Leakage problems in dams built on evaporites. The case of La Loteta Dam (NE Spain), a reservoir in a large karstic depression generated by interstratal salt dissolution

Francisco Gutiérrez a,⁎, Morteza Mozafari b, Domingo Carbonel a, René Gómez c, Ezzatollah Raeisi b

a Departamento de Ciencias de la Tierra, Universidad de Zaragoza, C/ Pedro Cerbuna 12, 50009 Zaragoza, Spain
b Department of Earth Sciences, Shiraz University, Iran
c Confederación Hidrográfica del Ebro, Paseo Sagasta 24-28, Zaragoza, Spain

1. Introduction

The number of accessible papers and reports documenting problems related to evaporite karst in dams and reservoirs is rather limited (Calcano and Alzurra, 1967; James, 1992; Pearson, 1999; Johnson, 2008; Milanovic, 2011; Cooper and Gutiérrez, 2013), especially if compared with the extensive literature dealing with the impacts of carbonate karst on dams (e.g., Romanov et al., 2003; Milanovic, 2004). This circumstance, despite the extensive areas covered by evaporite rocks at or near the surface worldwide (Warren, 2006), may be attributed to several factors: (1) evaporites, due to their high solubility, tend to be avoided in dam site selection; (2) carbonate rocks, with higher mechanical strength and lower erodibility than evaporites (mainly gypsum), commonly form more suitable water gaps for dam construction from the topographic and mechanical standpoints (i.e., narrow canyons flanked by resistant abutments); and (3) most probably, a significant proportion of case histories from numerous countries have not been documented or remain confidential (James, 1992; Pearson, 1999).

The presence of gypsum in dam sites and/or reservoirs may pose significant problems that may (1) require costly and prolonged remedial measures; (2) reduce or annul the efficiency of the hydraulic structure; and (3) eventually lead to catastrophic failures (James, 1992; Johnson, 2008). The impounding of a reservoir entails imposing unprecedented and unnatural high hydraulic gradients. The stored water may escape through pre-existing karst cavities located beneath the dam and/or at the abutments. Some dams have failed to ever retain any significant amount of water due to excessive leakage related to the presence of well-developed gypsum karst; e.g., Hondo Reservoir, New Mexico (James, 1992; Pearson, 1999), Cedar Canyon Dam, South Dakota (Rahn and Davies, 1996), and Anchor Dam, Wyoming (Jarvis, 2003). Anchor Dam was built despite more than 50 sinkholes and stream losses...
associated with karstified Triassic gypsum had been reported in the reservoir area. During the first attempt to fill the reservoir, numerous additional sinkholes were reported. A collapse around 100 m across and 20 m deep occurred upstream of the concrete dam and was isolated by the construction of an additional dike that limited the operational water level of the reservoir and reduced by 50% its storage capacity. After 30 years of costly attempts to repair the reservoir, it has never held more than a small pond (Jarvis, 2003).

The water escaping from the reservoir may rapidly increase the permeability of the dam foundation and abutments through two main processes: (1) washing out of sediments filling dissolutional features, frequently referred to as internal erosion or piping; and (2) dissolving gypsum with the consequent enlargement of pre-existing karst channels or the creation of new leakage pathways. Karstification proceeds at a much higher rate in gypsum than in carbonate rocks due to the higher solubility and much rapid dissolution kinetics of the former (Gutiérrez and Cooper, 2013). The equilibrium solubilities of gypsum (CaSO₄·2H₂O) and halite (NaCl) are 2.4 g/l and 360 g/l, respectively. By comparison, the solubilities of calcite (CaCO₃) and dolomite (MgCa(CO₃)₂) are generally lower than 0.1 g/l in normal meteoric water (Dreybrodt, 2004; Ford and Williams, 2007). Moreover, the dissolution kinetics of gypsum is characterised by a mixed transport- and surface-reaction-controlled behaviour; i.e., dissolution rate largely depends on the hydrodynamic condition of the solvent. Experimental studies indicate a linear relationship between gypsum dissolution rate and flow velocity under a laminar flow regime. Under these conditions, the speed at which discontinuity planes widen by dissolution in limestone and gypsum does not differ much. However, when the fissures or conduits reach the critical size at which the flow turns into turbulent (breakthrough conditions), dissolution rate increases abruptly and exponentially (Raines and Dewers, 1997; Jeschke et al., 2001). The dissolutional enlargement of flow paths is a self-accelerating process, whereby larger openings lead progressively to higher discharge and consequently more rapid dissolution (James, 1992). The rapidity at which leakage water from reservoirs may enlarge karst pathways by dissolution in gypsum formations is illustrated by mathematical models developed by Romanov et al. (2003), considering a hydraulic head of 150 m, a grout curtain 97 m deep beneath the dam axis, and fractures with an average width of 0.2 mm. According to these models, water leakage through the enlarging fractures increases steadily until a breakthrough situation with turbulent flow is reached within the lifetime of the structure. At this stage, dissolutional widening increases abruptly in specific fractures reaching rates as high as 10 cm/yr, with the consequent exponential increase in the amount of water losses.

In dam foundations where gypsum occurs as a secondary mineral component like veins or detrital particles, dissolution may also create significant leakage pathways in a short period of time (James, 1992). In Caspe Dam, NE Spain, founded on argillaceous rocks traversed by abundant gypsum-filled joints, seepage rates increased exponentially (around 4 times in 20–30 days), until they were minimized by grouting to negligible values. According to mass balance calculations, leakage water was removing around 1000–1500 kg of dissolved gypsum per day from the dam foundation (Araoz, 1992; Mancebo-Piquerías et al., 2012). In Gheisaragh Dam, NW Iran, where the foundation includes claystones and marls with gypsum veins, increasing water leakage was recorded soon after the first impounding in 2005, reducing the reservoir water level. The composition of the seepage water, with concentrations in calcium and sulphate 6–12 times higher than in the reservoir, indicates that the dam foundation was affected by significant subsurface chemical and possibly mechanical erosion. A cut-off wall beneath the heel of the dam was proposed as the main measure to remediate the problem (Moradi and Abbasnejad, 2011). Kiyani et al. (2008) assessed the impact of dissolution of gypsum veins in the argillaceous rocks that occur in the foundation of the Upper Gotvand Dam, Iran. This is a 178 m high earth dam on the Karun River in the Zagros Mountains. The results of 2D and 3D seepage models utilising a finite element method suggest a permeability increase of the order of 75–300 times due to complete dissolution of the gypsum veins that would increase by 240–360 times the leakage rate. The presented examples and modelling results clearly indicate that the success in remediating problems related to gypsum dissolution in dam sites, a process characterised by a very rapid kinetics, largely depends on the promptness at which corrective measures are applied.

