Geofísica Internacional (1999), Vol. 38, Num. 1, pp. 49-59

Modelling deep-seated slope failures in semi-arid southern Spain

Irasema Alcántara-Ayala
Department of Geography, King's College, London, U.K.
***Present address**: Massachusetts Institute of Technology,* Cambridge, MA, *USA.*

Received: April 30, 1998; accepted: October 26, 1998.

RESUMEN

Diversas investigaciones se han centrado en el estudio de los factores que controlan los deslizamientos superficiales y aquellos asentados a profundidad. Los deslizamientos superficiales han sido analizados con base en diferentes técnicas de mapeo, monitoreo y modelaje, etc., mientras que el principal objetivo de los estudios de deslizamientos asentados a profundidad está en relación con los mecanismos de movimiento y con los factores que afectan los cambios de niveles freáticos, y por lo tanto afectan la estabilidad de las laderas. Los deslizamientos a profundidad están controlados por las propiedades de los materiales, los rasgos geológicos y las condiciones hidrológicas. En regiones mediterráneas de clima semiárido, como en las Alpujarras (sureste de España), donde la presente investigación fue desarrollada, estos factores tienen gran importancia. Debido a la presencia de eventos extraordinarios de precipitación, comunes en este tipo de ambientes, los cambios en las condiciones hidrológicas juegan un papel trascendental en la ocurrencia de este tipo de deslizamientos. Dado lo anterior, el objetivo de este trabajo fue investigar los posibles escenarios en los cuales se pueden llevar a cabo este tipo de fenómenos. La metodología utilizada considera la combinación de tres diferentes modelos que han sido calibrados con datos de campo, los cuales se aplicaron en forma de un análisis en cascada. Diferentes series de datos de precipitación fueron utilizadas como base para el modelo de percolación del suelo, el cual permitió obtener los datos necesarios para establecer el modelo de infiltración, cuyos resultados fueron finalmente incorporados en el análisis de estabilidad de laderas. Los resultados del modelaje indican que existe la posibilidad de que haya grandes fluctuaciones en los niveles freáticos, lo cual afectaría la estabilidad de las laderas. Estas fluctuaciones ocurrirían si los valores de percolación fueran 20% del valor medio de la precipitación. La presencia de eventos extraordinarios, un cambio en las condiciones climáticas y/o en la cubierta vegetal, darían lugar a un incremento en los valores de percolación, y por ende tendría repercusión en la inestabilidad de las laderas.

PALABRAS CLAVE: deslizamientos asentados a profundidad, semiárido, hidrología, estabilidad de laderas, sur de España.

ABSTRACT

The aim of this research was to investigate the possible scenarios of occurrence of deep-seated failures under semi-arid Mediterranean and mountainous conditions, triggered by water-table shifts caused by changes in the precipitation regimen in an area of Andalucía, Spain. The methodology involved the combination of three different models calibrated with field data. The models were applied in a cascade analysis. The input of the soil water budget model was provided by rainfall, supplying the upper boundary for the seepage model, which was then used for conventional slope stability analysis. Modelling results indicated that large water-table and pressure head fluctuations would occur and affect slope stability when percolation rates reach 20% of the mean rainfall value. These conditions could be the result of the presence of extreme events, a change in the climate regime or the removal of the vegetation cover.

KEYWORDS: deep-seated failures, semi-arid, hydrology, slope stability, southern Spain.

INTRODUCTION

The area of study, the Alpujarras, comprises part of the Guadalfeo basin, south of the Sierra Nevada in Andalucía, Spain (Figure 1). This typical Mediterranean environment is characterised by mountain slopes, frequently undercut by ephemeral rivers. The whole basin is drained by the Andarax river to the east, the Guadalfeo river to the west and the Chico river in the central sector. The climate is Mediterranean. The main precipitation occurs in autumn, winter and during the first half of spring, while the dry season occurs in the summer months from June to October (Figure 2). The mean annual rainfall at nearby meteorological stations is 525 mm at Torvizcón, 471 mm at Lanjarón and 490 mm at Orgiva. The mean annual temperature is 18^{o}C, but during the summer it can reach up to 34^{o}C. Mediterranean semi-arid climate is characterised by a marked dry period, seasonal concentration, high inter-annual variability of rainfall intensity, intense

