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Núria M. Pinyol · Eduardo E. Alonso · Jordi Corominas · José Moya

Canelles landslide: modelling rapid drawdown and fast potential sliding

Abstract A large landslide (40×10^6m^3) was reactivated on the left bank of Canelles reservoir, Spain. The instability was made evident after a considerable reduction of the reservoir level. The drawdown took place during the summer of 2006 after several years of high water levels. The drawdown velocity reached values between 0.5 and 1.2m/day (registered at low elevations). The paper reports the geological and geotechnical investigations performed to define the movement. The geometry of the slip surface was established from the detailed analysis of the continuous cores recovered in deep borings and from limited information provided by inclinometers. Deep piezometric records provided also valuable information on the pore water pressure in the vicinity of the failure surface. These data allowed validating a flow–deformation coupled calculation model, which takes into account the changes in water level that occurred 4 years previous to the failure as well as the average rainfall. The analysis indicates that the most likely reason for the instability is the rapid drawdown that took place during the summer of 2006. The potential sudden acceleration of the slide is also analysed in the paper introducing coupled thermal hydraulic and mechanical effects that may develop at the basal shearing surface of the sliding mass. The results indicate that the slide velocity may reach values around 16m/s when displacement reaches 250m.

Keywords Landslide · Analysis · Modelling · Finite elements · Stabilisation · Rapid drawdown · Fast sliding

Introduction

The Canelles dam, a 151-m-high double curvature arch structure, creates one of the largest reservoirs in Spain (maximum storage volume 560 Hm^3) (Fig. 1). The dam was built in the period 1958–1962 and therefore a long time record of reservoir elevation is available. The dam was designed with several objectives: hydrologic regulation of the Noguera Ribagorçana river, land irrigation, water supply to the lower reach of the river basin and power generation.

Water demands and rainfall intensity in the watershed control the evolution of water elevation in the reservoir. Figure 2 shows the recorded absolute elevation in the period 1987–2009. As a reference, the maximum water elevation in the reservoir is 506 m. The elevation of dam crest is 508 m. The significant decrease of annual rainfall in the period 2005–2006 resulted in a considerable reduction of the average water level (Fig. 2). In addition, irrigation demands in spring and summer resulted in additional water level reductions. During the summer of 2006, the drawdown velocity reached values of 1.2 m/day in the first days of August. This is a high rate of drawdown in general terms except for reservoirs associated with reverse pumping schemes.

At a certain point during the summer of 2006, a large landslide was reactivated on the left bank of the reservoir (Fig. 1b). The first indication of instability was the development of a long continuous tension crack (Fig. 3) whose opening varies between 0.1 and 0.3 m. Subsequent investigation, reported in this paper, led to an estimation of the landslide volume of around 40×10^6 m^3. The magnitude of the landslide and its potential for sudden acceleration were of special concern for the reservoir owners and state authorities. Several questions were put forward. They referred to the reasons for the landslide development, its likely evolution, the relationship between reservoir operation and landslide motion, the risk of a fast sliding and its consequences and the implications for the management of the reservoir in the future.

This paper reports the main conclusion of the geological and geotechnical investigations performed and the set of analyses carried out. It also provides an answer to the questions raised. At the time of writing the manuscript, the Canelles slide is essentially stable and the proposed stabilisation measures are being designed. The Canelles slide is an interesting case of landslide reactivation induced by a fast drawdown. It also allowed applying some recent developments concerning the explanation and the prediction of fast sliding. They explain the potential high velocity of the landslide by the coupled thermal hydraulic and mechanical effects which may develop at the basal shear surface. These developments have been described in some recent papers (Vardoulakis 2002; Pinyol and Alonso 2010a, b).

Geology

The Canelles dam and landslide are located at the Blancafort Sierra in the outer Pyrenean ranges (Fig. 4). The uplift of the Pyrenees during the Alpine orogeny was associated with thrusting and displacement of large nappes (Upper Thrust Sheets) that covered distances of more than 150 km southwards (Fig. 4a). The Blancafort Sierra is outer zone of the range, located just south of a main thrust front (the Montsec Sierra thrust front, Fig. 4b).

The emplacement of the nappes was accompanied by parallel folding of the strata. Main folds show wavelengths of several kilometres. The Blancafort Sierra forms the northern flank of the Canelles anticline and its foot ends in the Blancafort syncline (Fig. 4b). Development of parallel folds during the orogeny involved slipping on bedding surfaces and, consequently, a reduction of the shear strength of these surfaces.

The local geology of the Canelles landslide was established by air photo interpretation, by field mapping and by interpreting 16 borehole logs (Fig. 5).

The bedrock outcropping in the area consists of a sequence of sedimentary rock units that correspond to the transit of the Upper Cretaceous to the Lower Paleocene. The stratigraphic column is from bottom to top:

(a) Lower grey limestones: grayey limestones of lacustrine origin interbedded with grey marls of Campanian to Maastrichtian age. A minimum unit thickness of 40 m.
(b) Grey sandstones: predominantly medium to coarse grained sandstones of grey and ochre colour, interbedded with thin layers of multicoloured (grey, red, ochre) clayey siltstones, sandy siltstones and conglomerates of Maastrichtian age. Observed unit thickness between 35 and 55 m.
(c) Clayey limestones: thin layer of grey and white limestones and marly limestones that appear only locally (boreholes