Active dissolution and internal erosion by leakage water in the foundation of a dam may cause, in addition to permeability increase, a rapid degradation in the mechanical properties of the material bearing the dam body and associated structures. The consequent local or general loss of basal support may lead to settlements (e.g., Murray and Browning, 1984) and even the occurrence of sinkholes, compromising the serviceability and integrity of the dam. Pearson (1999) presented a compilation of 34 case histories of dams impacted by problems related to gypsum karst. The inventory includes 12 cases (35%) of catastrophic failures. Obviously, most of them correspond to old structures with designs and monitoring systems that would not meet the current standards. The failure of St. Francis Dam, California, resulted in a flood that killed around 600 people in 1928. The collapse of the dam has been attributed to a drastic reduction in the mechanical strength of the conglomerates at the right abutment due to dissolution of gypsum veins acting as cement. Seepage water with high calcium and sulphate concentration emanating from the conglomerates was detected since the beginning of the impoundment (Ransome, 1928; James, 1992). The Quail Creek Dike, Utah, failed in 1989, five years after its completion. Significant leakage had been recorded along the downstream toe and left abutment. The bedrock exposed in the breach zone revealed thinly bedded gypsiferous beds with solutionally-enlarged joints and conduits. The new dike, a concrete gravity dam with a cut-off trench 23 m deep, is also affected by leakage and more than 200 sinkholes have been documented within a band 120 m wide upstream of the dam. The remedial measures applied include a foundation grouting programme and the installation of a clay blanket upstream of the dam (Payton and Hansen, 2003). The weir, locks, and powerhouse at Hessigheim on the River Neckar, Germany, have suffered from severe subsidence related to cavernous Triassic gypsum-rich bedrock. The power plant settled 16 cm during construction and 20 cm subsidence was recorded in the lock chambers. A grout curtain was successfully constructed at the upstream side of the structures (Wittke and Hermentin, 1997). Mosul Dam is a 113 m high and 3.4 km long earth dam on the Tigris River, Iraq. It was completed in 1984 and is one of the most important projects of the country. The reservoir has a storage capacity of 11.1 billion m³ and is located 50 km upstream of Mosul city, with a population of 3 million people. The foundation corresponds to the Miocene Fat’ha Formation, including 6–8 m thick gypsum/anhydrite units interbedded with other lithologies. Since the initial filling and despite the permanent grouting programme, reservoir water flowing through the foundation at depths as high as 100 m is causing major gypsum dissolution (42–80 tons per day) and significant settlement in the dam, compromising the safety of the structure and creating social alarm (Guzina et al., 1991; Sissakian et al., 2014). It has been estimated that the peak of the potential flood generated by a catastrophic failure of the dam would arrive in Mosul in about 9 h with a stage of 20 m and affecting an area occupied by 2 million people. Badush Dam is being constructed upstream Mosul city to act as a backstop structure in the event of a dam burst (Guzina et al., 1991; Sissakian et al., 2014).

A common problem in reservoirs underlain by evaporites is the development of human-induced sinkholes. Sinkholes that form within the reservoir area, especially in the vicinity of the dam, may act as effective outlet points for leakage water. Several factors may favour subsidence phenomena (Gutiérrez et al., 2014): (1) overloading imposed by the stored water; (2) rapid and increasing ground water flows under high hydraulic gradients with the consequent enlargement of voids by internal erosion and dissolution; (3) cyclic flooding and drainage of karst conduits at the margin of the reservoir related to the oscillating reservoir water level. The decline of the reservoir level and groundwater table may cause buoyancy loss in cavity roofs; and (4) thawing of ground ice in permafrost areas. As explained above, the inability to hold water in
Anchor Dam, Wyoming, was mainly related to the occurrence of large sinkholes upstream of the dam (Jarvis, 2003). In the 1980’s Horsetooth Reservoir, Colorado, underlain by a Permian/Triassic gypsumiferous formation, was affected by sinkholes associated with collapse chimneys up to 100 m deep. In 2000, a sinkhole was discovered at the upstream toe of the dam, which was affected by increased seepage and high artesian pressure (Pearson, 1999; Johnson, 2008). Huoshipo Dam, China, was built upon karstified gypsum without any previous geological site investigation. The reservoir has been affected by significant leakage of water flowing through sinkholes formed around 100 m upstream of the dam (Yarou and Cooper, 1997). In Kama Reservoir, pre-Ural region, Russia, the hydrogeological changes related to the project have reactivated a gypsum karst inducing numerous collapse sinkholes with severe land-use implications (Klimchouk and Andrichuk, 1996). The Bratsk Reservoir, Siberia, has caused the partial thawing of the permafrost and the development of numerous collapse sinkholes along some coastal sectors. During reservoir impounding (1963–1966), sinkhole occurrence reached a spatial-temporal frequency of 200 sinkholes/km²/year, causing severe damage to buildings and structures outside the reservoir area (Eraso et al., 1995; Trzinski, 1996; Trzhtsinsky, 2002). The Mont Cenis Reservoir (Moncenisio Reservoir) is located in a glacial overdeepened basin in the Alps, at the French–Italian border, and the left abutment of the dam is underlain by Triassic evaporites. In addition to leakage problems, the reservoir has induced numerous sinkholes and geodetic surveys reveal rapid subsidence (6 cm between 1986 and 1988) in an area covering around 6 ha on the margin of the reservoir (Deletie et al., 1980).

Although infrequent, an additional potential problem that might be encountered under adequate topographic and geological conditions is the flow of reservoir water through underground karst channels towards an adjacent watershed. A number of cases have been documented in carbonate karst areas in which groundwater flows escaping from reservoirs traverse topographic divides and discharge at springs in other surface catchments (e.g., Milanovic, 2004). Johnson (2003a) indicates that the presence of cavernous gypsum units associated with a fault zone in the uppermost sector of the proposed Lower Mangum Reservoir, Oklahoma, could cause the loss of water into an adjacent watershed. This factor might reduce the storage capacity of the projected reservoir by around 55%.