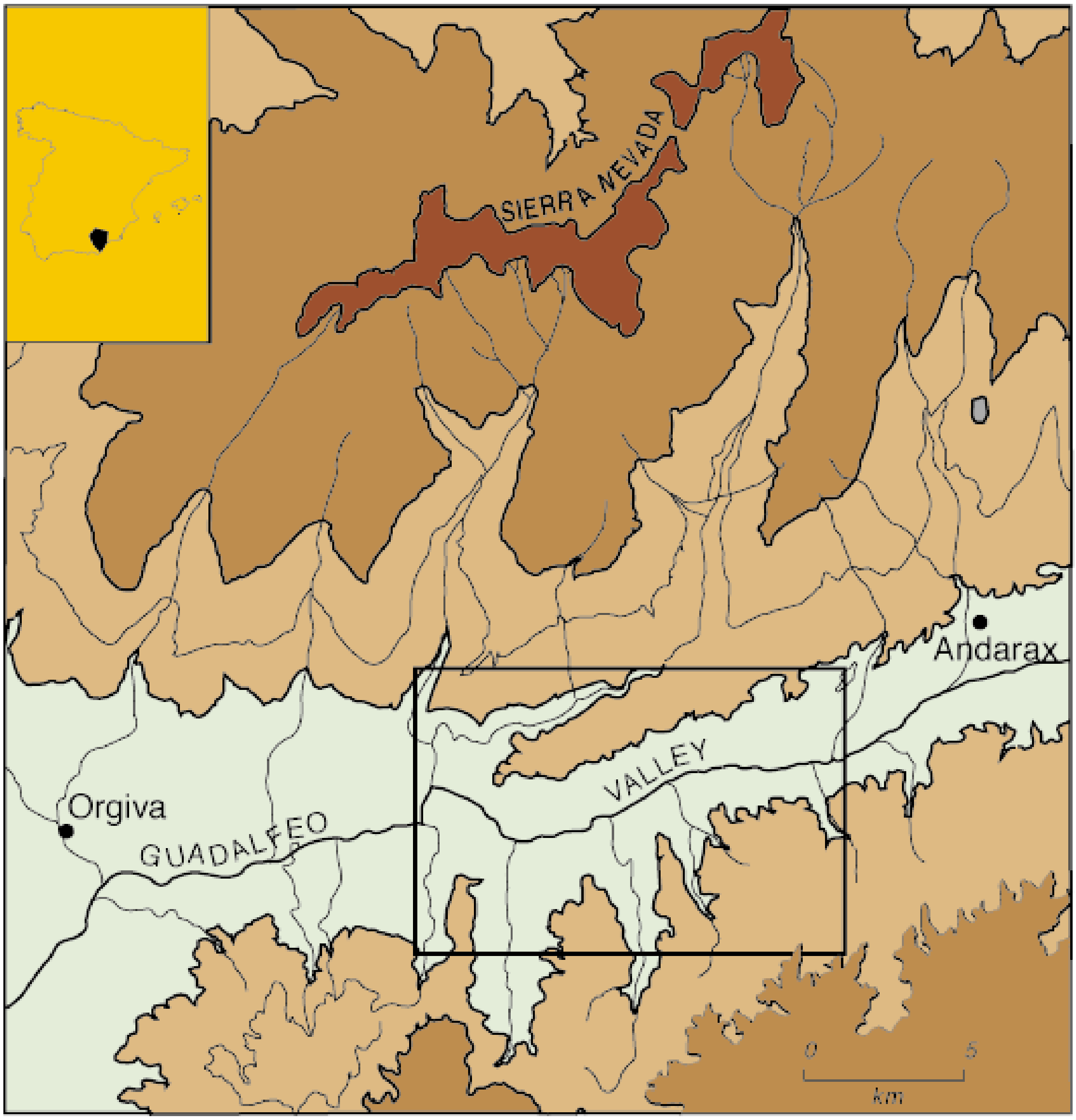

Fig. 1. Location of the studied area.

insolation, high temperatures and high potential evapotranspiration with a strong tendency to aridity (López-Bermúdez, 1983).

The Alpujarride Complex includes five nappes of metamorphic and sedimentary rocks of Triassic and Permian age (Aldaya, 1969; Aldaya *et al*., 1979) that resulted by overthrusting, due to the northwards motion of the African plate during the Alpine orogeny. The field site is located within the Alcázar nappe, containing mostly phyllites. Mass movement within the nappes is important and relevant to the causation of landslides, a serious natural hazard in Spain. Landslides, rock slides and rock falls occur mainly in mountainous zones and in eroded Tertiary basins, comprising about two-thirds of Spain's land surface (Ayala and Ferrer, 1989).

Phyllites play an important role in slope failures in southern Spain because of their relatively low strength, their lack of permeability and the interactions with the environmental conditions (Alcántara-Ayala and Thornes, 1996; Alcántara-Ayala (in preparation)). Shallow failures take place within the regolith surface and sometimes at depth of 2 or 3 meters within the profile. Deep-seated failures occur mainly along the Guadalfeo river, both in the soil profile and in the bedrock.

Petley (1996) has pointed out the difference between the shallow and deep-seated failures on the basis of shear surface depth. Most landslides feature shear surfaces at a depth of less than 30 m, whilst deep-seated failure may take place on shear surfaces of as much as 50 m below the surface. Deep-seated landslides, also known as deep-seated

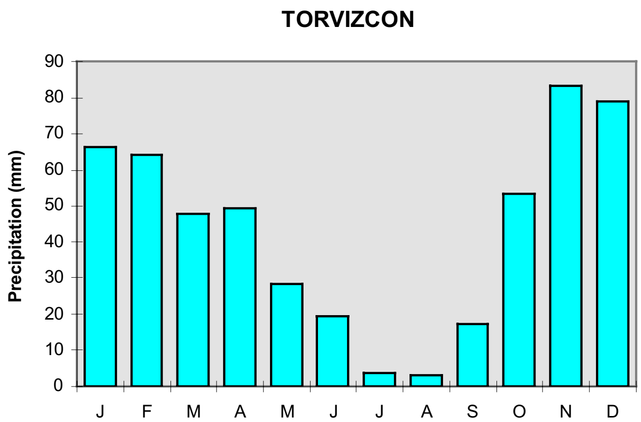

Fig. 2. Mean annual precipitation at Torvizcón meteorological station.

gravitational deformations (DSGD), are very rare events. They are not widely distributed spatially, but they can be associated with large catastrophic events, flooding and air blasting (Petley, 1996).

The Vaiont landslide (Voight and Faust, 1982 and 1992), the failure of Monte Faloria in Italy (Pasuto and Soldati, 1990), and Monte Huascarán in Peru (Plafker and Eriksen, 1978), are some examples. Deep-seated gravitational deformations involve creep and sudden failure. The former implies slow strain rates, whilst the latter produces high rates of movement and can produce catastrophic damage. Oyagi *et al*. (1994) suggest that both processes are interconnected, since creep acts as a process of preparation to trigger sudden failures.

During an early field campaign, two types of mass movement were observed. Shallow failures took place within the regolith, whilst deeper failures occurred both within the regolith and within the bedrock. The deeper failures involved a larger mass of soil and bedrock, and landslip surfaces could be easily identified at about 10-15 m depth, not at more than 50 m depth. They were related to water-table fluctuations, and thus to extreme events such as floods. While less extensive than the deep-seated failures defined by Petley (1996), they might induce or aggravate floods. In this research we investigate the possible scenarios of occurrence of these deep-seated failures, as a result of water-table fluctuations caused by changes in precipitation.

