The Diezma landslide (A-92 motorway, Southern Spain): history and potential for future reactivation

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Abstract A complete failure analysis of a complex landslide located in Southern Spain (the Diezma landslide) has been undertaken using geotechnical, geophysical and geological data. The triggering factors were a high groundwater level and the reduction in the shear strength parameters of the high-plasticity clay. The 2010 reactivation of the landslide was related to the poor performance of the first line of deep drainage wells, although the second and third line of wells and the anchored pile barrier were effective in preventing the landslide reaching the A-92 motorway. Analysis indicates that further reactivation of the Diezma landslide could take place following a period of heavy rain if the drainage wells are not properly maintained, or if an earthquake of M_w 4.0–5.0 occurs within 25 km of the site.

Keywords A-92 motorway · Betic Cordillera · Diezma · Drainage wells · Landslides · Newmark

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Résumé Une analyse complète d'un glissement complexe dans le sud de l'Espagne (le glissement de Diezma) a été réalisée, prenant en compte des données géologiques, géophysiques et géotechniques. Les facteurs de déclenchement étaient représentés par un niveau élevé de la nappe phréatique et une diminution des paramètres de résistance au cisaillement de l'argile de forte plasticité. La réactivation du glissement en 2010 correspondait à la faible performance de la première ligne de puits de drainage, bien que la deuxième et la troisième ligne de puits et le dispositif de pieux ancrés aient joué leur rôle par rapport à l'objectif de protéger l'autoroute A-92 du glissement. L'analyse indique qu'une prochaine réactivation du glissement de Diezma pourrait avoir lieu après une période de pluies intenses si les puits de drainage ne sont pas correctement entretenus, ou si un séisme de magnitude $M_w = 4.0–5.0$ a lieu à moins de 25 km du site.

Mots clés Autoroute A-92 · Cordillère bétique · Diezma · Puits de drainage · Glissements de terrain · Newmark

Introduction

Landslides commonly occur during rainy seasons due to the development of substantial pore water pressures in the slope mass. Measures for controlling the occurrence of landslides are usually designed on the basis of empirical criteria. However, there is no generally accepted model for considering the effectiveness of the different stabilising techniques. Trenches and wells are widely used to reduce the pore water pressure and while in marly and clayey soils these drainage works may be very effective, they have not been validated over time by direct or indirect observations.

In this paper, the effectiveness of the stabilisation measures, particularly deep drainage wells, has been analysed in a complex landslide affecting a motorway in SE Spain. The evolution of the Diezma landslide has been considered for five stages:

1. the slope before and after the A-92 motorway construction;
2. the slope during the 2001 Diezma landslide;
3. the slope after the stabilisation measures;
4. the slope at the time of the 2010 reactivation;
5. possible future reactivation.

In each case, the mechanism of slope failure was identified using detailed geotechnical, geophysical and geological data.

Diezma landslide

The Diezma landslide is located in the north Sierra Nevada Range (Betic Cordillera, Southern Spain), close to the village of Diezma (Fig. 1). The landslide mass comprises high to moderate plasticity clays, silts and marls containing embedded limestone and dolostone blocks. These lithologies were part of a flysch-type formation, which represents a turbiditic sequence of Cretaceous–Lower Miocene age (Bourgois et al. 1974). This flysch formation has a chaotic appearance because it was intensively deformed during the Alpine Orogeny. In the Diezma area (Fig. 2), the flysch formation is structurally superimposed over the shales, phyllites, sandstones and conglomerates of the Maláguide Complex (Alborán Domain). The South Iberian Domain is made up of Upper Jurassic limestones and dolostones belonging to the Subbetic Zone, which were thrust onto the Maláguide Complex. These carbonate rocks outcrop just to the north of the Diezma landslide and act as an unconfined karstic aquifer, which transfers an abundance of water to the south, very close to the head of the landslide. There are some significant springs at the contact surface between the carbonate rocks and the low-permeability soils beneath the slide, such that the water table is commonly high after a period of heavy rain.

The Diezma landslide took place on 18 March 2001 following a period of high precipitation and caused significant damage on the Sevilla-Almería motorway (A-92), which was closed for several days as the cutting slope failed completely/collapsed (Fig. 3). The stabilisation of the Diezma landslide began immediately and involved re-grading the slope and installing additional surface drainage systems and deep drainage wells, as well as the construction of a barrier of anchored piles (Oteo Mazo 2001, 2003). Despite these measures, the Diezma landslide was partially reactivated as a result of the heavy rainfall during the winter of December 2009–February 2010.