Several strategies may be considered from the dam site selection stage to prevent or reduce problems related to evaporite karst. A preventive alternative is to avoid valley reaches with evaporites at or near the surface, especially in dam sites. The proposed site for the Upper Mangum Dam, Oklahoma, was abandoned due to the presence of cavernous Permian gypsum beds in the dam foundation and reservoir area (Johnson, 2003b). A new site was selected 11 km downstream, the Lower Mangum Dam site, considered as an adequate location from the gypsum karst standpoint. Here, the karstified gypsum formation found in Upper Mangum, which dips upstream, is located above the normal maximum water level in most of the reservoir and the bedrock mainly corresponds to impervious shales (Johnson, 2003a). In the site proposed for the Cedar Ridge Dam, Texas, boreholes revealed the presence of unexpected gypsum beds in the valley sides and beneath the valley floor with an aggregate thickness of 10–15 m. In order to avoid these problematic rocks, gently dipping upstream, a new dam site was proposed 8 km upstream, where the top-most gypsum bed is situated 23 m beneath the valley bottom (Johnson and Wilkerson, 2013). In some cases in which the evaporites have a limited extent, a feasible alternative may be their removal by excavation from the dam site. A good example is the Casa de Piedra Dam in Argentina. Here, an unexpected gypsum bed more than 5 m thick with cavities and paleosinkholes was encountered on the left abutment. The gypsum layer was removed excavating a deep trench after lowering the water table 15 m (Marriotti et al., 1990). In case the evaporites cannot be avoided, the dam should incorporate elements aimed at preventing water leakage through the foundation and abutments of the dam such as cut-off walls, grout curtains or clay blankets. Milanovic (2004) presents a comprehensive review of the different measures that may be applied to prevent and/or remediate water leakage in dams associated with karst. The analysed case histories suggest that in most cases dams built on gypsum-bearing foundations require the application of successive post-construction grouting programmes. Probably the most dramatic example is Mosul Dam, Iraq, subject to a permanent grouting programme aimed at filling the voids that continuously form by gypsum dissolution in the dam foundation. Around 84,000 tons of solid material was injected between 1986 and 2004 (Sissakian et al., 2014).

A number of dams in Spain have been affected by problems caused or partially related to gypsum dissolution, such as leakage: Extremera Dam (Jiménez, 1949; Llamas, 1965), Alloz Dam (Fernández et al., 2001), Caspe Dam (Araoz, 1992; Mancebo-Piqueras et al., 2012); or failure: San Juan Reservoir (Gutiérrez et al., 2003). In this work we analyse leakage problems in La Loteta Dam, a very peculiar reservoir built in a large karst depression developed on subhorizontally-lying Tertiary evaporites in NE Spain. The main objectives of the paper include: (1) unravelling the origin of the karst depression integrating geomorphological mapping and the available borehole data; (2) characterising the dam site from the karst perspective mainly using data gathered during the construction of the structure; (3) analysing the spatial distribution of the leakage paths as well as their temporal evolution using monitoring data systematically collected by the Ebro Basin Water Authority; and (4) documenting subsidence evidence recorded along the main leakage path in one of the abutments.

2. The project of La Loteta Reservoir

La Loteta Reservoir is located on the southern margin of the Ebro River valley, NE Spain, around 40 km upstream Zaragoza City (Figure 1). Here, the valley has been carved in a thick Tertiary continental succession consisting of subhorizontally-lying halite- and glauberite-bearing evaporites and argillaceous units. These sediments of the Ebro Cenozoic basin fill are extensively covered by gravelly terraces and pediments on the southern margin of the valley. The basin of La Loteta Reservoir has a peculiar origin. It does not correspond to a dammed valley section, but to a NW–SE trending dissolution-induced subsidence depression around 6 km long captured on its NE side by a small ephemeral stream; the Arroyo del Carrizal (Figure 1). This semi-enclosed flat-floored basin, surrounded by steep slopes along its whole perimeter, except at the water gap carved by the Arroyo del Carrizal, was considered an excellent topographic setting for the construction of a reservoir. It allows the impoundment of a large volume of water (104.85 hm³) at a strategic location with the construction of a relative low dam (29 m above the valley floor) (Lafuente, 2004; Lafuente et al., 2006). Due to its unparallel geomorphic nature, the reservoir has a limited contributing area (25 km²) compared with the maximum impoundment surface area (11 km²). Consequently, it has to be filled with water from outside its catchment. The inflow produced by a flood with a return period of 1000 yr would contribute with a volume of water lower than 1.5% of the maximum capacity of the reservoir, involving an elevation in the reservoir water level (RWL) of ca. 0.4 m (Lafuente, 2004).

La Loteta project was conceived with two main aims: (1) Regulating the Imperial Canal in its middle reach. This is a remarkable hydraulic structure 110 km long constructed in the second half of the 18th century along the southern margin of the Ebro Valley for irrigation and navigation purposes (Sástago, 1796). The reservoir may store water pumped from the Imperial Canal and may also supply water to the canal through a ca. 3 km double-pipe conduit system. (2) Quality water supply to Zaragoza City and its environs. The reservoir may receive water with low-ionic content from the Yesa Reservoir in the Pyrenees, via the La Sora Ditch. The execution of the project, with a cost of 72 million euro, lasted from November 1998 to the beginning of 2009. The impoundment of the reservoir started in February 2009.
Fig. 1. Location of La Loteta Reservoir on the southern margin of the Ebro Valley, upstream Zaragoza City, NE Spain. The shaded relief model shows the ca. 6 km long subsidence basin generated by interstratal dissolution of salt-bearing evaporites used for the construction of the reservoir. The dam is located at the water gap where the Arroyo del Carrizal captured the karstic depression. The flat surface in the reservoir corresponds to impounded water. Note the enclosed Valcardera Depression to the NW of La Loteta Reservoir. Also note the proximity of the reservoir to the El Bayo stream, lying at a lower elevation than the maximum water level of the reservoir. UTM coordinates correspond to the geodetic system ETRS89.

Fig. 2. Longitudinal section of the dam and distribution of stratigraphic units. The section shows the distribution of dissolution and subsidence features encountered during the excavation of the foundation in both abutments, and the approximate location of the high resistivity anomalies identified at the right abutment. The different features are projected on the axial plane of the dam. The sector on the left edge of the dam crest affected by anomalously high settlement is indicated.
3. Characteristics of the dam and grout curtain

La Loteta Dam was built across the broad Arroyo del Carrizal valley, at the capture point of the karstic depression on its NE margin (Figure 1). It is a 1472 m long earthen dam with a maximum height of 34 m between the footprint (≥ 258 m a.s.l.) and the crest (292 m a.s.l.) (Figures 2 and 3). The maximum normal water level of the reservoir is 288 m a.s.l. The dam has a spillway at that elevation located in a tower built within the reservoir to reach to the gates of the dam. It also has a complementary bottom outlet. The lower part of the dam body is built into the bedrock. The trench dug for the construction of the dam reached depths below the previous topography of 20 m and 16 m in the left and right abutments, respectively (Figure 2).