METHODOLOGY AND RESULTS

We coupled different models parameterised by field experiments. Observations followed the strategy shown in Figure 3. Three models were combined in a cascade analysis,

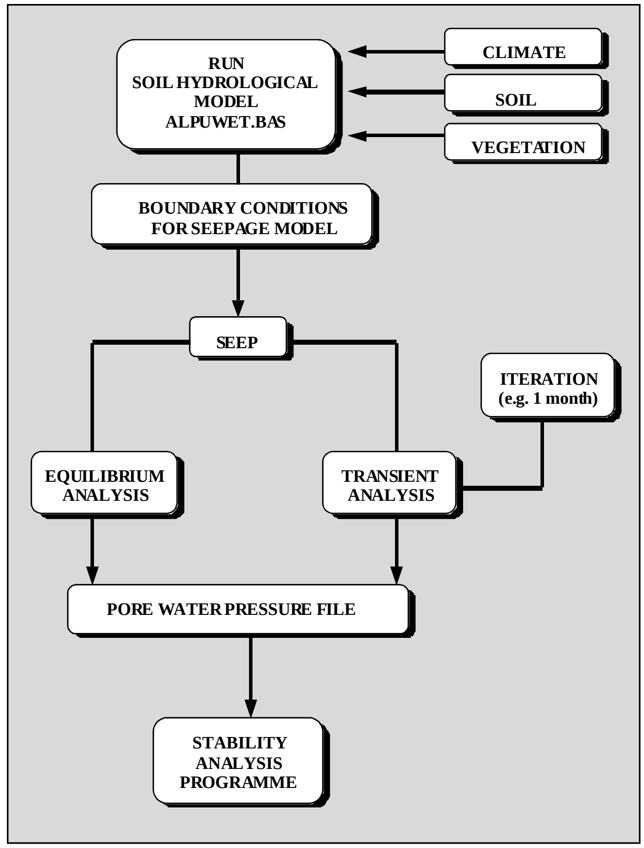

Fig. 3. Strategy followed by this research.

calibrated with field data. The input of the soil water budget is provided by rainfall. This supplies the upper boundary of the seepage model, which is used for conventional slope stability analysis.

Soil percolation model

A soil-water budget model (Obando, 1996) was used to simulate the soil moisture regime within the area. Rainfall series have been incorporated into the model as inputs. Three different rainfall series were selected to run the model. Saturated hydraulic conductivity was set at 5.05^{-6} m/s and 8.58^{-6} m/s; the former value was obtained by Alcántara-Ayala (1997), the latter, by Obando (1996) in semi-arid Spain. The soil was assumed to have a moisture capacity of 28%, but the same model was also run with values of 18% and 49%. Table 1 summarises the inputs used in modelling.

Daily precipitation records over 36 years were available at Torvizcón meteorological station. Figure 4 shows the variability of the rainfall regime in the area of study. Periods of relative dryness, wetness, and average rainfall were identified. As input for the water budget model, daily rainfall series must be used. Model inputs included three sets of five-

Table 1

Inputs used in the soil percolation model.

Rainfall series	*Biomass*	*Soil moisture capacity*	*K_{sat} (Hydraulic conductivity)*
Wet series (1961-1965)	Bare surface 36% biomass 51% biomass	18%, 28%, 49% 18%, 28%, 49% 18%, 28%, 49%	5.05 x 10^{-6} m/s, 8.58 x 10^{-6} m/s 5.05 x 10^{-6} m/s, 8.58 x 10^{-6} m/s 5.05 x 10^{-6} m/s, 8.58 x 10^{-6} m/s
Mean series (1976-1980)	Bare surface 36% biomass 51% biomass	18%, 28%, 49% 18%, 28%, 49% 18%, 28%, 49%	5.05 x 10^{-6} m/s, 8.58 x 10^{-6} m/s 5.05 x 10^{-6} m/s, 8.58 x 10^{-6} m/s 5.05 x 10^{-6} m/s, 8.58 x 10^{-6} m/s
Dry series (1991-1995)	Bare surface 36% biomass 51% biomass	18%, 28%, 49% 18%, 28%, 49% 18%, 28%, 49%	5.05 x 10^{-6} m/s, 8.58 x 10^{-6} m/s 5.05 x 10^{-6} m/s, 8.58 x 10^{-6} m/s 5.05 x 10^{-6} m/s, 8.58 x 10^{-6} m/s

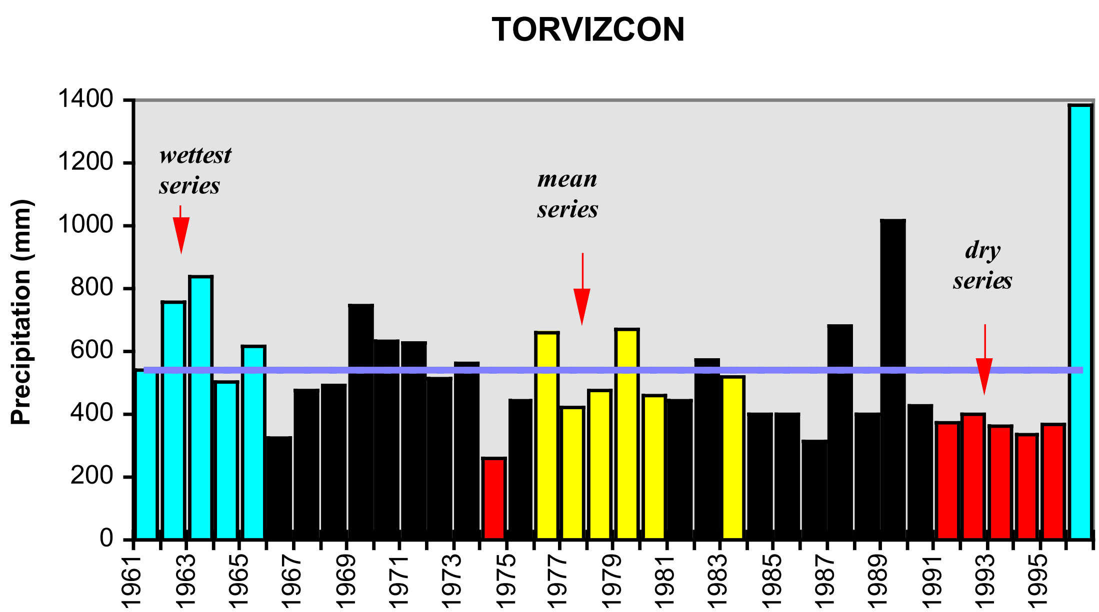

Fig. 4. Daily precipitation records of 36 years (Torvizcón meteorological station).

year periods, which represent wet, dry, and average years. Thus, the study of the impact of short-term water inputs on mass failure occurrence, may be simulated under different conditions of moisture.

