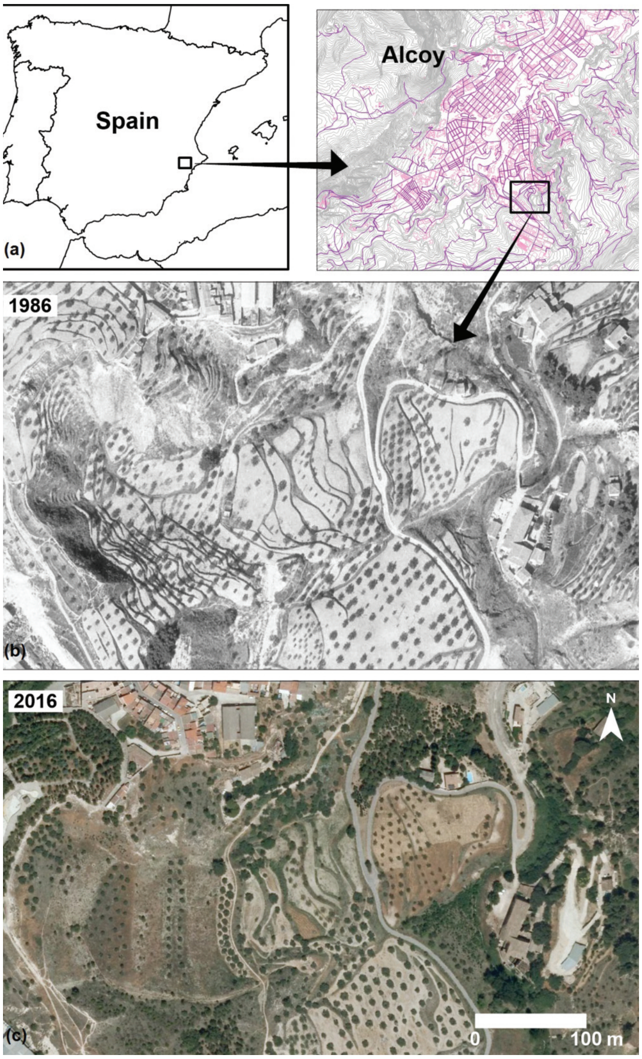

Figure 1. (a) Location map of the study zone. The figure also shows the state of landslide at different periods, 1986 (b) and 2016 (c), to show the fills done at the head of the slide body.

Figura 1. (a) Localização da área de estudo. A figura também mostra a progressão do deslizamento em diferentes períodos, 1986 (b) e 2016 (c), de modo a salientar a evolução da zona de rutura.

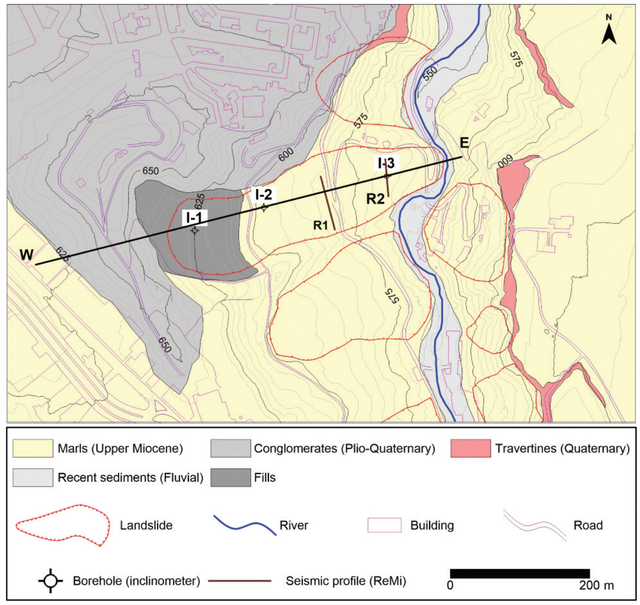

Figure 2. Lithological map of the study zone. The figure also shows the location of several landslides in the area and the location of geotechnical/geophysical studies done in the area.

Figura 2. Mapa litológico da área de estudo. Na figura também estão identificadas as localizações de vários deslizamentos, assim como de vários estudos geotécnicos/geofísicos efetuados na área.