The Diezma landslide is a complex movement which covers an area of 7.76 ha, with a maximum length of 510 m and maximum width of 205 m (Fig. 4). The landslide volume is approximately 1.2 hm^3, with an average thickness of 20 m. From field observations, the landslide body can be divided into three different parts: the head, and the intermediate and toe zones.

The head area is located very close to the old Granada-Almería road (CN-342) where several metre-scale scarps were observed. The main scarp, corresponding to the 2010 reactivation of the Diezma landslide, is located approximately 50 m to the north of this road, which partially collapsed (Fig. 4).

The intermediate part of the landslide is related to the occurrence of lateral spreading and some secondary scarps, which produce ponds and bulges with tension cracks at the crests (Azañón et al. 2010). In addition, there are many decimetre-scale lateral cracks with the same trend as the mass movement, which had damaged the intermediate road built during the slope restoration works.

At the toe sector, the thickness of the mass movement is greater in the central area (about 30 m) and the main cracks are opened obliquely to the direction of the slide. These cracks can be interpreted as the scarp related to the first failure surface of the slope. The lower half of the toe corresponds to the accumulation zone of an earth flow, which partially covered the A-92 motorway.

All of the observed scarps are related to rotational landslides developed successively in the clay-rich soils from the flysch formation. These low-permeability soils have also favoured the development of ponds at the head and intermediate zones of the landslide.

Geotechnical investigations

In the Diezma landslide area, three different lithological units can be distinguished (Fig. 2). The main failure surface of the landslide was located using available borehole and geophysical data (Azañón et al. 2006, 2010) complemented by field observations. The geophysical data—transversal and longitudinal electrical resistivity tomography (ERT) cross sections (Fig. 4)—allowed the shape of the contact between the landslide body and the bedrock to be determined. The thickness of the disturbed deposit, as derived from the ERTs, varies from less than 10 m to 30 m. The geophysical data were compared with the data from inclinometers and extensometers installed in the boreholes to verify the depth of the slide surface. This critical surface is related to an oversaturated smectite-rich layer, which is the boundary between the debris units and high-plasticity

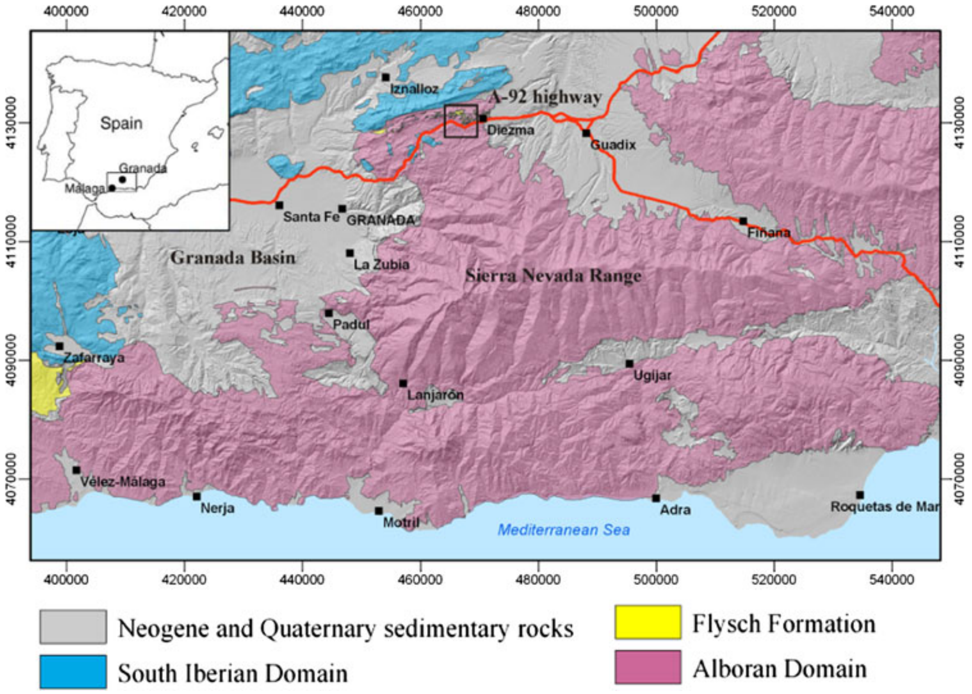

Fig. 1 Simplified geological sketch of the central part of the Betic Cordillera (South Spain). The location of the Diezma landslide is marked with a *rectangle*