The 36-year series (Figure 4) features a mean precipitation of 539.39 mm/year. The minimum total annual rainfall was 259.8 mm, and the maximum was 1381 mm. The wet series had a mean of 649.68 mm, a minimum precipitation of 503.7 mm and a maximum of 834.9 mm, which represent 20% above the mean of the 36-year series. The average or normal series were closest to the mean. In the average rainfall series of 1976-1980, a mean precipitation of 538.16 mm was recorded, which is 0.23% lower than the overall mean. The minimum precipitation was 423.7 mm and the maximum 671.2 mm. Finally, the dry series (1991-1995) had a mean rainfall of 368.9 mm, only 68.39% of the overall mean, whilst the minimum precipitation was 337 mm, and the maximum 403 mm. This is less than 50% of the maximum precipitation for the wet series.

There is a good correlation with the number of rainy days and the mean rainfall per rainy day for all three series. The wet series had 258 rainy days and 12.59 mm mean daily, whilst the dry series had 168 rainy days and 10.97 mm mean daily rainfall.

Table 2

Outputs of the soil percolation model.

Ksat = 5.05 x10-6 m/s		***Smc = 18%***			***Smc = 28%***			***Smc = 49%***		
Rainfall series	**Biomass (g)**	**Mean**	**Min.**	**Max.**	**Mean**	**Min.**	**Max.**	**Mean**	**Min.**	**Max.**
1961-1965 Wet series	0.1	0.258	0.0144	0.436	0.287	0.047	0.436	0.314	0.089	0.436
	300	0.182	0	0.436	0.204	$1x10^{-4}$	0.436	0.231	0.004	0.436
	600	0.165	0	0.436	0.186	0	0.436	0.211	$9x10^{-4}$	0.436
1976-1980 Mean series	0.1	0.268	0.0216	0.436	0.297	0.0608	0.436	0.326	0.07	0.436
	300	0.185	0	0.436	0.208	0.0002	0.436	0.233	0.004	0.436
	600	0.165	0	0.436	0.187	0	0.436	0.21	$1x10^{-3}$	0.436
1991-1995 Dry series	0.1	0.233	0.0076	0.436	0.266	0.0314	0.436	0.301	0.076	0.436
	300	0.154	0	0.436	0.177	0	0.436	0.203	0.001	0.436
	600	0.137	0	0.436	0.157	0	0.436	0.181	$2x10^{-4}$	0.436
Ksat = 8.58 x10-6 m/s		***Smc = 18%***			***Smc = 28%***			***Smc = 49%***		
Rainfall series	**Biomass (g)**	**Mean**	**Min.**	**Max.**	**Mean**	**Min.**	**Max.**	**Mean**	**Min.**	**Max.**
1961-1965 Wet series	0.1	0.367	0.003	0.742	0.418	0.0212	0.742	0.474	0.093	0.742
	300	0.274	0	0. 742	0.312	0	0. 742	0.358	0.003	0. 742
	600	0.25	0	0. 742	0.286	0	0. 742	0.329	$7x10^{-4}$	0. 742
1976-1980 Mean series	0.1	0.384	0.0058	0.742	0.435	0.0328	0.742	0.491	0.1	0.742
	300	0.277	0	0.742	0.317	$1x10^{-4}$	0.742	0.36	0.004	0.742
	600	0.249	0	0. 742	0.285	0	0. 742	0.326	$7x10^{-4}$	0. 742
1991-1995 Dry series	0.1	0.318	0.001	0. 742	0.372	0.0106	0. 742	0.431	0.063	0. 742
	300	0.227	0	0. 742	0.262	0	0. 742	0.304	$9x10^{-4}$	0. 742
	600	0.204	0	0. 742	0.234	0	0. 742	0.273	$1x10^{-4}$	0. 742

Soil percolation model output

A total of 54 runs were performed to predict the output of the percolation variations for different parameters. Table 2 shows the results. The upper section assumes a K_{sat} value of 5.05 x 10^{-6} m/s and the second a value of K_{sat}=8.58 x 10^{-6} m/s. A similar pattern for different variables is observed. The main difference is due to different hydraulic conductivity values; thus the runs using a value of K_{sat} = 5.05 x 10^{-6} m/s yield a maximum percolation of 0.436 mm/day, whilst for K_{sat} = 8.58 x 10^{-6} m/s the percolation increases to 0.741 mm/day. These results depend on the percentage of biomass and on the soil moisture capacity. As biomass decreases, the percolation increases, and as the soil moisture content increases so does the drainage. A further description and analysis of the results yields a soil moisture capacity of 28% and a K_{sat} value of 5.05 x 10^{-6}m/s, close to the real field conditions.

The daily percolation pattern of the 1991-1995 dry series is similar for different biomass conditions, but drainage into the soil increases as vegetation decreases. Thus the higher value of mean percolation (0.266 mm/day) is found for the bare surface and the lowest for 51% of biomass (0.157 mm/day). Under all conditions of biomass the highest percolation takes place during winter. In the summer months the drainage is very low because of the absence of rainfall. However, when comparing the results for different percentages of biomass, the bare surface is likely to have the highest monthly percolation rate in the dry season. For example, if a mean value of 0.17 mm/day (36% biomass and 28% of soil moisture capacity) percolates into the soil, this would represent 17.5% of the total precipitation of the 5-year period. On the other hand if the biomass were to decrease, a bare surface would be capable of percolate 26.35% of the total rainfall. For either value of hydraulic conductivity, there is a high probability of low values, and a low probability of high values of percolation, when the biomass is either 36% or 51%. However, when the biomass is reduced to a bare surface, the probability of high values of percolation increases.

The output of the 1976-1980 mean series yields a mean daily percolation of 0.29 mm for a bare surface, 0.20 mm for a surface with 36% of biomass and 0.18 mm for 51% of biomass. This amounts to 20%, 14% and 12% of the total five-year period of rainfall. The mean series yields a very high probability of low values for surfaces with biomass of 36% and 51%, whilst the other percolation values increase as the probability decreases.

