The Torvizcón, Spain, landslide of February 1996: the role of lithology in a semi-arid climate

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RESUMEN

En este trabajo se presenta un análisis de deslizamientos superficiales en terrenos metamórficos bajo condiciones de semiaridez en las Alpujarras, España. Los extensos afloramientos de filitas y de micaesquistos son factores claves para el entendimiento de este tipo de procesos de ladera en esta región. La esquistosidad ofrece planos de debilidad, por los cuales el agua puede penetrar y fragmentar la roca. Eventos de precipitación extremos causaron daños a la infraestructura local y regional, incrementando la probabilidad de que se desarrollen desastres naturales. A partir de la prueba directa de resistencia al esfuerzo cortante se presenta un análisis retrospectivo del deslizamiento Torvizcón, utilizando el modelo de ladera infinita de Skempton y DeLory. El análisis de sensibilidad indicó que uno de los factores de control más importante de este tipo de movimientos está relacionado con las propiedades de los materiales, por lo cual el ángulo de inclinación de las laderas no es el único elemento que debe ser considerado en el establecimiento de los umbrales de estabilidad.

PALABRAS CLAVE: deslizamientos superficiales, terrenos metamórficos, modelo infinito de ladera, análisis retrospectivo, análisis de sensitividad.

ABSTRACT

The analysis of a shallow landslide in las Alpujarras, a metamorphic terrain of semi-arid Spain is presented. The extensive outcropping of phyllites and mica-schist is one of the most important keys in the understanding of mass failure. The degree of schistosity offers planes of weakness where water can penetrate and cause mass movement processes by increasing pore water pressures. A shallow slope movement occurred during extreme events, causing damage to the local and regional infrastructure and increasing the likelihood of natural disasters. By using the infinite slope model of Skempton and DeLory, a back analysis of an observed shallow landslide was carried out. The results of the sensitivity analysis indicated that material properties play a significant role in controlling slope processes and that the slope angle should not be considered as the only parameter to define instability threshold.

KEY WORDS: Shallow failures, metamorphic terrains, infinite slope model, back analysis, sensitivity analysis.

INTRODUCTION

Rainfall acts as one of the main triggering factors of landslides in sub-arctic climates (Sandersen *et al*., 1996), humid temperate regions (Dowdeswell *et al*., 1988), the Pyrenees (Corominas and Moya, 1996), Mediterranean environments (Dietrich *et al*., 1986; Montgomery and Dietrich, 1994, Gostelow *et al*., 1996), humid sub-tropical areas (Garland and Olivier, 1993), tropical zones (Terlien, 1996) and semi-arid environments (Alcántara-Ayala and Thornes, 1996). However, shallow landsliding is influenced to a greater extent by material properties, slope stepness and depth of the potential failure plane. Geomorphological research related to landslides often considers morphological attributes and climatic variables, but material properties are generally neglected. Landslides on igneous and sedimentary rocks have been recently discussed (Carson, 1975; Varnes, 1975, Selby, 1980; Fell *et al*., 1988), but there is little information and research on landslides in metamorphic rocks and especially on phyllites (Caine and Mool, 1982; Wu and Thornes, 1994; Dykes and Thornes, 1996).

In semi-arid Mediterranean Spain, a considerable percentage of landslides takes place in metamorphic lithologies. In this paper we focus on the material properties of phyllites and their relation to slope processes. A back analysis of an observed failure, the 1996 Torvizcón landslide, was undertaken and subsequently examined on the basis of a sensitivity analysis.

The Torvizcón landslide (Figure 1) was a shallow failure of the debris-slide type. The initial failure occurred on February 2 1996 after an intense rainfall period (Figure 2). From November to January, the cumulative rainfall was 637 mm. The landslide took place on February 2, after 57 mm of precipitation were registered on the previous day. Less than

Fig. 1. Torvizcón landslide after the event of February, 1996.