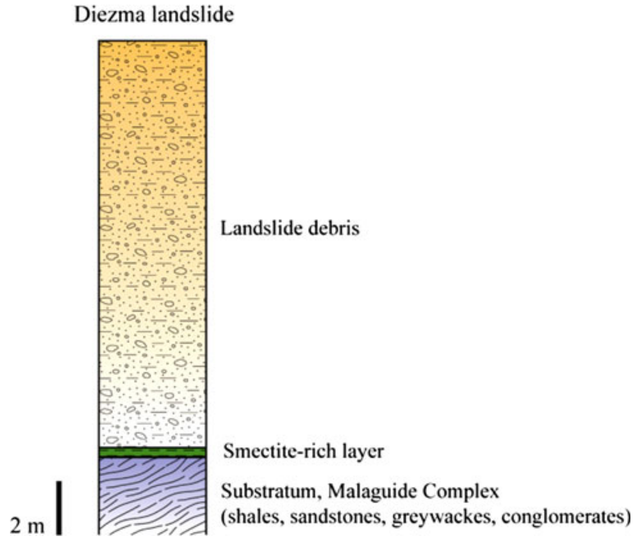

Fig. 2 Simplified stratigraphic succession of the Diezma landslide, from bottom to top: **a** bedrock, comprising dark grey shales and phyllites with conglomerates and greywackes of the Maláguide Complex (Alborán Domain); **b** a thick layer of a green smectite-rich clay; **c** chaotic landslide debris, mainly composed of reddish and yellowish clays with sandstone and dolostone blocks

Fig. 3 Panoramic view of the toe of the Diezma landslide during the 2001 collapse over the A-92 motorway, which was closed for several days

clayey soils. In addition, Azañón et al. (2006) noted that several inclinometers indicated three slip surfaces within the slope mass.

The main shear strength parameters corresponding to the lithological units (Table 1) have been obtained from direct shear tests under consolidated drained (CD) conditions on unweathered samples extracted from the boreholes in the landslide. These parameters have been used in the back analysis of the Diezma landslide reported here.

Reconstruction of the Diezma landslide

The back analyses of the Diezma landslide have been made using Slide (Rocscience Inc. 2003), a 2D slope stability software which calculates safety factors (SF) for circular and non-circular slope failure surfaces based on a number of widely used limit equilibrium methods. The Morgenstern–Price method was used as it is considered the most

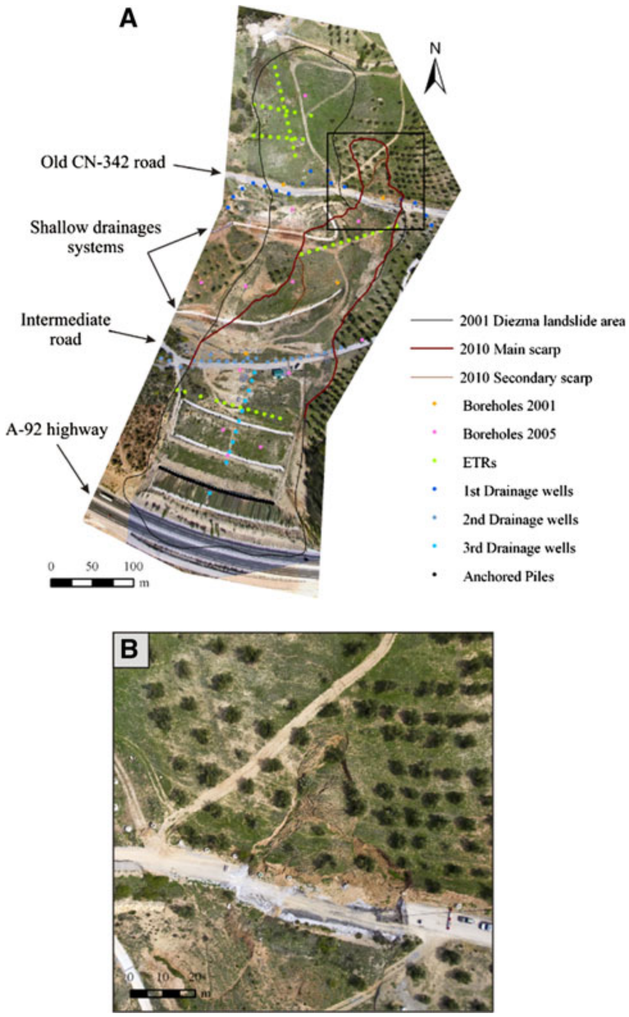

Fig. 4 **a** Map of the Diezma landslide showing the geotechnical and geophysical investigations and the location of the slope stabilisation measures. The photograph used for depicting the different parts of the landslide is a vertical aerial view taken after the 2010 landslide reactivation. **b** Detailed view of the 2010 main scarp at the head of the landslide