During the 1961-1965 wet series, the mean value of daily percolation is 0.286 mm for a bare surface, 0.204 for a surface with 36% biomass and 0.186 mm with 51% biomass. These percolation values represent 16%, 11.4% and 10.4% of the total 5-year period of rainfall, 1963 was the wettest year, and the highest monthly percolation occurred during winter at a rate of 12.5 mm, whilst in summer it decreased to 0.5 mm/month. However, the general tendency in most months is to have a high rate of percolation, as high as 4 mm in August, the driest month. Finally, for the wet series, there is a high probability of high values of percolation and a low probability of low values for a bare surface with either hydraulic conductivity. Given biomass percentages of 36% and 51%, the low values (0.1 mm/day) have a probability of 42% to occur, whereas the highest percolation values (0.5 or 0.8 mm/day, depending on K_{sat}) have a 15% probability. The intermediate percolation values such as 0.3 mm/day have the lowest probability (12%).

In general the frequency distribution of the daily percolation values from the model suggest that there is a very high probability of very low values, reflecting overall low soil drainage. Other values tend to be more uniform suggesting that extreme events or large storms may actually provide a significant increase in the percolation. A seasonal bias is clearly shown in the calculated values of the percolation. Even in large storms, the soil is able to filter the impact of these extreme events on the percolation rate, which falls to a value of almost zero at the end of the summer season.

Note high sensitivity of the percolation rate to porosity and vegetation cover. A lower vegetation cover leads to higher percolation rates due to lower transpiration losses, which depends on intensity. Vegetation cover tends to reduce runoff at low intensities, but at high intensity the losses at the surface are high regardless of cover. A bare surface implies the removal of the vegetation cover almost completely (leaving only enough for reseeding). The upper bound of 300 g/m^2 (36% biomass) is the actual upper limit of biomass due to limiting rainfall in this area (Thornes and Brandt, 1993). Finally, 600 g/m^2 (52% biomass) may correspond to the vegetation cover in the historic past, since soil thickness has diminished as a result of intensive erosion (Thornes, 1976).

Our results suggest that recharge is strongly seasonal, and that it may average as high as 16% of the annual average precipitation in the Alpujarras despite the low rainfall. This is at least in part a result of the shorter growing season and the lower evapotranspirational losses.

Seepage model

Steady state and transient solutions have been attempted. Steady-state runs were intended to investigate long-term variations in percolation, and to provide the initial conditions for transient solutions. Transient runs were carried out to examine seasonal and short-term variations, and the role-played by topography.

The Almegijar landslide is in the north-eastern Guadalfeo valley, south of the Sierra Nevada. It occurred in metamorphic rocks, typically phyllites. The profile runs perpendicular to the Guadalfeo valley, from north to south, and the maximum height is 1190 m. Boundary conditions were assumed zero flux conditions at a distance from the Guadalfeo valley. The left-hand boundary corresponds to the watershed of La Lomilla, north of the Trevelez river, a tributary of the Guadalfeo river, which runs north-east of the town of Almegijar towards the main valley. The watershed of the Contraviesa Sierra, south-east of Torvizcón and near Las Piedras de Carmona, was chosen as the right boundary. The ground surface or upper boundary was taken as an infiltrating boundary unless the water table reaches the surface; in this case the boundary was fixed at the total head at that point and the flux was directed outwards as seepage.

Steady-state analysis

Steady-state simulations were undertaken in order to investigate the conditions for significant movements of the water table for variations in steady-state percolation inputs. The climate was assumed to remain stationary. A value of 8.4 x 10^{-7} m/s was used for the saturated conductivity of the phyllites and mica-schists within the area, and the water capacity was taken to be 15% by volume. The upper boundary was set up at a local percolation rate, which was kept constant through time. Anisotropy of the hydraulic conductance was also considered. The simulations were carried out with percolation inputs of 3.4183 x 10^{-10} m/s (10.78 mm/year), 8.5000 x 10^{-10} m/s (26.80 mm/year), 1.7091 x 10^{-9} m/s (53.90 mm/year), 3.4338 x 10^{-9} m/s (108.29 mm/year), and 4.2491 x 10^{-9} m/s (134 mm/year).

The simulation suggests that the water table is very sensitive to mean input rates of 4.2491 x 10^{-9} m/s and lower (Figure 5). With mean input values of 3.4183 x 10^{-10} m/s (10.78 mm/year), the water table is low over the whole mountainous complex. With inputs of 1.7091 x 10^{-9} m/s (53.90 mm/year, the equivalent of 10% of the mean annual precipitation), the water table occupies a middle position, somewhat closer to the ground surface in the Almegijar area. For mean inputs equivalent to 20 and 25% of the total annual rainfall, 3.4338 x 10^{-9} m/s and 4.2491 x 10^{-9} m/s respectively, the water table is near to the surface on either side of the Guadalfeo river. However, north of the river, where mass failure took place, the water table is closest to the ground surface.

