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Discussion on “Large landslides associated with a diapiric fold in Canelles reservoir (Spanish Pyrenees): Detailed geological–geomorphological mapping, trenching and electrical resistivity imaging” by Gutiérrez et al. (2015)

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ABSTRACT

This discussion a) reviews the geological model adopted for the landslide analysis and argues that there is nothing new in the reference paper, b) examines the conditions for fast catastrophic sliding and demonstrates that conditions for such a phenomenon may be present in the case of Canelles slide, against the opinion of the authors, and c) justifies the corrective measures adopted to stabilize the landslide.

1. Introduction

Gutiérrez et al. (2015) describe a geomorphological study of the left margin of the Canelles reservoir in the Spanish Pyrenees. The study reveals the presence of several landslides based on local geology, stratigraphy, trenching techniques, electrical resistivity imaging, geomorphological mapping and geophysical surveys. No borehole data were used in the study. An important part of Gutiérrez et al. (2015) focuses on the evaluation of a previously published paper by Pinyol et al. 2012). The paper identified and analysed one of the landslides described in Gutiérrez et al. (2015) in detail, following the discovery of a continuous crack, subparallel to the reservoir water line, approximately 1 km long. The aims of Pinyol et al. (2012) paper were clearly noted in the paper:

- Identification and description of the unstable mass with the purpose of determining its geometry, volume, position of the sliding surface and materials involved.
- Evaluation of the risk of potential acceleration of the landslide
- Establishing the relationship between reservoir operation and landslide stability for the future management of the reservoir.
- Proposal of corrective measures to ensure that the slope remains stable during the management of the reservoir in the future.

The criticisms presented by Gutiérrez et al. (2015) to Pinyol et al. (2012) refer to three aspects: 1) the geological model described and the methodology used for its construction; 2) the conclusions from the analysis to evaluate the risk of rapid sliding; and 3) the effectiveness of the corrective measures proposed. In the following sections these points will be discussed. A section of additional comments is also presented regarding some statements by Gutiérrez et al. (2015) that are, in our opinion, misleading.

2. Geological model of landslide L4

After describing the geological setting and stratigraphy of the study area, Gutiérrez et al. (2015, p. 228) state that Pinyol et al. (2012) present a litho-stratigraphy different from the Garumn facies, because the borehole data used were from the Canelles landslide. This is not correct. The litho-stratigraphy was based on the analyses of the sedimentary rock units outcropping in the area as well as the borehole logs (Pinyol et al. 2012, p. 33). The lithotypes shown by Pinyol et al. (2012) were simplified for publication purposes. No significant discrepancy exists between the stratigraphic logs presented by Gutiérrez et al.

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Table 1
Comparison of stratigraphic logs of Canelles landslide.

Pinyol et al. (2012)		Gutiérrez et al. (2015)	
Lithotypes	Age	Lithotypes	Age
(a) Lower grey limestones. Grayey limestones of lacustrine origin interbedded with grey marls	Campanian to Maastrichtian	Montclús Fm. Grey, micritic and fetid lacustrine limestones.	Late Cretaceous, Maastrichtian
(b) Grey sandstones: predominantly medium to coarse grained sandstones of gray and ochre colour, interbedded with thin layers of multicoloured (grey, red, ochre) clayey siltstones, sandy siltstones and conglomerates of age.	Maastrichtian	Lower detrital unit (G1). Red mudstones and abundant intercalations of ochre cross-bedded and massive sandstones (…). The sandstone packages are up to several metres thick.	Maastrichtian
(c) Clayey limestones: thin layer of grey and white limestones and marly limestones that appear only locally (boreholes)	Maastrichtian		
(d) Red claystones. Clayey siltstones and silty claystones reddish and ochre coloured of continental origin. Locally interbedded with thin limestone and marly layers 1–2 m thick — lower facies).	Paleocene (Garumnian)		
(e) White limestones: massive grey to white limestone layer having either micritic or brecciated facies, the latter with silty or clayey multicoloured matrix (reddish, grey, ochre, brown)	Paleocene age (Garumnian facies).	Intermediate calcareous unit (G2). White and light-grey micritic limestone with charophytes and marl intercalations in the lower part	Paleocene, Danian
(f) Siltstones and limestones. Heterogeneous unit composed of clayey silts and siltstones, silty clays, and multicoloured calcareous marls, which are predominant and layers of calcarenites, micritic limestones and brecciated limestones.	Lower Paleocene age (Garumnian facies)	Upper detrital unit (G3). Red mudstones with tabular beds of micritic charophyte bearing limestone, more abundant in the upper part of the unit.	Paleocene, Selandian–Thanetian

(2015) and the litho-stratigraphic units recognized by Pinyol et al. (2012) (Table 1).

