Review of landslide occurrence in Spain and its relation to climate

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Outline

- Context of the landslide occurrence in Spain
- Climate-related triggers of Landslides
- What the climate models foresee for Spain
- Expected changes in landslide pattern associated to the climate change
- Current climate change adaptation strategies
- Observed trends and Final remarks
Main morphostructural units of Spain:
Hercynian Basement (grey), Outer Alpine Ranges (light green)
Inner Alpine Ranges (dark green), Cenozoic basins (yellow), and volcanic islands (orange).

Context of the landslide occurrence in Spain

<table>
<thead>
<tr>
<th>Lithology</th>
<th>Age</th>
<th>Type of failure</th>
<th>Contour</th>
</tr>
</thead>
<tbody>
<tr>
<td>Black shales</td>
<td>Carboniferous/Permian</td>
<td>Slides, earthflows</td>
<td>Pyrenees and Cantabrian Range</td>
</tr>
<tr>
<td>Marls and schists</td>
<td>Mesozoic and Paleozoic</td>
<td>Slides</td>
<td>Baetic ranges (Nevado Filabride and Alpujarrides Complex)</td>
</tr>
<tr>
<td>Claystones, marls and</td>
<td>Keuper</td>
<td>Rotational and translational slides, earthflows</td>
<td>Pyrenees, Central Ranges of Catalonia, Cantabrian Range, Baetic ranges</td>
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<td>evaporites</td>
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<tr>
<td>Red-Marlous clays, marls and silstones (Weald Facies)</td>
<td>Lower Cretaceous</td>
<td>Rotational and translational slides</td>
<td>Cantabrian and Baetic ranges</td>
</tr>
<tr>
<td>Alternances of blue marls with limestones</td>
<td>Aptian</td>
<td>Rotational and translational slides and earthflows</td>
<td>Baetic Range</td>
</tr>
<tr>
<td>Alternances of marls, and sandstones, lignites (Garum Facies)</td>
<td>Upper Cretaceous</td>
<td>Rotational and translational slides and earthflows</td>
<td>Pyrenees</td>
</tr>
<tr>
<td>Claystones and alternances of sandstones, clays and limestones (Flysch)</td>
<td>Lower Eocene -- Lutecian</td>
<td>Rotational slides and earthflows</td>
<td>Pre-Pyrenees, Pre-Baetic Ranges</td>
</tr>
<tr>
<td>Massive gypsum</td>
<td>Oligocene -- Lutecian</td>
<td>Rotational slides and earthflows</td>
<td>Pyrenees, Cantabrian coast</td>
</tr>
<tr>
<td>Clay, siltstones, silts, and clays</td>
<td>Pliocene</td>
<td>Debris flows and avalanches, rotational slides</td>
<td>Pyrenees, Cantabrian Range</td>
</tr>
<tr>
<td>Boulders and gravels with sandy-silt or clayey matrix (Glacial till)</td>
<td>Pleistocene</td>
<td>Debris flows and avalanches, rotational slides</td>
<td>Pyrenees, Cantabrian Range, montaneous depressions (valles-Penedes)</td>
</tr>
<tr>
<td>Gravels, sand, till and clays (colluvium)</td>
<td>Pleistocene-Holocene</td>
<td>Shallow slides and debris flow</td>
<td>All the mountain ranges</td>
</tr>
<tr>
<td>Basalts and volcanic ashes</td>
<td>Miocene -- Pliocene, Holocene</td>
<td>Large slides and rockfalls</td>
<td>Canary isles</td>
</tr>
</tbody>
</table>

Unstable lithologies in Spain, associated types of failure and geographical distribution (synthesis based on data from Corominas, 1989; Araña et al. 1992; Diaz de Terán et al. 1997).
Context of the landslide occurrence in Spain

Alpine Ranges

Structural and lithologic control
Weak often tectonized rock formations

Large earthflow reactivated in June 2013 in the Cantabrian Range, during an abnormal wet episode, which coincides with a decreasing trend of the annual precipitation during the last decades in Northern Spain (photo taken by A. González Díez).

Context of the landslide occurrence in Spain

Rotational slide in the glacier-related deposits of Cerler (Huesca), Central Pyrenees. The erosion of the Remáscaro creek is one of the main triggers of the landslide.
Context of the landslide occurrence in Spain

Cenozoic Basins

Earthflow at Zubiza, Navarra, Ebro Basin triggered after an abnormally rainy winter in early March 2013 (photo taken by J.R. Mendózoz).

Context of the landslide occurrence in Spain

Coastal Cliffs

Spain has a coastline of 7,880 kilometers which houses about 65% Spanish population.