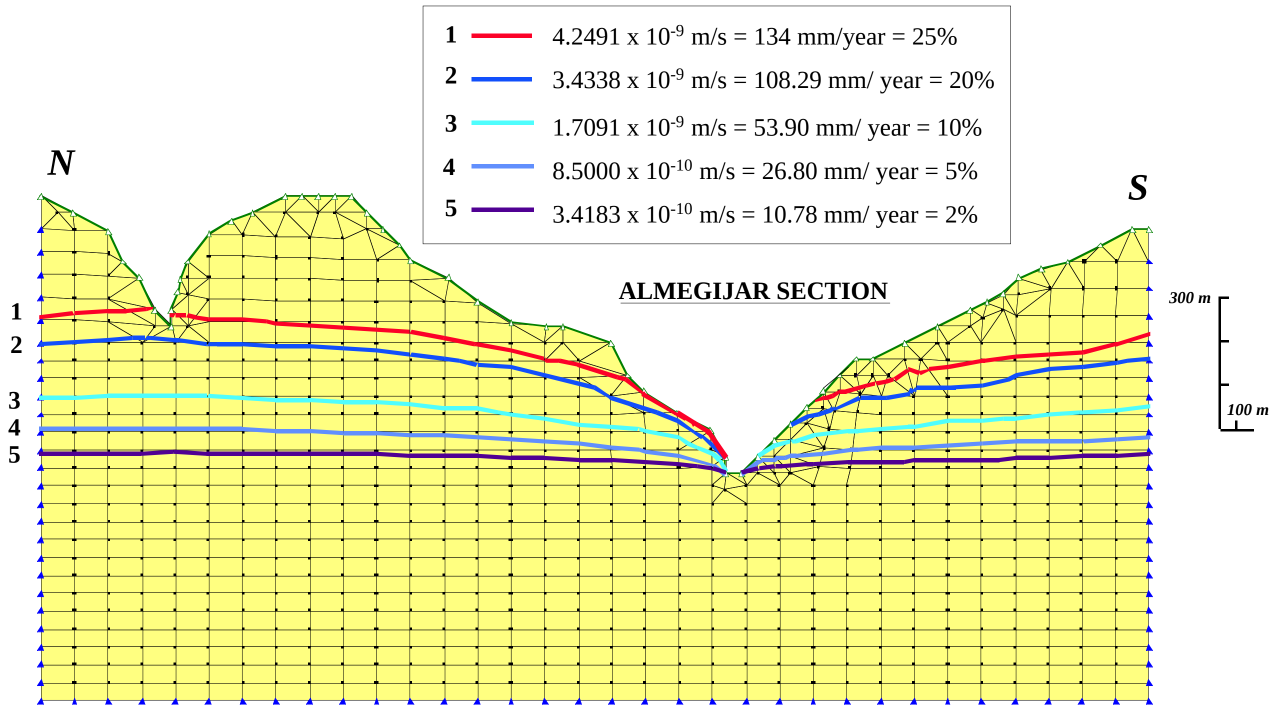

Fig. 5. Output of the steady-state analysis of the Almegijar section. The water table is very sensitive to mean input rates of 4.2491 x 10^{-9} m/s and lower values.

Transient analysis

According to the preceding steady-state analysis, climatic or vegetation changes in the Alpujarride complex would require a period of time to reach a new equilibrium state. The time needed for this would be very long. In a transient experiment, an input of about 10% of the current rainfall value at Torvizcón meteorological station was combined with stripping of the vegetation cover to study the possible responses of the water table after a further run of 99 years for the Almegijar section.

The long-term transient experiment in the Almegijar section shows a substantial water-table change. A saturated wedge develops at the bottom of the slopes on both sides of the Guadalfeo valley (Figure 6). Results show an inward-moving wetting front like that of the Jubiley section described by Thornes and Alcántara-Ayala (1998). The pressure head (Figure 7) increases after about 50 years at nodes 547, 579 and 481, and continues increasing thereafter. Node 574 at the south side of the valley shows a similar increase of the pressure head but of a lower magnitude, which causes no major problems of mass movement. The head pressure conditions remain more or less stable at node 508, indicating more stable conditions in this part of the mountain. There is a decrease of the pressure head at node 507 after 50 years, and an increase after 80 years.

The results suggest that a change in percolation rates either by decreasing rainfall or removal of the vegetation cover may affect the long-term water table conditions and may trigger landslides at the bottom of the slope on the north side of the valley.

Slope stability

Slope stability analyses were undertaken using the Geo-slope software (Geo-slope, 1994, Version 3). The program Slope/W uses the transient or steady-state groundwater conditions estimated by the Seep/W program (Geo-slope, 1992) to compute slope stability using the same mesh. The simulation permits critical angles to be defined such that the cohesive strength can be set as a ratio of the regular cohesion of the rock; this has been used to represent the weaker structural elements in the mica-schists and phyllites.

To carry out the stability analysis of the Almegijar profile, a subsection of transect was selected. This section is located north of the Guadalfeo river and south of Almegijar. Steady-state groundwater conditions with recharges from 2% to 25% were used in the analysis. Unweathered phyllites were tested in a triaxial Hooke cell, to find the cohesion and the angle of internal friction. An angle of internal friction ϕ = 32.9 and a cohesion value c = 12.6 MPa/m^2 were obtained.

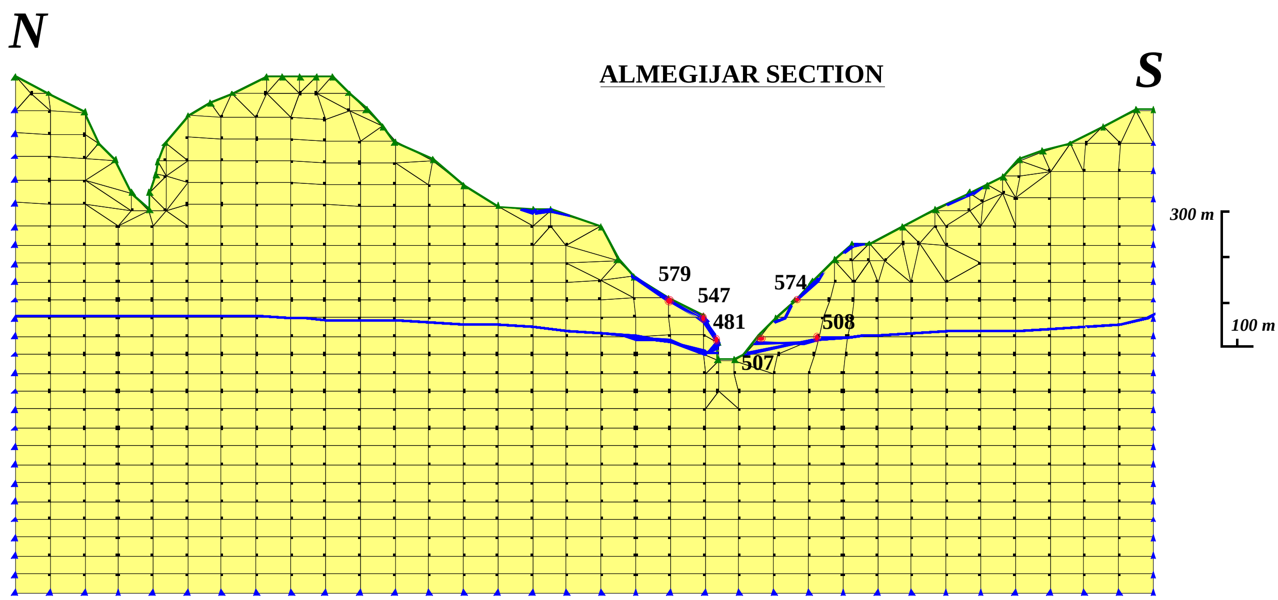

Fig. 6. Long-term transient analysis output. The water table change is represented by the development of a saturated wedge at the bottom of the slopes on both sides of the river.