The watertightness system incorporated into the cross-section of the dam includes three elements (Lafuente, 2004; Lafuente et al., 2006) (Figure 3): (1) A vertical clay core; (2) A horizontal clay blanket on the upstream side, connected to the clay core. The blanket is 6 m thick, has a maximum width of 128 m in the central sector of the structure, and is overlain by the upstream shoulder and a 4 m thick bed of compacted gravel. (3) A cement-flyash-bentonite cut-off wall built close to the upstream edge of the clay blanket with an average depth of 23 m. The diaphragm wall is 1587 m long and 0.8 m wide, and was built along a continuous single-slot cutter trench using the panel wall technique. This is the longest cut-off wall built so far in Spain (Lafuente et al., 2006). The distance between the dam axis and the cut-off wall reaches 125 m in the central sector of the structure. The aim of the clay blanket combined with the cut-off wall located at a significant distance upstream of the dam axis was to reduce the hydraulic gradient and enlarge the path of potential underground water flow through the dam foundation.

The dam shoulders have been constructed with gravels from nearby terraces and pediments. The upstream shoulder has a 2.5 m wide transition zone (fines and gravels <5 cm) at the contact with the clay core and its outer face is protected from wave erosion by rip-rap (Figure 3). Between the clay core and the downstream shoulder there is a fine-grained filter and a gravelly drain, each 2.5 m wide. These layers extend along the base of the shoulder with lower thicknesses; 0.65 m and 0.35 m, respectively (Figure 3). The base of the drain has 20-cm-diameter pipes slotted in the upper side to collect leakage water. This drainage system is divided into eight zones connected with two gauging stations through independent closed pipes, also 20 cm in diameter. This zonation allows monitoring water leakage at different sections of the dam. A total of 28 profiles perpendicular to the dam axis were established for design and monitoring purposes, some of which coincide with the limits of the drainage zones (Figures 2 and 3).

Grout curtains were constructed on both abutments (Figure 4). Their design was conditioned by the presence of a horizontal gypsum unit between 279 m and 268 m a.s.l. (Figure 5). The as-built grout curtain in the right abutment starts on the edge of the clay core at the dam axis, is 255 m long, and has a NW–SE orientation roughly coincident with that of the dam. Initially, a single row of 86 primary boreholes with a regular spacing of 3 m was projected. The number of drillholes was increased in the sectors with high grout takes (mainly between the primary boreholes 1–50, 65–68, and 73–86). The final number of boreholes reached 154. The maximum absorption was reached between the primary boreholes 65 and 68, with values as high as 900 kg/m. Here, the spacing between boreholes is 0.75 m (Figure 4). An additional row of 11 boreholes was also performed between the edge of the cut-off wall and the main grout curtain, in order to fill the gap between them.

Before the impoundment of the reservoir, the grout curtain in the left abutment consisted of several boring lines (Figure 4):

1. A main row of boreholes 675 m long connected to the cut-off wall. This curtain, which was performed next to the access road of the dam, has an arquate trace with a significant downstream deviation with respect to orientation of the dam axis. In the
25 m long stretch located next to the edge of the cut-off wall, 35 boreholes were drilled with a spacing of around 0.7 m (row I in Figure 4). In the remaining stretch, the curtain comprises 215 boreholes with a spacing of 3 m. High grout take was recorded in a section between 435 m and 459 m (distance from the origin of the curtain), with absorption values as high as 1496 kg/m (Figure 4).

(2) Three secondary rows 12–25 m long within a band 3 m wide just downstream of the main borehole line and associated with the edge of the dam (rows designated as II in Figure 4). Borehole spacing in these rows vary between 1.3 and 1.5 m. In the two northernmost rows, the highest consumption was reached in the section between 3 m and 14.5 m (distance from the origin of the curtain), with grout takes as high as 1590 kg/m. This cavernous zone is partially located beneath the dam body and its location seems to coincide with the base of the gypsum unit.

(3) A 33 m long borehole line with orthogonal geometry that connects the main boring line with the dam axis beyond the edge of the clay blanket (line III in Figure 4). This line includes 30 boreholes with a regular spacing of 1.5 m and the section perpendicular to the main curtain includes two rows 1.5 m apart.

With the aforementioned layout, a difficult to perceive gap has been detected at the left abutment in the watertightness system of the dam (Figure 4). Water has the chance to flow downwards through bedrock in the sector framed by the edge of the horizontal clay blanket and the adjacent orthogonal borehole rows (II and III). Such gap would not exist if the transversal boring row (line III in Figure 4) would have connects the main boring line with the dam axis beyond the edge of the clay blanket (line III in Figure 4). This line includes 30 boreholes with a regular spacing of 1.5 m and the section perpendicular to the main curtain includes two rows 1.5 m apart.

Grouting performed before the impoundment of the reservoir was applied along a 28 m vertical section between 260 m a.s.l. (8 m below the base of the gypsum unit) and 288 m a.s.l. (9 m above the top of the gypsum unit) (Figure 2). A cement–water mixture with a ratio of 2–2.5 was injected by the upstage method (bottom-up) in five sections 5–8 m long each. Injection pressure varied between 0.5 kg/cm² and 10 kg/cm², depending on the absorption rate; the higher the consumption, the lower the pressure.

Additional grouting was carried out in the left abutment after the impoundment of the reservoir due to leakage problems (Figure 4). In 2011 and 2012 the main line of boreholes was reinforced between the primary boreholes 10 and 65 with an additional 170 m long row of 58 borings. In this phase grouting was applied by the down-stage method (top-down). In November 2013, two trial boreholes were drilled through the dam body, next to the edge of the clay blanket and around 6 m upstream the dam axis (Figure 4). The high absorption between 266 m and 270 m a.s.l. revealed the presence of a cavernous zone at the lower part of the gypsum unit, right beneath the dam body (Figure 2). Initially, 20,000 kg of cement was injected and subsequently 3000 kg of a cement–sand mortar, without completely filling the voids.