appropriate for slope ruptures developed in soils and is valid for circular and non-circular failure surfaces. In general, to evaluate the stability of a slope, the Slide program calculates a significant number of possible circular slip surfaces in order to find the location of the most critical one with the minimum safety factor value. The location of the main failure surface in depth was constrained by combining data from boreholes, geophysical surveys and field observations; the circular ruptures computed by the program were only used to complete the rupture surface at the head and toe zones.

The Diezma landslide before the A-92 motorway construction

Before the construction of the A-92 motorway, the Diezma landslide was stable. The slope stability analysis indicated a high safety factor when considering peak shear strength values (SF = 2.43) and a satisfactory SF for the residual state (1.15), assuming a deep water table. From the analysis, the slope would remain stable even after a period of heavy rain with a water table only 3 m below ground level. In this case, the minimum safety factor for peak shear strength conditions is still very high (SF = 2.23), while for residual shear strength values it gets close to the instability condition (SF = 1.09).

The Diezma landslide after the A-92 motorway construction

The construction of the A-92 motorway in 1993 substantially modified the geometry of the natural slope at the toe. The projected talus had a 1:1.5 (~35°) profile including one intermediate berm (Fig. 5). Even after this significant modification of the topography, the slope remained stable. According to the analysis, the SF for peak shear strength parameters and a deep water table (18–20 m) is still very high (SF = 2.12), while considering residual shear strength values the slope is just stable (SF = 1.05). This situation fits very well with the occurrence of the small, shallow landslide, which took place in May 2000 at the toe of the slope—the first sign of instability of the Diezma landslide area after the A-92 motorway construction.

The Diezma landslide during the 2001 collapse

The complete failure of the Diezma landslide involved three consecutive movements:

Table 1 Summary of the main geotechnical properties of the lithological units found in the Diezma landslide

Lithological unit	γ (kN/m^3)	γ_{sat} (kN/m^3)	c_p (kPa)	Φ_p (°)	c_r (kPa)	Φ_r (°)
Landslide debris	18.19 (±0.91)	20.60	5.4 (±3.2)	31 (±4)	0.6 (±0.5)	11 (±3)
Smectite-rich clay	15.24 (±0.49)	17.66	1.3 (±0.7)	21 (±4)	0.4 (±0.3)	8 (±1)
Bedrock (shales)	25.02	25.51	49.1	35	–	–

The range of the parameters is in brackets

γ Unsaturated unit weight, γ_{sat} saturated unit weight, c_p peak cohesion, Φ_p peak friction angle, c_r residual cohesion, Φ_r residual friction angle

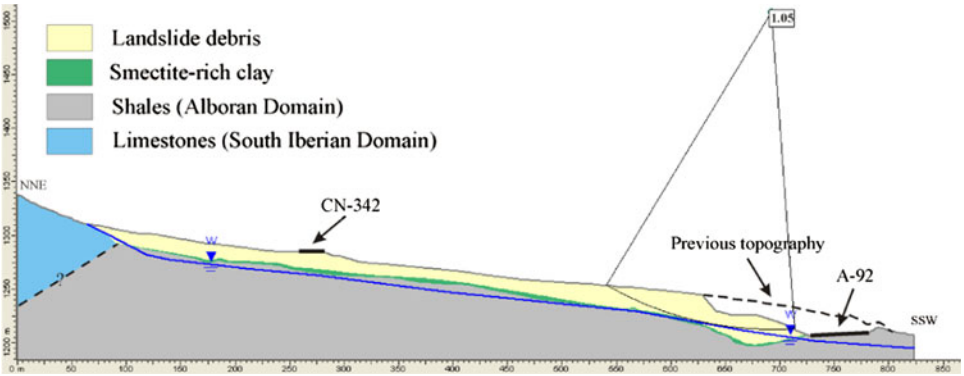

Fig. 5 Longitudinal cross section of the Diezma landslide after the construction of the A-92 motorway considering a deep water table (*blue line*) and residual shear strength parameters

(a) The first took place on 18 March 2001 following a period of heavy rainfall, which was clearly the main triggering factor. As can be seen from the daily and cumulative rainfall chart (Fig. 6a), the cumulative precipitation at the date of the landslide (357 mm) was higher than the average cumulative value for 2001 based on the previous ten years (227 mm). The landslide covered the toe of the slope, which collapsed onto the A-92 motorway changing the topography, releasing water and hence affecting the depth of the water table (Fig. 7). Using residual shear strength parameters and a high ground water level, an SF as low as 0.53 was calculated.