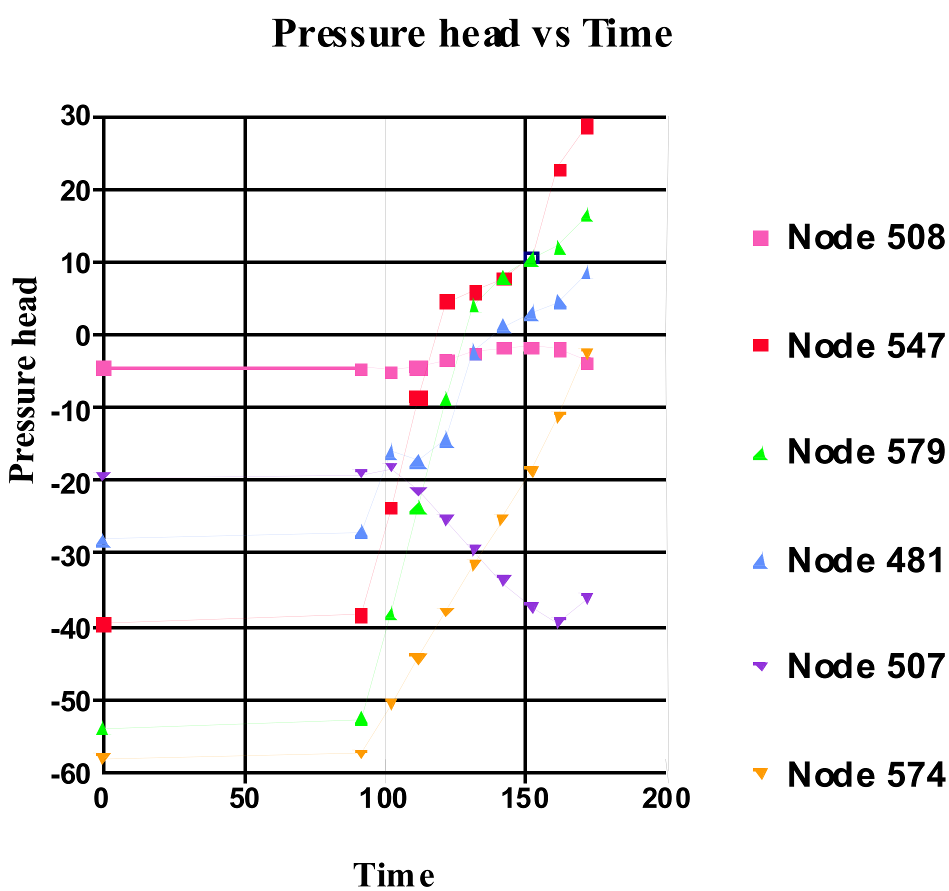

Fig. 7. Pressure head graph showing an increase in the pressure head after about 50 years at nodes 547, 579 and 481. Change in the percolation rates would affect the long-term water table conditions and therefore the stability of the slope.

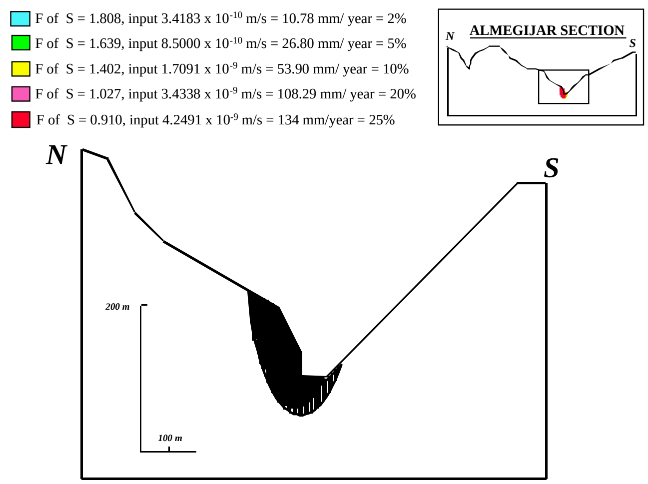

Fig. 8. Slope stability analysis based on the steady state outputs of the Almegijar section. Under these conditions the water table would produce considerable changes on the stability at the foot of the slope.

Slope stability analysis (Figure 8) suggested that for these steady-state conditions, any shifts in the water-table would produce considerable changes in stability at the foot of the Almegijar profile along the Guadalfeo valley. With recharge inputs of 3.4183 x 10^{-10} m/s (10.78 mm/year) or 8.5000 x 10^{-10} m/s (26 mm/year), the slope of the section remains stable. With mean inputs of 1.7091 x 10^{-9} m/s (53.9 mm/year) the area is still relatively stable. However, when the input reaches 20% to 25% of the annual rainfall, the conditions are unstable.

From our soil percolation model about 19-20% of the total rain would percolate into the soil under rainfall conditions such as those given in the wet, mean or dry series, assuming a bare surface. Even for unchanged rainfall conditions, the removal of the vegetation cover is enough to destabilize the slope.

For the wettest year (1996) the percolation rate is 3.8056 x 10^{-9} m/s (120.01 mm/year) corresponding to 22.26% of the annual precipitation (Alcántara-Ayala, 1997). When this percolates into the bedrock, it causes instability at the foot of the Almegijar section, where the Almegijar landslide took place. Field observations suggest that an extreme event in 1996 increased the instability of the area, while the actual movement of the Almegijar landslide has not been recorded, photographs from 1993 to date show the evolution of the landslide in time under different rainfall conditions. Figure 9 shows the Almegijar landslide before and after the 1996 event.

DISCUSSION

The performed experiments suggest that for the present vegetation cover (36%), recharge rates comparable with historically recorded droughts were unlikely to have produced a significant lowering of the steady state position of the water table. However, the potential effects of change of the vegetation cover were demonstrated by removing the vegetation cover almost completely. The overall soil drainage rate into the bedrock, increased in all rainfall series by around 6% of the percolation value for a vegetation cover of 36%. For instance, the percolation rate with a contemporary cover (36%) in the wettest year (1996) is 2.7557 x 10^{-9} m/s (86.906 mm/year), rising to 3.8056 x 10^{-9} m/s (120.01 mm/year) after removal of the cover, mainly due to the reduction of interception and evapotranspiration losses.