4. Geology and geomorphology of the basin and the dam site

4.1. General geological setting and stratigraphy

La Loteta Reservoir is located in the central sector of the Ebro Cenozoic basin, NE Spain (Figure 1). The bedrock corresponds to subhorizontally lying evaporitic sediments of the late Oligocene–Miocene Zaragoza Formation, deposited in a large high-salinity playa-lake (Quirantes, 1978; Ortí and Salvany, 1997). This formation, more than 850 m in thickness, includes anhydrite, halite and gauherite in the subsurface and secondary gypsum in outcrop (Salvany et al., 2007; Salvany, 2009). Torrescusa and Klimowitz (1990), based on oil exploration boreholes, distinguished two members within the Zaragoza Formation and identified their contact at around 350–400 m below the bottom of the Ebro Valley. The upper member, up to 600 m thick, consists of 140 m of marls and clays at the base, and a thick evaporitic succession whose upper part is exposed at the surface. On the basis of boreholes drilled along the Ebro Valley, stretching from La Loteta to the surroundings of Zaragoza City, this upper evaporitic sequence has been divided into four lithostratigraphic units, in ascending order (Salvany et al., 2007; Salvany, 2009): (1) marl and anhydrite basal unit; (2) halite unit; (3) gauherite–halite unit; and (4) anhydrite unit. The Miocene rocks exposed in La Loteta Reservoir basin and dam site correspond to the uppermost anhydrite unit. Here, this unit has a high proportion of clays and marls, and the exposed gypsum beds mostly correspond to a secondary lithofacies derived from the replacement (gypsisification) of anhydrite. The contact between the anhydrite unit and the underlying gauherite–halite unit in La Loteta area, as defined by Salvany et al. (2007), corresponds to the top of a halite- and gauherite-rich unit situated 62 m below the footprint of the dam (196 m a.s.l.) (Figure 2).

4.2. Stratigraphy at the dam site

Geotechnical reports systematically refer to a stratigraphic type section for the dam site, comprising 14 laterally continuous subhorizontal units (Lafuente, 2004; Lafuente et al., 2006). For the objectives of this study, such section is simplified into the following four units on the basis of the type and proportion of soluble rocks, in descending order (Figure 2).

Unit I (subunits 1.1, 1.2, and 1.3 of the reports). The base of this unit, exposed on the valley sides, is situated at 279 m a.s.l. (13 m below the dam crest) and is locally overlain by Quaternary alluvium. It consists of clays and marls with minor amounts of gypsum (Figure 5).

Unit II (subunit 2.1 of the reports). This unit extends from 279 m to 268 m a.s.l. It consists of 11 m of well-stratified gypsum with interbedded marls (Figure 5). In boreholes drilled within the reservoir basin (LO-2 and LO-3) (Figure 6), this unit includes centimetre-thick halite beds. Large cubic gypsum pseudomorphs after precursor halite were
found in this unit during the excavation of the foundation. Unit II was considered as the most problematic due to the presence of abundant evidence of dissolution and subsidence identified in boreholes and in the excavation of the dam foundation. During the excavation of the footprint of the dam, it was decided to remove most of this unit from the left abutment (Figure 2). This karstified unit is present beneath the right portion of the dam body along a stretch of about 500 m, west of profile P-19, and beyond the dam edges on both sides of the valley. Moreover, it forms extensive outcrops on both sides of the dam, where reservoir water is in direct contact with gypsum. After the impoundment of the reservoir, the exposures of the left side have been partially covered by clay aimed at reducing water losses. This subunit yielded highly variable hydraulic conductivity values in Lugeon and falling-head Lefranc tests, with permeability values as high as \(10^{-2}\) cm/s and complete loss of water in some cases. Permeability in the rest of the units was dominantly of the order of \(10^{-6}-10^{-5}\) cm/s.

Unit III (units 2.2 to 12 of the reports). This unexposed unit is situated between 268 m to 188 m a.s.l. It constitutes the foundation of the dam in its central sector and the base of the cut-off wall along it whole length (Figure 2). It is essentially composed of variegated clays and marls with some intercalated gypsum, displaying limited signs of dissolution. Two laterally continuous alabastrine gypsum beds (units 6 and 8 of the reports) 4 m and 1 m thick, whose bases lie at 240 m and 234 m a.s.l., respectively, were differentiated. The upper one is partially intersected by the diaphragm wall.

Unit IV (units 13 and 14 of the reports). The top of this halite- and glaubeite-bearing unit is situated at 188 m a.s.l. It constitutes the foundation of the dam in its central sector and the base of the cut-off wall (Figure 2). The upper 7.7 m consists of halite with anhydrite nodules and clay intercalations. The lower 5.5 m thick section is mostly composed of glaubeite crystals cemented by halite.

In boreholes LO-5 and S-39, located 0.9 km upstream and 0.2 km downstream of the dam, respectively (Figure 6), deeper glaubeite–halite units of 10.4 m and 15.7 m thick were found, respectively (units 16 and 19 of the reports). The top of these units is situated at 172 m and 153 m a.s.l. in the borehole drilled next to the dam (S-39). No evidence of dissolution was found in the halite and glaubeite units.

4.3. Geomorphology and origin of La Loteta Depression

In the study area, the Ebro River valley displays a marked asymmetry, with a stepped sequence of terraces and mantled pediments on the southern margin, and a prominent gypsum escarpment on the northern flank. These geomorphic features record a long-term evolution of the fluvial system characterised by alternating episodes of aggradation and entrenchment, together with an overall northward migration (Gutiérrez et al., 1994; Guerrero et al., 2012). In the mapped sector around La Loteta Depression, we have recognised a sequence of ten terrace levels including the flood plain (T1: +235 m; T2: +200 m; T3: +110–105 m; T4: +90 m; T5: +80 m; T6: +63–57 m; T7: +50 m; T8: +37–32 m; T9: +23–20 m; T10: +5–3 m), and mantled pediments correlative to four of the terrace levels (Figure 6). The Ebro River Stream to the SE of the La Loteta Depression has also developed a sequence of terraces that can be correlated with some of the Ebro River terraces on the basis of cartographic relationships. The remnants of the highest preserved terrace of the Ebro River, perched 235 m above the current channel, indicate a lateral migration of the fluvial system of at least 10 km. The long-term lateral shift of the river has resulted in the development of extensive terrace and pediment surfaces underlain by gravel deposits, typically a few metres thick, on the southern margin of the Ebro Valley. However, the Quaternary gravels are locally interrupted large subsidence depressions superimposed to and inset into some of the alluvial surfaces. These topographic basins show a broad geomorphic spectrum representing different evolutionary stages, allowing the substitution of time by space for their interpretation (ergodic concept).