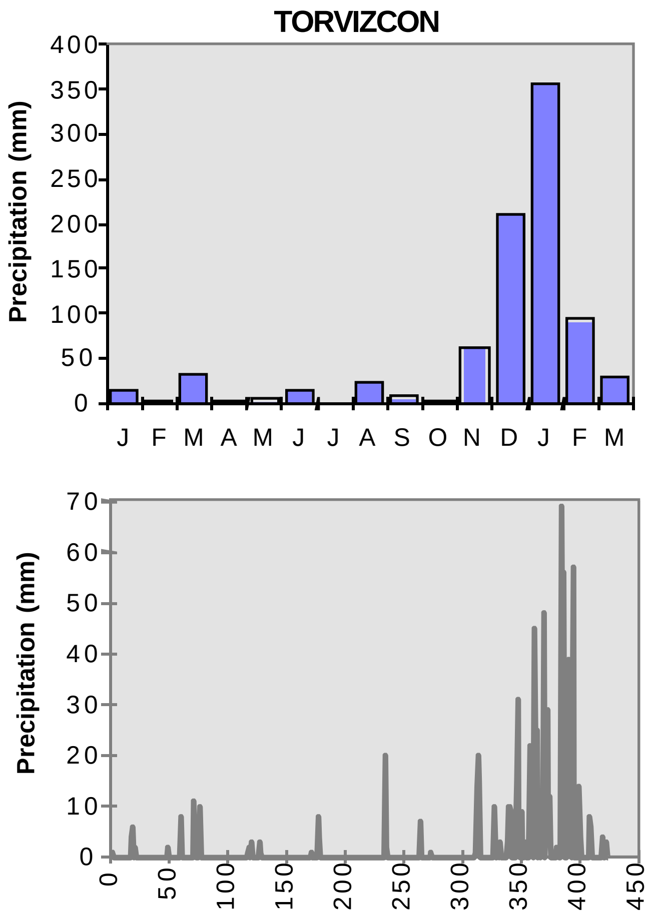

Fig. 2. Monthly and daily precipitation data from January 1995 to February 1996, Torvizcón meteorological station.

a year later, in November 1996, the slide was reactivated as a result of another rainfall event of 146 mm in a single day.

Slope stability analysis using the infinite slope model

Reviews on slope stability assessment may be found in Bromhead (1986), Nash (1987) and Espinoza *et al*. (1992). In this study, we use the Skempton and DeLory (1957) infinite slope model (Figure 3). This model involves a single linear equation and assumes failures parallel to the surface and a slope of infinite extent. Our analysis was carried out in two dimensions assuming that the failure has a fixed unit width and the groundwater conditions remain the same throughout the slope.

It was assumed that the depth of the regolith was 2 m on a 38^o uniform slope. The saturated unit weight of soil was 17.8 kN/m^3, the angle of internal friction was $\phi'_r = 25^o$, cohesion was $c'_r = 8.97$ kPa, and the worst case for groundwater was m=1 (water table at the soil surface, [Skempton and DeLory, 1957]). The SLOPES computer program developed by Bromhead (1988) was utilized with the above parameters based on laboratory testing. The back analysis of the failure yielded a factor of safety of 0.784.

Sensitivity analysis

By using the infinite slope model, Gray and Mahan (1981) performed a sensitivity analysis for the Idaho batholith. They took into account the direction of change in the safety factor corresponding to a change in any input variable. According to Pearce and O'Loughlin (1985), a sensitivity analysis requires a realistic range of values of each variable. Next, a working safety factor must be calculated by using the median value of each variable. Third, each input variable must be modified over its range of values, keeping the other variables constant, and finally, the results are plotted as relative percentages.

Following this approach we seek a combination of variables yielding a factor of safety of unity. The factor of safety obtained from the back analysis was 0.748, a value lower than the initiation of instability. The worst-case groundwater condition is the only assumption that causes the slope to be unstable without the presence of other external factors. The depth of the soil profile is kept constant since an increased slope would decrease stability. A change in the effective soil cohesion was allowed since the measured cohesion was not the effective value, but rather an estimate of the residual value, because of the use of disturbed samples.

A cohesion value of 12.76 kN/m^3 yielded a factor of safety equal to unity. Thus we may perform the sensitivity analysis as suggested by Dykes (1995), under conditions of initial instability and with a factor of safety equals to 1. The parameters and ranges are given in Table 1. In all cases, water table was assumed at the surface (Figure 4).

Note that the factor of safety is most sensitive to soil cohesion (c'_r), depth of soil (z), and slope angle (β). The angle of internal friction (ϕ'_r), the unit weight of soil (γs), and the changes of the water table were less sensitive parameters. Figure 5 shows the changes in the factor of safety for different combinations of variables used in the infinite model analysis.