The steady-state experiments show the significance of the spatial occurrence of seepage. Because the divide on the northern side is higher and the slopes longer, seepage rates and pore water pressures are likely to be higher than to the south. This confirms the observation of Foster and Smith (1988) that the overall topography is likely to play a major role in the development of pore water-induced stress, seepage and landform evolution. In the Alpujarras, at least, the controlling conditions of mass failures include long-term geomorphological evolution or the presence of extreme events either by raising the water-table or by slope undercutting.

The experiment underscores the significance of climate change for slope stability. Mediterranean areas are subjected to desertification and therefore, changes of the vegetation cover are involved. These changes are also expected to cause hydrological shifts, especially in semi-arid areas (Kirkby *et al*., 1996). Changes in rainfall distribution, duration, frequency and intensity influence infiltration rates and seepage. Our results show the impact of precipitation and vegetation changes on slope stability. Large water-table fluctuations are illustrated by the development of an inward-moving wetting front, and the increase of the pressure head after 50 years, due to the removal of vegetation and the increase in precipitation. Conditions of instability at the foot of the slopes were demonstrated on a long-term basis.

ACKNOWLEDGEMENTS

I thank Prof. John B. Thornes (King's College London) for his guidance and support during this work. This research was supported by D.G.A.P.A. (UNAM), as part of a PhD scholarship at the University of London. Thanks are also due to Dr. Jorge Membrillo-Hernández, who improved the readability of this paper, and to the two anonymous reviewers for their constructive suggestions.

Fig. 9. Almegijar landslide along the Guadalfeo river before and after the 1996 rainfall event.

BIBLIOGRAPHY

ALCANTARA-AYALA, I. and J.B. THORNES, 1996. The environmental dimensions of mass failure in semi-arid Spain. *In*: Senneset, K. (ed.), Landslides, Glissements de terrain, Proceedings of the seventh international symposium on landslides, 3, Balkema, Rotterdam 1837-1842.

ALCANTARA-AYALA, I., 1997. Modelling mass movement risk under semi-arid mountainous conditions: the Alpujarride Complex, Spain. Unpublished PhD Thesis, University of London, 370 pp.

ALCANTARA-AYALA, I., (in preparation). Procesos de remoción en masa en condiciones de semiaridez: dimensiones ambientales.

ALDAYA, F., 1969. Los Mantos Alpujárrides al Sur de Sierra Nevada. Unpublished PhD Thesis, Universidad de Granada.

ALDAYA, F., V. GARCIA-DUEÑAS, and F. NAVARRO-VILA, 1979. Los mantos Alpujárrides del tercio central de las Cordilleras Béticas, *Acta Geológica Hispánica*, España, *14*, 154-166.

AYALA, F.J. and M. FERRER, 1989. Extent and economic significance of landslides in Spain, *In*: Brabb, E. E. and B. L. Harrod, (eds), Landslides: Extent and Economic Significance. Proceedings of the 28th International Geological Congress: Symposium on landslides, Washington, D.C. 169-178.

FOSTER, C. and L. SMITH, 1988. Groundwater Flow Systems in Mountainous Terrain: 1. Numerical Modelling Technique. *Water Resources Research*, 24, 7, 999-1010.

GEO-SLOPE INTERNATIONAL, 1992. SEEP/W, User's Guide. Calgary, Alberta, Canada.

GEO-SLOPE INTERNATIONAL, 1994. SLOPE/W, User's Guide. Calgary, Alberta, Canada.

LOPEZ-BERMUDEZ, F., 1983. La erosión hídrica de los suelos en el dominio mediterráneo español. Percepción y diagnóstico geográfico. Departamento de Geografía de la Universidad de Barcelona. Terraco. Cuadernos de Geografía, 4-5.

OBANDO, J.A., 1996. Modelling the impact of land abandonment on runoff and soil erosion in a semi-arid catchment, Unpublished PhD Thesis, University of London.

OYAGI, N., M. SORRISO-VALVO, and B. VOIGHT, 1994. Introduction to the special issue of the symposium on deep-seated landslides and large-scale rock avalanches, *Engineering Geology*, *38*, 187-188.

PASUTO, M. and A. SOLDATI, 1990. Some cases of deep-seated gravitational deformations in the area of Cortina d' Ampezza (Dolomites), *Proceedings of the European Short Course on Applied Geomorphology*, 2, 91-104.

PETLEY, D., 1996. The Mechanics and Landforms of Deep-Seated Landslides, *In*: Anderson, M. A. and S. Brooks, (eds), Advances in Hillslope Processes, 2, Wiley, Chichester, 822-835.

PLAFKER, G. and G.E. ERIKSEN, 1978. Nevados Huascarán avalanches, Perú, *In*: Voight (ed), Rockslides and Avalanches, Elsevier, Amsterdam, 607-657.

THORNES, J.B., 1976. Semi-arid erosional systems: case studies from Spain. *Geographical Papers*, London School of Economics. 7, 104 pp.

THORNES, J.B. and J. BRANDT, 1993. Erosion-Vegetation Competition in a Stochastic Environment Undergoing Climatic Change. *In:* Millington, A. C. and K. Pye, (eds). Environmental Change in Drylands. Chichester, John Wiley & Sons. 305-320.

THORNES, J.B. and I. ALCANTARA-AYALA, 1998. Modelling mass failure in a Mediterranean mountain environment: climatic, geological, topographical and erosional controls, *Geomorphology* (in press).

VOIGHT, B. and C. FAUST, 1982. Frictional heat and strength loss in some rapid landslides. *Géotechnique*, *32*, 43-54.

VOIGHT, B. and C. FAUST, 1992. Frictional heat and strength loss in some rapid landslides: error correction and affirmation of mechanism for the Vaiont landslide, *Géotechnique*, 42, 641-643.

Irasema Alcántara-Ayala
Department of Geography, King's College London, Strand, London WC2R 2LS, U.K.
***Present address**: Massachusetts Institute of Technology, Department of Civil and Environmental Engineering, Room 1-330*
77 Massachusetts Avenue, Cambridge, MA,
02139-4307, USA
***E-mail**: irasema@mit.edu*