La Loteta Depression is a 6-km-long NW–SE trending elongated depression covering around 20 km². The orientation of the depression coincides with that of the most penetrative joint set in the central sector of the Ebro Cenozoic Basin (Arlegui and Simón, 2001), which plays a significant control on the development of sinkholes and large dissolution-induced depressions (Quiñantes, 1978; Gutiérrez et al., 2007; Galve et al., 2009; Guerrero et al., 2012). The basin is mostly surrounded by scarped slopes on clayey and gypsum Tertiary successions capped by cemented Quaternary gravels (Figure 6). An extensive P5 pediment forms the NW edge of the depression. Terraces T3, T4 and T5 cover the bedrock in the NE margin, which has been breached by headward expansion of the Arroyo del Carrizal Stream. Terraces T3 of the Ebro River, and terrace T5 of the El Bayo Stream occur on the SE edge. The SW margin is less well-defined and more dissected, with remnants of terrace T2, and gypsum-capped mesas. The depression has a relatively flat bottom, perched above the adjacent El Bayo Stream. A relevant aspect regarding potential water losses from the reservoir is that the El Bayo Stream is situated around 10 m below the maximum normal water level of the reservoir (288 m a.s.l.). The 288 m contour lines in La Loteta Depression and El Bayo valley are located 1.5 km apart.

Three mantled pediment levels with a thin veneer of gravelly silts and sands have been mapped within La Loteta depression (PL1, PL2, PL3) (Figure 6). Probably, the oldest pediment (PL1) was formed when the basin was still an enclosed depression with internal drainage. The two younger pediments (PL2, PL3) and the inset flat-bottom valley record alternating entrenchment and aggradation phases developed.
after the capture of the depression by the Arroyo del Carrizal. Two sectors may be differentiated in the bottom of the depression with contrasting geomorphological features. The SE portion is characterised by flat, gently-sloping and non-dissected surfaces of pediment PL3. The NW sector is dominated by a flat-bottom valley system connected to the Arroyo del Carrizal. This drainage system displays anomalous features attributable to limited surface drainage due to infiltration into karstified gypsum bedrock. The wide valleys in the floor of La Loteta Depression have (1) very low gradient, (2) a poorly ranked and anastomosed pattern, locally surrounding inliers of Tertiary sediments capped by pediment deposits, and (3) merged headwaters in first order channels. Downstream of the capture-related water gap (dam site), the Arroyo del Carrizal displays a completely different geomorphic style, with a narrow linear channel incised into bedrock. This change is related to the recent connection of two different drainage basins after the capture of the depression by the Arroyo del Carrizal Stream. The higher dissection in the NW half of the depression seems to be related to lithological changes caused by differential interstratal karstification and subsidence, as explained below. Cartographic relationships indicate that the development of La Loteta Depression started sometime after deposition of terrace T5, and that most probably it was captured before the formation of pediment PL2.

Other subsidence depressions have been identified in the mapped area (Figure 6). El Plano Depression, west of La Loteta, is a flat-floored 2.2-km long topographic basin recently captured by a stream dissecting pediment P5. The NE–SW-oriented Valcardera Depression, NW of La Loteta, is an internally drained, scarp-edged basin 2.7 km long and 0.6 km wide. The basin, superimposed on the gravel pediment P5, is 13 m deep and its flat bottom lies at 310 m a.s.l., 22 m above the maximum normal water level of the reservoir. Consequently, it cannot be flooded by potential groundwater flow coming from the reservoir. North of La Loteta Dam and south of Gallur village, there is a broad 2.6 km-long and NNE–SSW-trending depression between terraces T6 and T8. This subsidence depression, younger than terrace T8, has been recently captured by a drainage on its SE edge. Additional subsidence depressions may have developed SE of the Arroyo del Carrizal between terraces T6 and T8, which have been integrated into the drainage network as anomalously wide flat-bottom valleys.

![Fig. 6. Geomorphological map of La Loteta depression and surrounding area.](image-url)
Similar large closed depressions up to 7 km long and inset into Quaternary terraces and pediments have been documented along the margins of the Ebro Valley in the vicinity of Zaragoza City, 30–60 km downstream of La Loteta. Deep trenches excavated for the construction of the Madrid-Barcelona high-speed railway in the floor of some of those basins, together with borehole data, revealed that their origin is related to subsidence phenomena induced by interstratal dissolution of evaporites, mainly glauberite and halite (Guerrero et al., 2012). Those exposures display hectometre-scale sagging structures affecting gypsum bedrock with as much as 10 m of structural throw. The sagged gypsum has been frequently transformed into breccias with a variable degree of distortion, ranging from crudely bedded packbreccias to chaotic and intensely karstified floatbreccias. These features record: (1) deep-seated interstratal karstification of the glauberite- and halite-rich evaporite bedrock; (2) subsidence by progressive sagging of the overlying bedrock and cover sediments; and (3) local fracturing of the subsided competent beds and karstification of the resulting high-permeability breccias.

Unfortunately, in La Loteta basin and in the nearby depressions, the dissolution-induced subsidence phenomena cannot be proved by exposures with evidence of gravitational deformation. However, such interpretation is strongly supported by stratigraphic changes documented by means of boreholes drilled in the floor of La Loteta Depression and on its margin (dam site) (Figure 6): (1) In boreholes LO-4 and LO-2, drilled in the NW and central sectors of the basin floor, respectively, the stratigraphic contact between units I and II lies at an elevation around 10–20 m lower than in the margin of the depression. (2) The gypsum unit II shows a thickness decrease of 8.6 m between borehole LO-3, located on the SW edge of the depression, and borehole LO-5, drilled in the northern-central sector, 0.9 km west of the dam. Unit II includes halite beds up to 10 cm thick in boreholes LO-2 and LO-3. (3) In borehole LO-5, located in the northern sector of the basin floor, stratigraphic contacts, including those beneath unit II, are consistently situated at elevations 7–8 m lower than in the dam site. All these data indicate that the Miocene sediments underlying the bottom of the depression have been affected by differential subsidence with a vertical displacement as high as 20 m. Part of that subsidence may be attributed to dissolution within unit II, as suggested by the reported decrease in thickness of 8.6 m. Pre-existing halite and possible glauberite beds may have been removed by dissolution. Additional deep-seated interstratal dissolution is needed to explain the elevation drop of 7–8 m of the stratigraphic contacts beneath unit II. This evidence suggests deep-seated dissolution of glauberite and/or halite beds at an unknown depth. Most probably, interstratal dissolution has been favoured by the progressive long-term entrenchment of the base level and the consequent deepening of groundwater flows. Other processes such as aeolian deflation or suffusion of cover deposits through dissolutional conduits, although may have played some role, cannot account for the formation of kilometre-sized depression superimposed on pediments and terraces underlain by cobble–pebble gravels that cannot be entrained by the wind.