RESULTS

The sensitivity analysis suggests that cohesion is the most critical factor of slope stability. As cohesion decreases, so does the stability. This illustrates the influence of weathering on long-term hillslope stability, as weathering reduces the cohesive component of the soil shear resistance. In the case of phyllites, weathering may be due to mechanical weak-

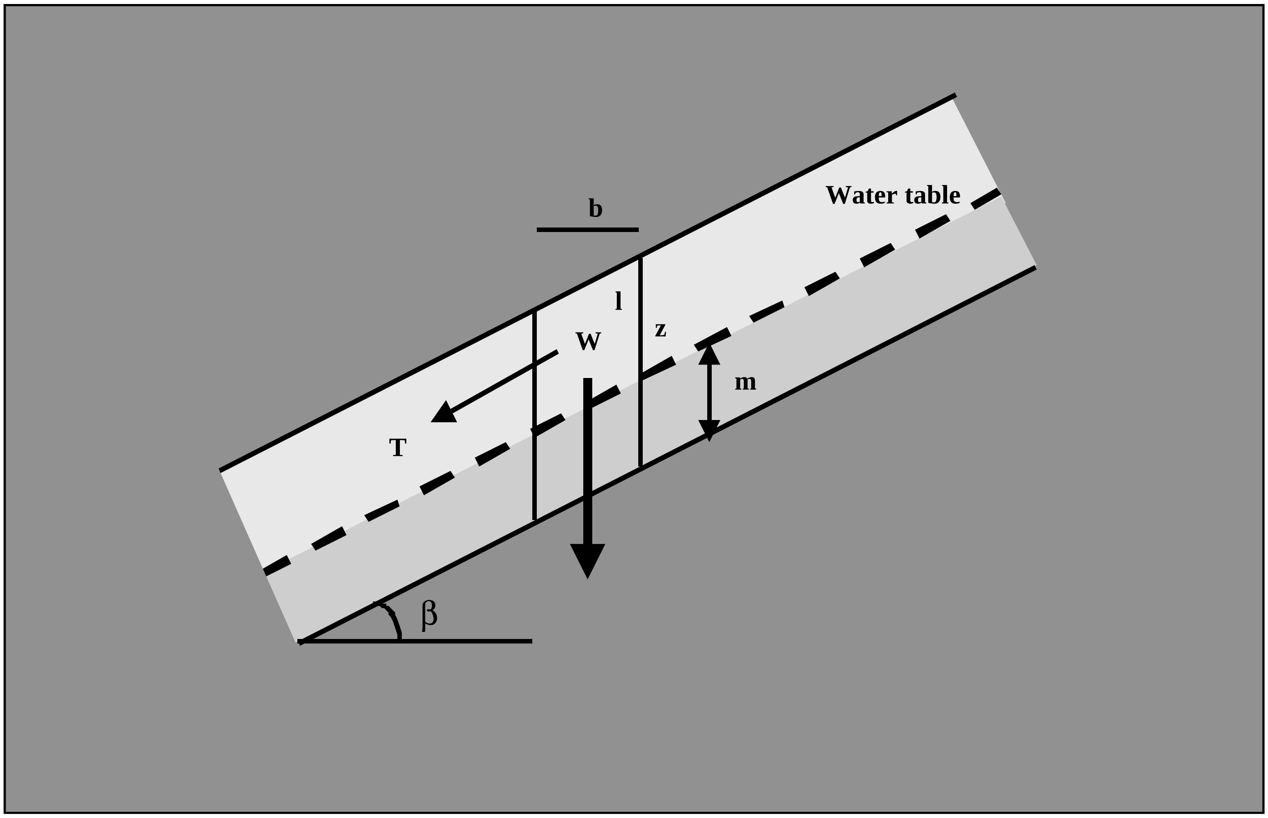

Fig. 3. Infinite Slope Model.

Table 1

Parameters for the sensitivity analysis.

Parameters	Values	Range
Slope angle (β)	38°	20-56°
Depth of soil/shear plane (z)	2.0 m	0.5-3.5 m
Soils unit weight (γs)	18.10 kN/m^3	13.10-23.10 kN/m^3
Cohesion (c'_r)	12.76 kN/m^3	8.76-16.76 kN/n^3
Angle of internal friction (ϕ'_r)	25°	12-38°

ness and also to the climate where cycles of dryness and extreme wetness are common. Cohesion varies spatially and within the soil profile as lenses of quartz and concentrations of phyllo-silicate minerals are common. In conclusion, temporal and spatial distribution of cohesion and slope stability, will depend on the weathering rates resulting from the interaction of lithological units with climate.

The factor of safety decreases as the depth of soil over the potential slip surface increases. Slope conditions are stable when there is not enough soil for the shear strength to be exceeded. However, even on deeper soil profiles, the safety factor can be lowered.

As the slope decreases the stability increases, and vice versa, up to a limit of 52^o. For larger angles the stability increases again. This behavior can be explained from the geometrical derivation of the infinite slope model (see Figure 3). For a given width of the slope profile b, and a given thickness z, when β increases, the length of the shearing surface l along the base is l = b/cosβ. The shear stress acting on the base of the slice is proportional to sinβcosβ. When β is steeper than 52^o, the shearing strength is higher than the shear stress and stability is increased.