Sa Caixota coastal landslide (Ibiza, Balearic islands) on 18th September 2005, triggered after intense rains (> 150mm /24 h). Numerous dwellings were affected and people evacuated.
Context of the landslide occurrence in Spain

**Flank collapse of volcanic edifices**

- 1700 km²
- 150 km³
- 150-170 ka

- 2100 km²
- < 500 km³
- 0.5-0.6 Ma

- 780 km²
- 95 km³
- 0.1-0.5 Ma

- 1500 km²
- 180 km³
- 15 ka

- 1600 km²
- >120 km³
- 0.8 Ma

**Sub-aerial rockslides in volcanoes**

**Pajonales-Rosiana rockslide complex**

Tirajana basin, Gran Canaria, Canary Islands
Climatic triggers of landslides in Spain

Landslides are multicausal phenomena. First-time failures for avalanches, large rockslides, large landslides, sagging show poor relation with climate although, in some particular cases, this relation exist.
Climatic triggers of landslides in Spain

(a) Short lasting (hours/days) high intensity storms that trigger shallow landslides (debris avalanches & debris flows). Antecedent rain may be required.

(b) Long lasting (days/weeks) low to moderate intensity storms that trigger or reactivate landslides and earthflows, usually in clayey materials.

(c) Abnormally wet seasonal/annual rainy periods that trigger or reactivate large landslides.

Landslide triggered by short lasting high intensity storms

These type of events typically generate multiple-occurrence of regional landslide events

(a) First-time failures
(b) Fast landslides: shallow slides, debris flows and debris avalanches

Debris flow generated in August 1997, confined by lateral levees. Somiedo Natural Park, Asturias.
Typically, two slope responses:

(a) Slope covered with pervious colluvium. The build-up and dissipation of positive pore pressure could be very rapid (less than 24 hours).

(b) In low-permeability soils (clayey-rich soils), pre-saturation of the superficial formation is often a necessary condition for failure. However, macropores play a fundamental role.

Role of fissures and macropores
Landslides triggered by long lasting moderate-intensity storms

Triggering and/or reactivation of mid-size \((10^4-10^6 \text{ m}^3)\) landslides and earthflows, mostly in clayey materials.

Duration: several days or weeks

Large landslides

Poor correlation with rainfall events

Relation may improve when considering seasonal or multiannual periods
Large landslides may also react to intense short-lasting rainstorms

The karstic limestone formation located at the landslide crown, collects and quickly transfers the infiltrated water, from the Toloriu plateau to the slide.

Particular geological contexts

Vallecebre, E. Pyrenees, Spain
What do climate models foresee for Spain?


A) Average MAP (1971-2000). B) Annual maximum temperature changes in 2041-2070 based on the model ECHAM4. C, D and E, examples of total annual precipitation changes for Spain for different time periods with respect to 1961-1990 data. C) precipitation changes in 2011-2040 according to the model CGCM2, on the basis of emission scenario SRES A2, and analogues method (Anal_FIC) for downscaling; D) precipitation changes in 2041-2070 based on the model ECHAM4, which considers the scenario SRES A2, and analogues method for downscaling; E) precipitation changes in 2071-2100 according to the model CGCM2 (scenario A2) and using a grid (Anal_INM) for downscaling. Time series of simulated annual precipitation and extreme precipitation indices obtained by dynamic regional downscaling and smoothed with a 10-year running mean; green lines show time series ensemble mean and green shading shows uncertainty: F) total annual precipitation change, G) Changes in the number of days with precipitation per year; H) dry periods duration; I) Intense precipitation occurrence rate.

Consequences of increase of $T^\beta$ on the occurrence of landslides

Indirect effects: forest fires

According to the Spanish meteorological agency (AEMET, 2009):

All model simulations show warming across the whole country and in all seasons (reduction of snow coverage and altitudinal displacement of vegetation).

In the central area of the Iberian Peninsula, the temperature increase may range from 5 $^\circ$C to 7$^\circ$C in summer and from 3$^\circ$C to 4$^\circ$C in winter (A2 scenario)

Intensities of summer heat waves will increase throughout the country.
Effects of changes in rainfall pattern on the occurrence of landslides

Increase of intense precipitation events

A marked contrast between winter and summer patterns of precipitation.

Intense precipitation events will increase across the whole country in frequency, especially in winter.

We must keep in mind that low the predictions for precipitation have low reliability for the Mediterranean context.

Effects of changes in rainfall pattern on the occurrence of landslides

Constrained sediment supply ↔ Lack of stationarity

Preparatory factors change. Two consecutive rainfall events (very close to each other) may not be able to de-stabilize the same slopes.

Movable material (colluvium, till) on the slopes is progressively swept down by debris flows and shallow landslides. Because the slopes have been emptied, the chances of a new storm could trigger further slope failures might have been drastically reduced.

We must keep in mind that low the predictions for precipitation have low reliability for the Mediterranean context.
Effects of changes in rainfall pattern on the occurrence of landslides

It is expected a reduction of the annual precipitation, < 10% in northern Spain and between 20 and 30% in the South.

In some locations the increase of rainfall will be matched by increase in evapotranspiration, leaving the frequency of large landslides unchanged or reduced.

Particular geological contexts are exceptions.

Consequences of sea level rise on the occurrence of landslides

Sea level rise and subsequent erosion

erosion of weak and/or unfavourable dipping layers in gentle slopes will trigger increasingly large landslides.

Sea-level rise may lead to an aggravation of the coastal erosion and inundation.
Consequences of the human intervention

It should be recalled that anthropic disturbances may produce significant changes in the frequency of the slope failures.