5. Jointing and evaporite karst evidence at the dam site

The joints affecting the Miocene bedrock exposed in the dam excavation have a dominantly vertical attitude and are frequently filled by gypsum precipitates. They show a prevalent N–S trend (10W–10E), and three secondary sets with 40–50E, 100–110E, and 150–160E orientations. According to Arlegui and Simón (2001), the joints in the central sector of the Ebro Basin have dominant NW–SE, E–W and N–S azimuths. The NW–SE trending joint set, parallel to the Ebro Valley and the major axis of La Loteta depression, has a particularly strong influence on the development of karst landforms in the central sector of the basin (e.g., Quirantes, 1978; Gutiérrez et al., 1994, 2007; Galve et al., 2009; Guerrero et al., 2012). Probably, the frequency of these fractures was underestimated, because most of the cuttings in the dam excavation were roughly parallel to that direction. Different types of dissolution and subsidence features were identified in the 11 m thick gypsum unit II exposed in the excavation of the dam foundation (Figure 7). This unit includes centimetre-thick stratiform solution-collapse breccias with marl matrix, probably related to the dissolution of pre-existing halite and/or glauberite beds, and the consequent fracturing and brecciation of the associated rocks (Warren, 2006). Halite beds were found within this unit in boreholes drilled within the reservoir basin (LO-2, LO-3 in Figure 6). Furthermore, gypsum beds up to 0.6 m thick have been completely removed by dissolution along broad sections (Figure 7A). Six dissolution–subsidence structures were identified and mapped in the ca. 1.5 km long and up to 20 m deep trench excavated along the dam axis (Figure 2). The location of these structures was referred to indicating the distance of their centre to the left edge of the dam axis (origin) and the excavation wall in which they were identified (downstream or upstream). Data on the location, size and characteristics of the dissolution and subsidence features are summarised in Table 1.

(1) Sagging structure 3 m wide with small-throw normal faults and supra-attenuated dips, located at the left edge of the excavation in the left abutment.

(2) In September 1999, during the excavation of the foundation, the ground was affected by a semicircular sinkhole 24 m in diameter and 0.7 m deep adjacent to the downstream wall of the trench. The depression had four nested air-filled vertical shafts with overhanging walls 1–3 m deep. Deeper excavation exposed on the downstream wall two subvertical tapering-upwards collapse structures up to 9 m deep and 5–6 m wide filled with chaotic marls, and clays (Figure 7B).

(3) Sagging structure 20 m wide and 5 m in vertical throw with collapse faults in the hinge zone. It shows collapse faults and dissolutional conduits filled with clayey sediments from the overlying unit I.
(4) Sagging and collapse structure 15 m wide and 10 m deep affecting the whole unit II, which was transformed into loose marl-rich chaotic breccia.

(5) Sagging structure around 6 m wide affecting units I and II, traversed by a vertical collapse approximately 2.5 m wide in its centre.

(6) Three spatially associated sagging structures with an aggregate length of 120 m affecting the clayey unit I and the overlying terrace deposits. The easternmost synform displayed antithetic reserve faults on their limbs. Unit II was not exposed in this sector of the trench. Electrical resistivity imaging suggests that these structures are related to dissolution around the base of unit II.

Four electrical resistivity tomography sections were acquired along the floor of the trench excavated for the dam foundation, two 400 m long at the left abutment and two 475 m in length in the right abutment. The sections obtained in the left abutment do not provide relevant information about the karstification of the dam foundation, since they were acquired after the excavation of gypsum unit II. The sections of the right abutment showed two clear anomalies (Figure 2). An anomaly between 1305 m and 1375 m (distance from the origin at the left edge of the dam) was interpreted as a paleosinkhole, which coincides with the paleosinkhole 6 exposed in the downstream wall of the excavation. The subsidence structure was expressed in the section as a high resistivity zone at the base of unit II, attributable to air-filled cavities, overlain by a high conductive zone that interrupts the resistive gypsum unit, ascribable to foundered clay sediments. The other high resistivity anomaly identified between 1020 m and 1035 m was attributed to air-filled cavities within the gypsum unit.

The available data reveals that: (1) the gypsum unit II is locally strongly karstified, especially on the left abutment (Figure 2); (2) karst features include metre-sized air-filled cavities and collapse structures that may reach volumes larger than 170 m³, as indicate the collapse pipes 9 m high and 5–6 m in diameter found in the left abutment (Figure 7B); (3) subsidence structures seem to be related to dissolution processes acting mainly within the gypsum unit II. Groundwater circulation and karstification is probably more intense at the contact with the underlying impervious clay-rich unit III (contact karst); (4) stratigraphic and structural relationships indicate that some of the subsidence structures have formed in the Quaternary, during or after the sedimentation of the T5 terrace deposits exposed on the right abutment.

6. Leakage problems

6.1. Leakage history

The impoundment of the reservoir started in February 5, 2009. The RWL, after a continuous rise, reached a maximum elevation of 287 m a.s.l. (1 m below the maximum normal level) by the end of May 2011 (Figure 8). The RWL declined from June 2011 till December 2012 up to 274.6 m a.s.l. This drop was followed by a rise that peaked at 284 m a.s.l. in July 2013. Since then, the RWL has decreased.

Soon after the initiation of the impoundment, water leakage was recorded in the drainage system of the dam. The water leakage discharge time series show a tight correlation with the RWL evolution, and around 80% of the water losses are recorded in zone Z2, between profiles P5 and P8 (Figures 3 and 8). Considerable discharge is also measured in zones Z1 and Z3.

![Fig. 8. Temporal evolution of the reservoir water level (RWL) and leakage discharge recorded in the whole drainage system and in zones Z1, Z2, and Z3. See location of drainage zones in Fig. 3.](image-url)
Z1 and Z3, whereas total water loss rate is lower than 10 l/s in the remaining zones. In April 2011, when the reservoir reached its maximum historical level, the total leakage reached 46 l/s, of which 37.5 l/s and 6.9 l/s were collected in zones Z2 and Z1, respectively. This must be considered as a minimum estimate of the water losses, since seepage was identified at several sites downstream of the dam.

During the second phase of RWL rise, leakage discharge increased abruptly and has remained at higher values than in April 2011, despite the lower RWL (Figure 8). Since July 2013, although the RWL has slightly declined, leakage rate has increased steadily, reaching 55.5 l/s in January 2014, at a RWL of 283.3 m a.s.l. At this time, leakage rate was 9.5 l/s higher than that measured when the RWL was at its historical maximum, 3.7 m above. These data indicate that leakage water comes from the reservoir and suggests that there has been an increase in permeability related to the enlargement and/or generation of conduits by dissolution and internal erosion of sediments filling pre-existing voids.