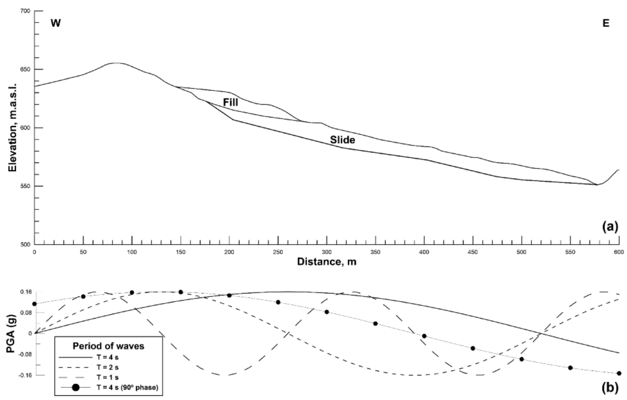

Figure 3. (a): cross-section used in the 2D analysis of stability. (b): effect of period of sine waves in its wavelength and comparison with the dimensions of the slide studied.

Figura 3. (a): perfil utilizado na análise de estabilidade 2D. (b): efeito de períodos de ondas senoidais no seu comprimento de onda e comparação com as dimensões do deslizamento em estudo.

based on ground surface, borehole and detailed topographical data. Because no data are available for the fill, we have used those of the marls for it (the fill is constituted by marls).

The Bishop coefficient (r_u) was used for studying the effect of water pressure on the slope stability. The value of r_u was varied across the range of the admissible values (*i.e.,* 0-0.49).

The study of stability under dynamic conditions was done following the unconventional pseudo-static method described by Delgado *et al.* (2015). In this method, the seismic force (pseudo-static coefficient k_x) is considered to vary along space as a function of frequency of seismic waves (Fig. 3). These waves are of sine type with wavelength ranging from 1300 m (F = 0.2 Hz) to 52 m (F = 5 Hz). The seismic action consisted in an acceleration of 0.16 g, which corresponds to the maximum expected acceleration for a return period of 475 years (Martínez Solares *et al.*, 2013).

4. Results and discussion

The analysis of stability under static conditions shows the high dependence of the safety factor on the position of water table (Fig. 4). For dry conditions, safety factor (SF) is 1.53; the exact equilibrium (SF = 1) occurs when r_u is 0.29. Because this value is difficult to be attained in field conditions, this may explain why this slide is inactive during long periods and only reactivates after long, intense rainy periods.

The pseudo-static analysis done shows the sensitivity of results to frequency and phase of waves (Fig. 5), in addition to the above mentioned effect of r_u. For low values of r_u (*i.e.,* 0), the slide is basically stable and SF only goes under unity when the waves have

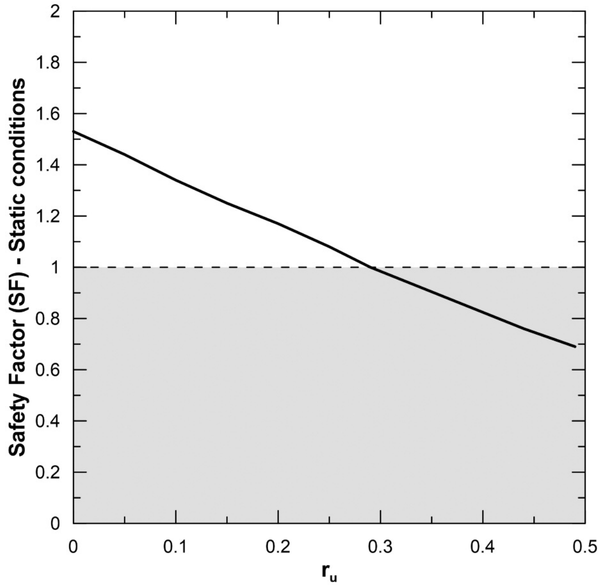

Figure 4. Results of static analysis: Variation of safety factor as a function of water content (r_u).

Figura 4. Resultado da análise estatística: Variação do factor de segurança em função do teor em água (r_u).