However, for a particular region, under specific climatic conditions and terrain characteristics, it is not possible to define a stability threshold based only on the slope angle. Sensitivity analysis suggests that material properties such as cohesion play a major role in controlling landslides. Every material has a stability threshold that can be established from the material properties, rather than from the slope angle alone.

The factor of safety was moderately sensitive to the angle of internal friction (ϕ'_r). However, in terms of strength properties, the angle of internal friction is related to cohesion. As expected, the stability of the slope is increased as the water table is lowered. The effect is greater for soils with low cohesion than for those with high cohesion.

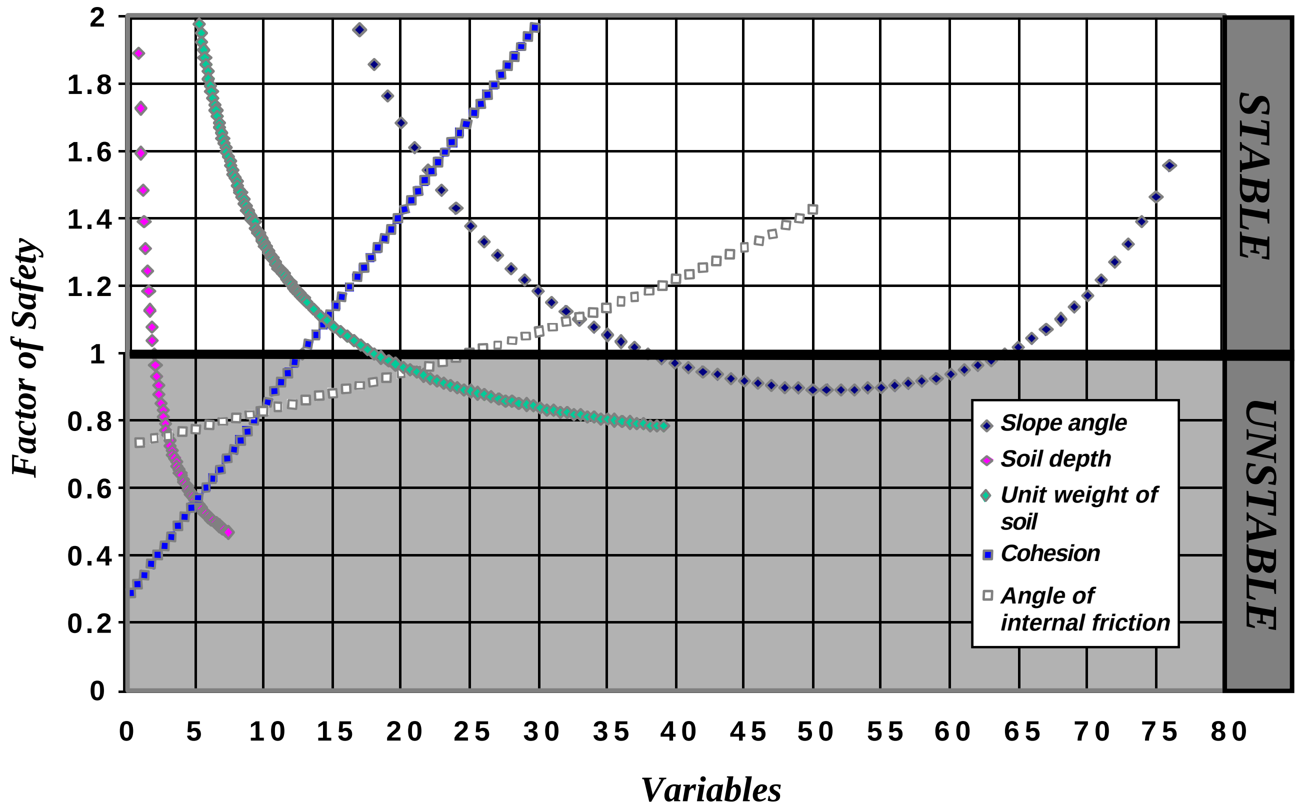

Fig. 4. Values of the factor of safety and their corresponding variables used in the sensitivity analysis.