(b) A few days later (20 March 2001), a second more extensive movement took place with a main scarp developing towards the intermediate part of the slope (Fig. 7). The safety factor obtained for this situation was 0.66.

(c) Shortly after, the third and last movement took place. This landslide involved practically the whole slope, with the main scarp extending close to the old CN-342 road, which was damaged (Fig. 7). The SF for this mass movement was calculated as 0.69.

The Diezma landslide after the restoration works

The stabilisation works carried out on the Diezma landslide consisted of four lines of surface drainage trenches, three lines of deep drainage wells and the construction of a barrier of anchored piles and a retaining wall at the toe of the slope (Oteo Mazo 2001, 2003); see Fig. 4. The deep drainage wells are interconnected by means of sub-horizontal pipes, which evacuate the water outside the landslide body. The first line of wells was designed to capture the water from the carbonate aquifer located a few metres above. The other two lines of wells were designed to ensure, as far as practical, that the water level remained deep (20 m or lower) and parallel to the ground surface along the axis of the landslide. For this situation, and assuming a perfect performance of the drainage systems, a safety factor of 1.44 was calculated using the residual shear strength parameters.

However, during field surveys in 2005, it was observed that the water table was very high in the head area of the Diezma landslide, indicating the drainage systems were not working properly in this zone (Azañón et al. 2006). In addition, some new cracks were found in the old CN-342 road evidencing that the landslide was still active and regressing up the slope. This appeared to be related to the unsatisfactory performance of the first line of wells. Nevertheless, when considering the piezometric levels recorded during the field surveys in 2005, a safety factor of 1.40 was calculated.

2010 reactivation of the Diezma landslide

The reactivation of the Diezma landslide took place following the winter of December 2009–February 2010. The cumulative rainfall at the date of the landslide (361 mm) was higher than the average cumulative value for 2010 based on the previous 10 years (141 mm); see Fig. 6b. The main scarp extended over the old CN-342 road, which failed and moved downhill. The first and second lines of drainage wells and the first shallow drainage system were also broken and moved by the landslide (Fig. 8). However, the retaining wall of anchored piles prevented the landslide reaching the A-92 motorway. A safety factor of 1.13 was calculated for the whole slope; considering only the part of the slope which moved, the safety factor was 0.97 (Fig. 9).

Possible future reactivation of the Diezma landslide

The future stability of the Diezma landslide depends on the correct performance of the drainage systems after periods of heavy rain, i.e cumulative rainfall values ≥360 mm. If all three lines of drainage wells fail and the whole slope is considered, the calculated SF is 0.81. In this critical situation, the anchored piles would no