During the past 20 years, a surface area of 44 hectares has been urbanized in Spain every day, and they have expanded into landslide-prone areas.

Road and railway cuts caused not only shallow failures but also large landslides. However, the most catastrophic human-induced event was the failure of the Aznalcóllar (Guadalquivir basin, SW Andalusia) tailings dam in 1998.

Human intervention: exposure

87 lives lost  
Damages: 55 Millions US$  
Rain storm lasted for 2hr

http://www.diariodenoticias.com
Most of the 40 check dams built between 1931 and 1950 were destroyed, releasing about 68,000 m³ of stored sediments which spread over the fan. Channel with capacity of 120 m³/s was overflooded and buried.

Adaptation to climate change: actions undertaken

<table>
<thead>
<tr>
<th>RELEVANT EVENTS</th>
<th>ACTIONS UNDERTAKEN</th>
<th>ORDINANCES</th>
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</thead>
<tbody>
<tr>
<td>November 1982</td>
<td>Floods and widespread landsliding</td>
<td>Land Use Law - 1975</td>
</tr>
<tr>
<td>October-November 1994</td>
<td>Floods and landslides</td>
<td>Land Use Law - 1994</td>
</tr>
<tr>
<td>Natural Hazards County Map 13 Maps: 1:50,000 scale 1984-1998</td>
<td>Natural Hazards Map 1:50,000 scale 2002-2007</td>
<td>Urban Planning Law 2005</td>
</tr>
<tr>
<td>Natural Hazard Maps 1:25,000 scale 2007-2020</td>
<td>PROCICAT 1995</td>
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</tbody>
</table>
Adaptation to climate change: actions undertaken

**Natural hazards mapping at 1:50,000 scale**

Corominas, 1985

Purely informative documents. No legal binding

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Adaptation to climate change: actions undertaken

**Land use law of 1998:** land potentially at risk must not be developable

The condition of land at risk has to be accredited by an official natural hazard map

Catalonian Civil Protection Plan 1995: Special Plans for floods (INUNCAT) and earthquakes (SISMICAT).

No Special Plan for landslides

INUNCAT, 2006
Adaptation to climate change: actions undertaken

Catalonian Urban Planning law 2005

Land development must provide protection to the population

Development should be avoided in areas threatened by natural hazards unless countermeasures are feasible

The assessment of natural hazards must take into account of official maps of the Catalonian Geological Institute (CGI)

Nowadays all local development plans are sent to CGI. Reports without legal binding

Adaptation to climate change: actions undertaken

CGI* has started a Plan for hazard mapping at 1:25,000. Completion program: 2007-2020

(*) Since 2015, Cartographic and Geological Institute of Catalonia

Geological Risks Prevention Map 1:25,000 IGC
Trends in the occurrence of natural hazards

The increase of exposure is the major cause of long-term increase of economic losses (ICCP 2102)

Natural catastrophe (UN criteria):
- Interregional or international assistance are necessary
- Thousands of people are killed
- Hundred thousands of people are made homeless
- Substantial economic losses
- Considerable insured losses

Climatic cycles

Reactivation episodes of earthflows in the Eastern Pyrenees and climate variability
Trends in the occurrence of landslides

In the Mediterranean area, the changing scenario should be evidenced by the increased frequency of high-intensity rainfall and a higher number of flash floods, debris flows, shallow slides and rockfalls. The analysis of the flash flood frequency during the last 700 years in Catalonia, NE Spain, does not show any clear trend.

Debris flow events are found more frequent probably because the increase of our observational capacity.

New data and monitored basins has allowed to refine (reduce) the previously established rainfall thresholds for debris flows (around 15mm/h and 90 to 100 minutes duration).
Trends in the occurrence of landslides

No clear trend is observed in the activity of the Vallcebre landslide.

Observed increase of mid-large rockfalls

Vilanova de Banat, Cadi Sierra, Eastern Pyrenees
Observed increase of mid-large rockfalls

Is it due to the availability of observations? Has it something to do with climate change?

Cortes de Pallás, April 9th, 2015
Source: RTVE

Paüls, Mont Sacre, Catalonian Coastal Ranges
February 2009

Final remarks

There exists a variety of triggers. Only a fraction of the slopes will respond to the climate change

More frequent intense rainfall events will increase debris flow and shallow landslide activity in most of Spain provided that sediment is available. In Central, Iberian and the outer Baetic ranges, one should not expect a significant increase of soil slope failures due to the calcareous nature of the rock formations and the scant soil cover

The main concern in terms of climate change is directed to locations where the increase of frequency could associated to an increase of landslide magnitude

The rise in sea level, along with the frequency of sea storms, will cause undermining, fall and sliding of coastal cliffs

We have found no indicators of an increase of intense rainfall events so far

During the last decades the number of exposed elements has significantly increased. Hazard maps must help in avoiding further increase of the exposure

The design of landslide mitigation measures is subjected to a large amount of uncertainty. Most engineering design cannot handle high-magnitude low-frequency events