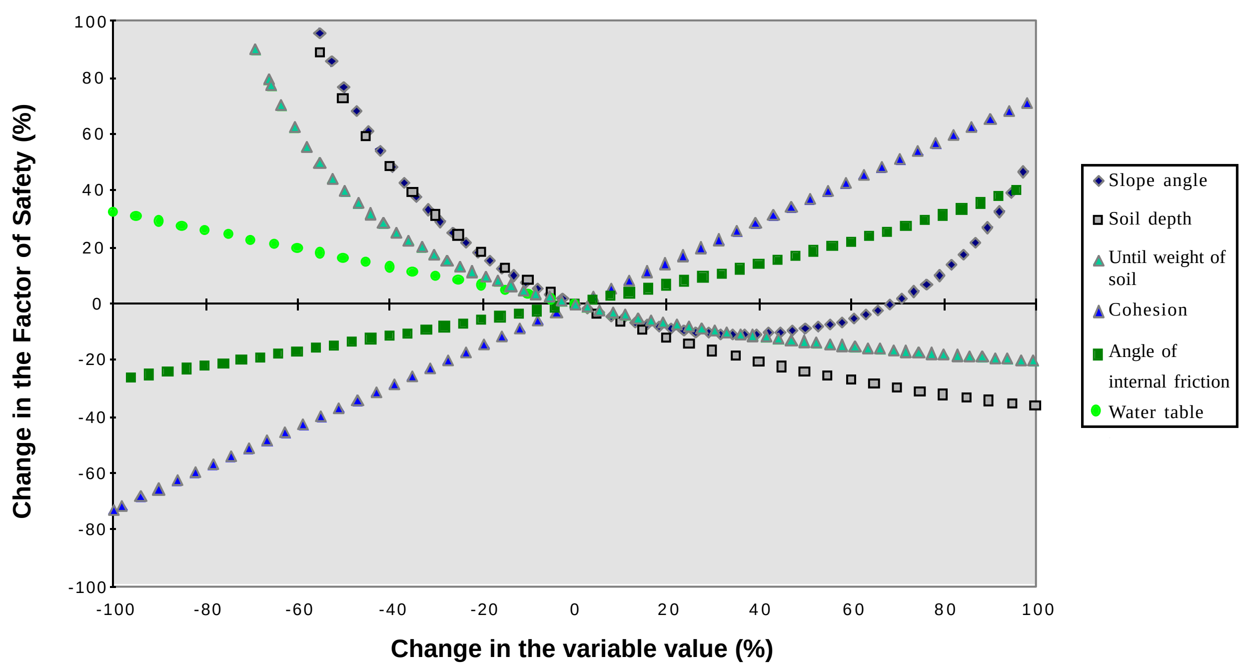

Fig. 5. Sensitivity analysis of the application of the infinite slope model to the Torvizcón landslide.

DISCUSSION

Field sampling and experimental testing of phyllites is difficult since the properties of these materials range from soil to rock, and laboratory tests consider the material either as a rock or soil. In addition, representation of the field properties from small specimens is rather poor.

The infinite slope model (Skempton and DeLory, 1957) is useful for shallow slides since it assumes a shallow layer of soil or regolith sliding on a plane parallel to the ground surface of the slope. Thus the infinite slope model has mostly been used for shallow translational slides. Wesley (1977) doubts whether the same method of stability analysis can be applied to very steep slopes. Rouse and Reading (1985) suggest that the methods developed for temperate regions may not be appropriate for tropical or steep slopes. However, important studies of threshold inclinations have been carried out using the infinite slope model (Carson and Petley, 1970; Carson, 1971, 1975; Chandler, 1982). The coupling of this model with a distributed hydrological model may offer a good approach to study the role of pedogenesis and climate change in slope stability (Brooks *et al.*,1993). Anderson and Howes (1985), and Iverson and Major (1986), used the infinite slope model in hydrological modeling, while Dietrich *et al.* (1992), and Montgomery and Dietrich (1988, 1989) applied it in geomorphology.

The importance of material properties on slope stability should be further explored by performing sensitivity analyses of different materials under similar environmental conditions, and by adequate field and laboratory testing.

The town of Torvizcón is located within the area of study; it presumably was built on the toe of an old landslide, on the east slope of one of a tributary of the Guadalfeo (Figure 6). The incision of the river may have caused a mass failure before the site was settled. After the material was transported down to the Guadalfeo, a period of relative equilibrium of the slope ensued. At present the scarp has been partially reactivated (Figure 7), and there is a possibility of a landslide which could involve part of the town. Figure 7 shows that the land has been subjected to preparation or re-adaptation to create a smooth surface for cultivation. Increasing the steepness of the slope enables failures. Signs of slope instability may be observed after the 1996 rainfall events

Fig. 6. Torvizcón Town and the ancient landslide scarp.

Fig. 7. Reactivation of the scarp.

(Figure 8). The different levels of the ground surface are marked by vegetation patches distributed as steps along the profiles. The trees are bending in the direction of the movement and the slope processes are sometimes worsened by human factors.

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Fig. 8. Slope processes on phyllites. The bending of the trees is a good indicator of mass movement.

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