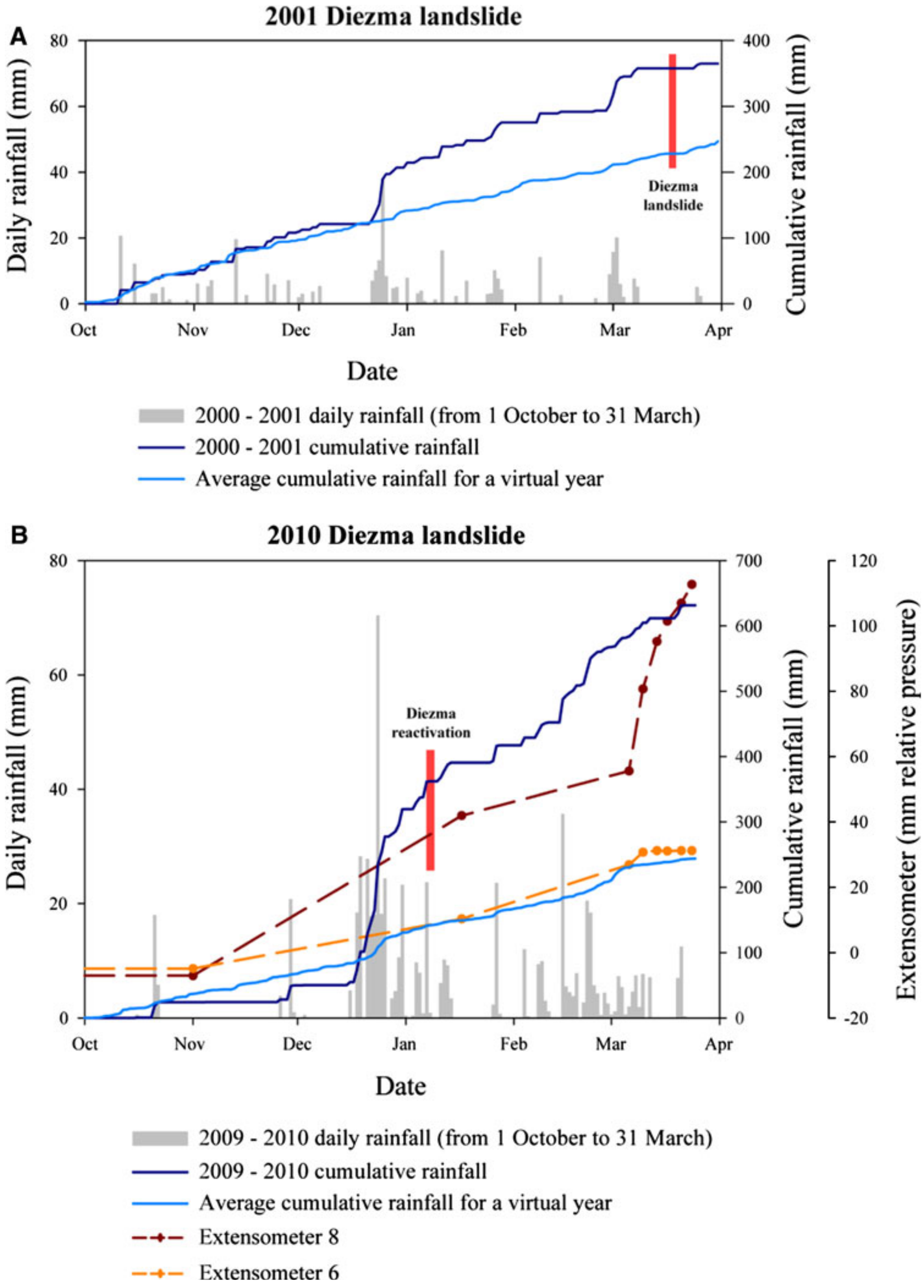

Fig. 6 Plots of daily and cumulative rainfall data for the Diezma landslide area. **a** 2001 landslide case. **b** 2010 landslide reactivation. The average cumulative rainfall for a virtual year has been derived from data of the 1990–2001 and 2000–2010 periods, respectively. Extensometer data are also plotted as evidence of the 2010 landslide movement at least from 16 January

longer be sufficient and the mass movement could reach the A-92 motorway.

Apart from heavy rains, another important triggering mechanism in landslide reactivation is seismicity. The Diezma landslide is located in the central Betic Cordillera, close to the Granada Basin, which is the most seismically active area in Spain. A number of significant earthquakes have taken place in this area since historical times, and hence the official seismic provisions (NCSE-02 2002) must be included in the engineering design and slope stability analysis (Rodríguez-Peces 2008, 2010). Assuming the conditions pertaining when the 2010 re-activation took place, the minimum seismic acceleration required for overcoming the shear resistance and initiating a further landslide can be calculated following Newmark (1965):

$$a_c = (\mathrm{SF} - 1) g \sin \alpha$$

where a_c is the critical acceleration (in gravity units, $1\ \mathrm{g} = 9.81\ \mathrm{m/s^2}$), g is the gravity acceleration, SF is the static safety factor and α is the angle between the vertical and a line connecting the centre of gravity of the landslide mass and the centre of the slip circle. The critical