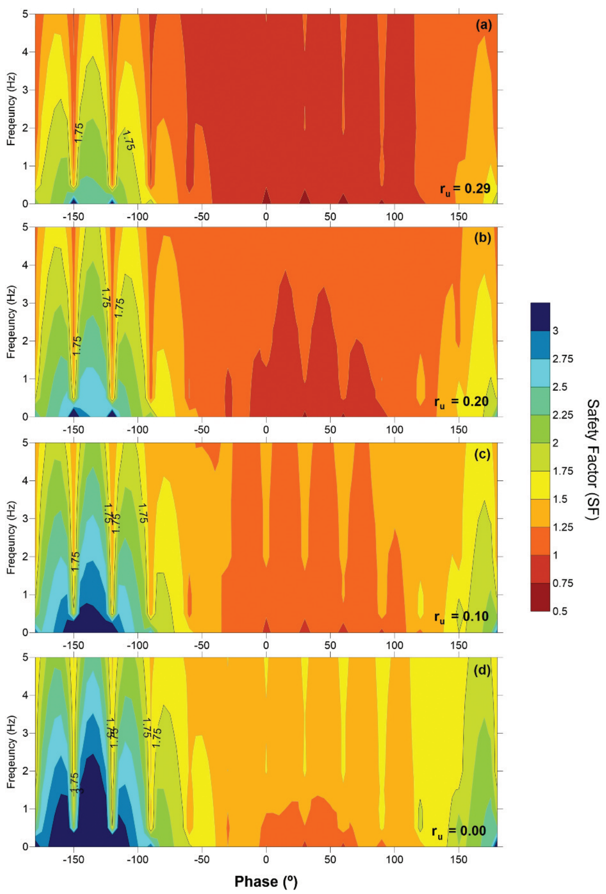

Figure 5. Results of pseudo-static analysis. Variation of safety factor as a function of water content (r_u): (a) r_u=0.29; (b) r_u=0.20; (c) r_u=0.10; (d) r_u=0.00, frequency and phase of sine waves applied to slide.

Figura 5. Resultado da análise pseudo-estática. Variação do factor de segurança em função do teor em água (r_u): (a) r_u=0,29; (b) r_u=0,20; (c) r_u=0,10; (d) r_u=0,00, frequências e fases de ondas senoidais aplicadas ao deslizamento.

very low frequencies (F = 0.2 Hz). In that case, the corresponding wavelength of the wave is high and the acceleration applied is quasi constant along the whole slide. On the contrary, for high frequencies, wavelengths are lower, and the acceleration vary significantly from one part of slide to others, in many cases with different sign, which implies mutual cancelation of forces applied. For high r_u values, SF reduces and for r_u = 0.25 the SF is close or lower than one in most cases analyzed.

Figure 6 shows the lower SF values obtained for each r_u and all possible sine wave analyzed (with phases ranging from $-\pi$ to π, in steps of 30º). This figure shows that this slide is not sensitive to frequencies higher than 2 Hz. In such cases, SF is constant and it is only controlled by the water content of the landslide mass (r_u). For frequencies below 2 Hz, SF reduces. In such cases, the corresponding wavelengths are larger than slide length (≈400 m) and all points in slide suffer similar seismic action.

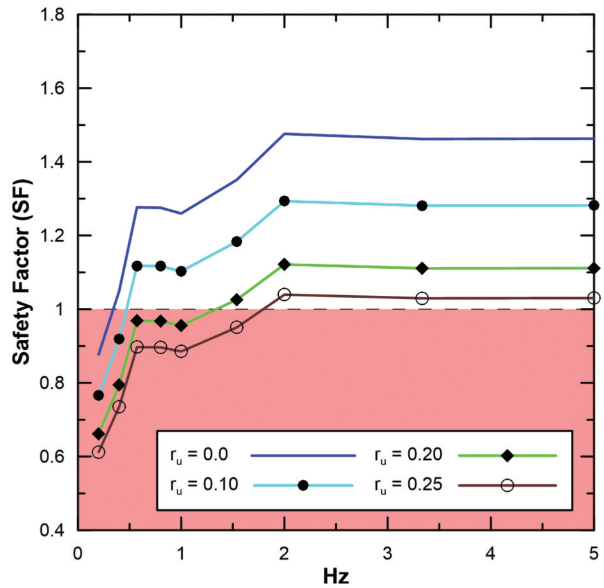

Figure 6. Results of the unconventional pseudostatic analysis in terms of minimum safety factor obtained vs. frequency for ru values varying from 0 to 0.25.

Figura 6. Resultado da análise pseudo-estática não convencional em termos de factor de segurança mínimo obtido vs. frequência do ru para valores entre 0 e 0,25.

5. Conclusions

The El Molinar slide is a translational slide that affects Upper Miocene marls near the city of Alcoy (Alicante, SE Spain). This landslide is well known in the area for having suffered multiple reactivations during the last centuries in relation to a moderate earthquake and, more frequently, to long, intense rainy periods.

For managing the hazard associated to possible reactivation of this slide, a stability analysis was conducted considering static and/or dynamic scenarios. The results shown that changes in water table position may induce very large variations in safety factor (from 1.53 up to 0.69), with potential reactivation (SF < 1) when factor r_u reach values of 0.29 (or above).

The dynamic stability has been studied through an unconventional pseudo-static methodology. The results show that this slide is not sensitive to waves with frequencies above 2 Hz, but it reduces significantly its safety factor when waves applied are characterized by lower frequencies, especially when their characteristic frequency is below 0.6 Hz. These results highlight the importance of considering non-constant forces and the frequency content of seismic scenario when evaluating the dynamic stability of a slope.

Acknowledgments

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