The main difference shown in Table 1 is that Gutiérrez et al. (2015) consider G1 as a single unit, while Pinyol et al. (2012) split it into three units (b to d). Unit b, which is composed predominantly of sandstones, and unit d, mostly claystones, match respectively to the lower and upper parts of the Unit G1 of the Blancafort section (see Fig. 2 of Gutiérrez et al. 2015). Unit c is a thin layer of limestones which, as mentioned by Pinyol et al. (2012), appears locally in some boreholes and, also, in an outcrop located 400 m to the west of the landslide boundary. This unit was unnoticed by Gutiérrez et al. (2015) probably because they worked with the regional stratigraphy rather than the local stratigraphy of the Canelles landslide provided by the borehole logs. On the other hand, splitting G1 into three lithotypes was fundamental for preparing the geological model of the Canelles landslide (landslide L4 of Gutiérrez et al. 2015). The reason is that the working hypothesis of Pinyol et al. (2012, p. 37) was that the slip surface should develop parallel to the strata, along a weak layer. Pinyol et al. (2012) considered unit d as a potential layer where the slip surface developed.

Gutiérrez et al. (2015), in their Introduction and Discussion sections, implicitly suggest that the geological model of the Canelles landslide provided by Pinyol et al. (2012) was wrong and it could have affected the results of the paper. However, Gutiérrez et al. (2015) did not provide any evidence of the supposed mismatch and, more importantly, the consequences of such mismatch. Rather, Gutiérrez et al. (2015, p. 238) indicate the slip surface develops through G1 (more precisely unit c) as Pinyol et al. (2012) concluded, which has been also corroborated with recent inclinometric measurements obtained after Pinyol et al. (2012) publication.

3. Landslide analysis and the risk of rapid sliding

Gutiérrez et al. (2015, p.232) refer to the description of the L4 landslide by Pinyol et al. (2012). The slide is described as a planar landslide with an average dip of the slip surface of 9–10°. This is a simplification of the landslide geometry, which Pinyol et al. (2012) never mentioned. Despite a description of the landslide as a reactivation of a dormant translational slide, Pinyol et al. (2012, Fig. 29) described the geometry as a double interacting block. Gutiérrez et al. (2015) did not realize that the landslide is actually a compound landslide (Hutchinson 1988; Hungr et al. 2014).

The simplification of a planar landslide by Gutiérrez et al. (2015) may lead to a stability analysis different from that by Pinyol et al. (2012). The specific geometry of the landslide determined by the topography and the failure surface geometry is a relevant factor to understand landslide mechanics. Pinyol et al. (2012) first identified the geometry of the landslide and they selected a representative section for a hydro-mechanical coupled analysis, which allows the estimation of the risk of rapid sliding. Despite the necessary simplification of the actual geometry of the selected cross section, Pinyol et al. (2012) maintained a fundamental aspect, namely that the failure surface was defined by two interacting masses which describe a compound slide (Fell et al. 2007). The moving mass is described as an upper wedge dipping 18° and a lower wedge sliding on a horizontal plane. The upper part acts as an active wedge which is inherently unstable because the inclination of the failure surface is higher than the residual friction angle assigned to the failure plane (10–12°) on the basis of tests performed. No cohesion is expected in the failure surface of a reactivated slide. The lower wedge and the interaction between both wedges provide the necessary strength to maintain the slope stable.

The major criticism of Gutiérrez et al. (2015) to the analysis by Pinyol et al. (2012) concerns the dynamic analysis of the post-failure response of the Canelles landslide. It is important to highlight that Gutiérrez et al. (2015) do not discuss Pinyol et al.'s (2012) analysis of the causes leading to the landslide in the summer of 2006.

The criticism from Gutiérrez et al. (2015) includes two arguments:

1) The landslide was never catastrophically reactivated in the past, although it reactivated several times.
2) No catastrophic reactivations have been documented in other large translational rockslides if the sliding surface has an average dip as low as 10°, which corresponds to their simplistic interpretation of the geometry of the L4 landslide.

These two points are discussed in the following. Note that in the present discussion we will refer to catastrophic landslides with a dominant sliding mode of deformation. Flow-like motions require a different consideration of the mechanical and hydraulic process involved in the run out.

First, why the catastrophic failure has not yet occurred? Gutiérrez et al. (2015) conclude that the behaviour of the landslide during its life time is completely different from the model predictions. They argue that the slide has been affected by historical earthquakes and drawdowns of the reservoir level without any catastrophic failure (Gutiérrez et al. 2015, p. 240). The implicit assumption of Gutiérrez et al. (2015) is that the slope conditions have remained constant over time. However, no evidence indicates that the slope had been subjected to similar hydrologic conditions (full saturation and rapid drawdown) in the past. Despite the authors' statement, the conditions following the drawdown event of 1991 cannot be used as an analog as will be discussed in more detail later. In addition, Gutiérrez et al. (2015) have