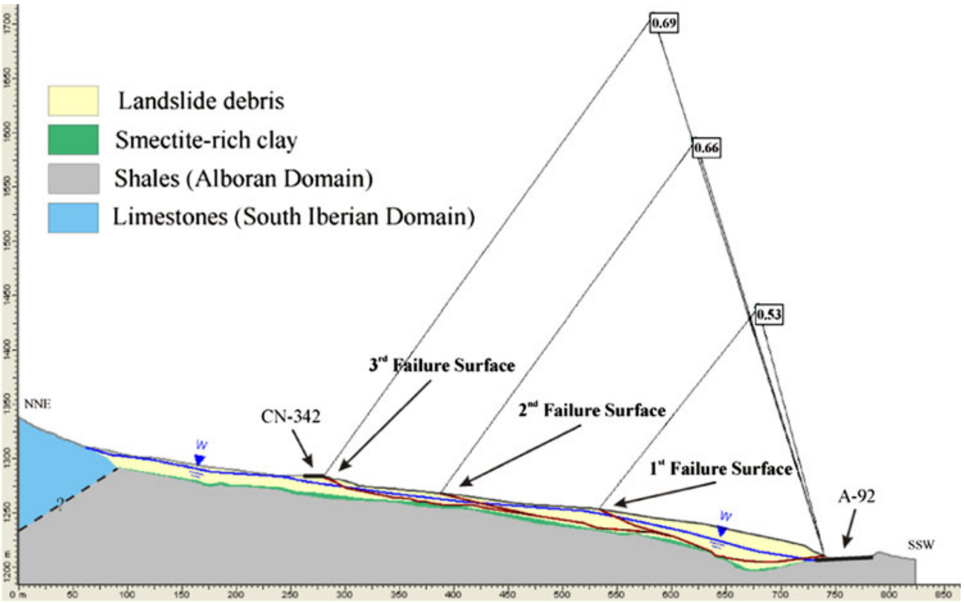

Fig. 7 Longitudinal cross section of the Diezma landslide after the A-92 motorway construction, considering a shallow water table (*blue line*) and residual shear strength parameters. Failure surfaces are shown by *red lines*

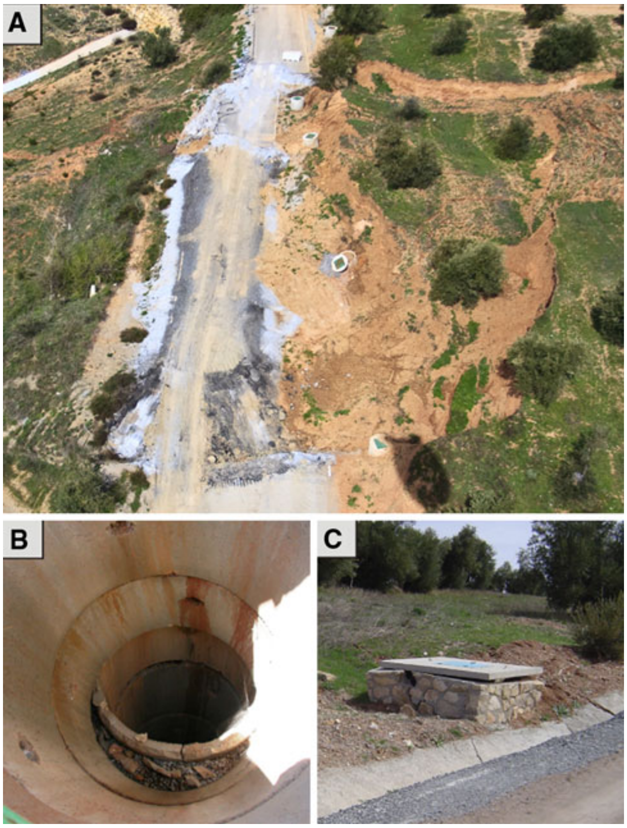

Fig. 8 **a** Aerial view of the first line of deep drainage wells and the old CN-342 road, which collapsed/moved during the 2010 landslide reactivation. **b** Broken well of the first line of drainage wells. **c** A damaged well in the second line of drainage wells

acceleration estimated for the Diezma landslide is 0.02 g, which is a low value. The most likely magnitude–distance pairs of potential earthquakes, whose horizontal peak ground acceleration could exceed the critical acceleration, were obtained using a number of ground motion prediction equations selected from the literature (Skarlatoudis et al. 2003; Ambraseys et al. 2005; Akkar and Bommer 2007; Bindi et al. 2010); see Table 2. This analysis indicates the reactivation of the Diezma landslide could be triggered by an earthquake of only $M_w = 4.0–5.0$, which is relatively frequent in the area (Morales et al. 1996; López-Casado 2001), provided that it takes place within <25 km of the landslide.

Discussion and conclusions

The typical Mediterranean rainfall regime of Southern Spain is a major factor controlling the triggering of landslides, especially in areas where high-plasticity expansive soils are present within clayey and marly sedimentary formations. Slope stabilisation measures typically comprise drainage systems, such as trenches and wells. An inappropriate design and/or maintenance of the drainage systems can lead to a reduction in their effectiveness in reducing pore water pressure.

The paper reports a reconstruction of the history of the Diezma landslide, in particular looking at the role played by the drainage systems deployed in the slope in relation to periods of heavy rain. It has been shown that the first signs of instability were noted after the modification of the topography at the toe of the slope as a consequence of the construction of the A-92 motorway in 1993. Calculations indicate that before this, the slope was stable even when considering residual shear strength parameters and a high water table.

About 8 years after the construction of the motorway (2001), the Diezma landslide moved significantly,

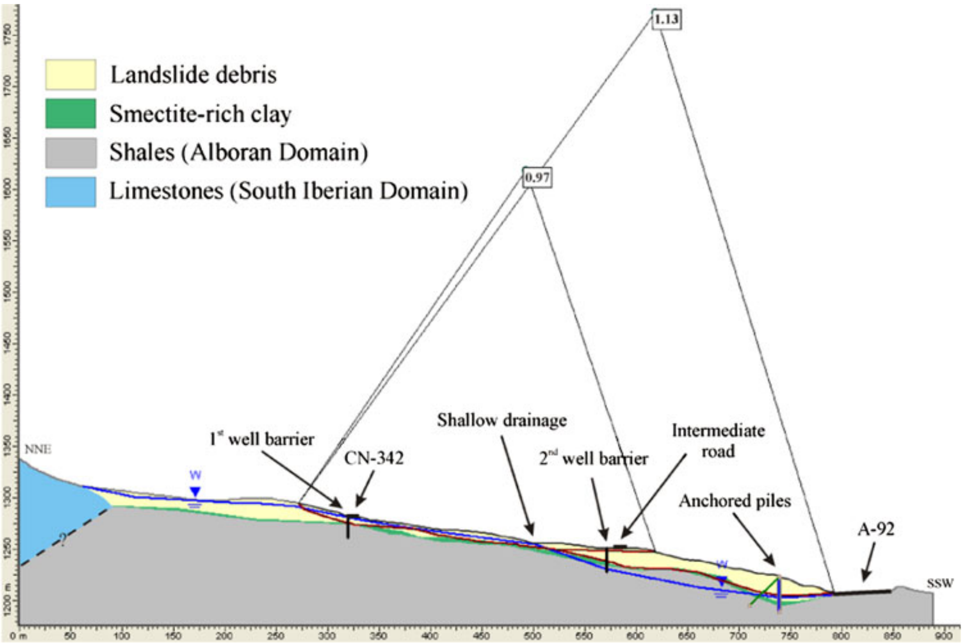

Fig. 9 Longitudinal cross section of the Diezma landslide after the 2010 reactivation considering a shallow water table (*blue line*) at the head zone and residual shear strength parameters. Failure surfaces are shown by *red lines*

Table 2 Most likely magnitude–distance pairs of potential earthquakes, which might exceed the critical acceleration for the present-day Diezma landslide

M_w	4.0	4.5	5.0	5.5	6.0	6.5
R_{ep}	≤ 10	≤ 15	≤ 25	≤ 40	≤ 60	≤ 100

M_w moment magnitude, R_{ep} epicentral distance to Diezma landslide (km)

coincident with a period of heavy rain. The increase in pore water pressure due to a shallow water table was recognised as the main triggering factor; hence, the stabilisation measures included a drainage system formed by four trenches and three lines of deep drainage wells interconnected by pipes.

The Diezma landslide remained stable for a further 9 years until 2010 when it was reactivated, again coinciding with a period of high cumulative precipitation. The main cause of the reactivation was the inadequate performance of the first line of deep drainage wells, which were known to have been working inadequately since at least 2005, due to the small movement at the head of the landslide.

Although the anchored wall of piles emplaced at the toe of the slope reduced the downslope effect such that the 2010 movement did not reach the motorway, it highlighted the danger of a total failure of the drainage system after a period of heavy rain, i.e. cumulative rainfall values ≥360 mm. Such a situation can be expected if the first and second lines of wells are not rebuilt and properly maintained on a regular basis. Calculations indicate that the reactivation of the landslide could also be triggered by a low-magnitude earthquake (4.0–5.0), such as those that occur frequently in the vicinity of the landslide.

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