Pore water pressure is systematically measured in the dam foundation, clay core and clay blanket by means of vibrating wire piezometers installed in the eight monitoring profiles perpendicular to the dam axis (see location of piezometers at profile P7 in Figure 3). The piezometric data collected at profile P7 indicate that there is no leakage through the dam body in zone Z2, despite its drainage system collects a great part of the water losses (Figure 9): (1) piezometers installed in the clay core (PZ7-272, PZ7-273 and PZ7-274) record nearly constant pore water pressure without any correlation with the RWL; (2) piezometer PZ7-272 in the upstream sector of the clay core, records lower water pressure than piezometer PZ7-273 located downstream in the clay core; (3) negative pore water pressure (unsaturated conditions) is measured in the piezometer located within the clay core further downstream (PZ7-274).

The piezometers at profile P7 that measure pore water pressure in the dam foundation, just downstream of the cut-off wall, show negligible correlation with reservoir water level (PZ7-1, PZ7-2, PZ7-3 in Figure 9). Potential water leakage through the dam foundation towards the drainage system in zone Z2 should be recorded in the boreholes located downstream (PB5a, PB5b, PB7a and PB7b in Figure 10). However, water level changes of those boreholes do not show any correspondence with water pressure recorded in the electrical piezometers of profile P7. In profiles P13 and P17 (Figure 3), water pressure measured in the foundation near the cut-off wall is significantly higher than those in profile P7, but water leakage in the drainage system is negligible.

As explained in the next section, piezometric data reveals that water from the reservoir flows through bedrock and the grout curtain at the left abutment beyond the cut-off wall, which shows a good performance. The reason why the highest discharge is measured in zone Z2, rather than in zone Z1, may be attributed to the design of the drainage system (Figures 2 and 3). In zone Z1 the footprint of the dam and the drainage pipe has a 3% inclination towards zone Z2. This gradient allows a great part of the leakage water to pass through this zone along the drain. In zone Z2, where the pipe is nearly horizontal, with a slight reverse inclination towards zone Z1 (Figure 2), leakage water reduces its flow velocity and can be effectively collected by the drainage system.

6.2. Main leakage paths

The good temporal correlation between the RWL and both water level changes recorded in boreholes downstream of the dam and the occurrence of seepages, indicate effective hydraulic connection between the reservoir and the downstream sector. Several alternatives may be considered for the water losses:

(1) Water flow in the abutments below the grout curtain. In both abutments, the base of the grout curtain is 8 m deeper than the base of gypsum unit II. It is unlikely to have any significant leakage through the clayey unit III (Figure 2).

(2) Through Tertiary bedrock beyond the end of the grout curtain. Water from the reservoir might escape through the gypsum unit II, exposed all along the NE margin of the reservoir. Voids may be also present in the overlying clay unit I, related to subsidence processes caused by the karstification of the underlying unit. The shortest distance between the impounded water at RWL of 287 m a.s.l. (historical maximum) and the left and right abutments is 680 m and 175 m, respectively (Figure 10). Consequently, there is a higher hydraulic gradient at the right abutment and a priori greater leakage potential. Fig. 11 shows that the RWL raises have caused very small water level ascents in borehole PZ4b located at the end of the grout curtain in the left abutment. Here, the maximum RWL raise (287 m a.s.l.) caused an elevation of 3.5 m in the groundwater level, with a hydraulic head loss of 13 m. In case there would be a significant flow, a lower hydraulic head difference would be expected. Moreover, no seepage points have been detected downstream of borehole

Fig. 9. Temporal evolution of the reservoir water level (RWL) and water level time series recorded by piezometers installed in the clay core, clay blanket and foundation at profile P7. Note the lack of correlation between both datasets.
Unfortunately, at the right abutment, there is no borehole at the end of the grout curtain. Therefore, it is not possible to elucidate whether there is any considerable water loss in that sector, despite that there is potentially higher probability than in the left abutment due to shorter distance and higher gradient.

(3) Water leakage through the grout curtain. The water levels recorded in pairs of monitoring boreholes at both sides the grout curtain reveal that there is significant water flow across the grout curtain in both abutments (Figure 11). The highly variable water level differences in the borehole pairs allow the identification of sections with relatively higher leakage rates. At the right abutment, the water level difference in borehole pairs PZ11–PZ1D was less than 1.2 m when the RWL was at 287 m a.s.l. (Figure 10A and 11). In the left abutment, borehole pairs PZ5a–PZ5b, PZ6a–PZ6b, PZ7a–PZ7b, PZ8a–PZ8b, and PZ2a–PZ2b show a head difference as low as 2 m. These data indicate inadequate performance of the grout curtain at both abutments. The water level differences in borehole pair PZ1a–PZ1b was 12.5 m (Figure 11). This difference, much higher than in the nearby boreholes PZ2a and PZ2b, can be explained by a rapid downward flow from PZ1b towards the pervious drainage system of the dam (Figure 10B).

An equipotential map has been constructed using water levels measured in 47 boreholes and the elevation of seepage points recorded in July 2011, when the RWL was at 285 m a.s.l. The location of the sinkholes and sinkhole clusters identified in the reservoir area, upstream the left abutment, are indicated with stars. B. Enlarged map of the left abutment.
July 2011, when the RWL was at 285 m a.s.l. after reaching its historical maximum (Figure 10). The isopleths map was generated with the 3D Analyst of ArcGIS after defining the boundaries of the area, considering the spatial distribution of the available data. Although this map just depicts a schematic picture of the actual groundwater level, it provides useful clues on the main leakage paths.

In the left abutment, the equipotential lines indicate that water flow through the grout curtain mainly occurs between the dam body and the pair of borehole PZ5. Two main flow paths may be differentiated. A general one centred around borehole pairs PZ6 and PZ7, produces a diverging water flow towards the base level. Boreholes in this sector have a similar response to the RWL variations (Figure 11), and the amplitude of the water level consistently attenuates along the flow lines. There is also a major leakage path associated with the left edge of the dam, where a gap in the watertightness system has been detected. When the RWL was at 285 m a.s.l., water level in borehole PZ2b was 0.5 m higher than in PZ1b, indicating water flow towards the edge of the dam. Water level data recorded in the boreholes downstream of the dam show a good correlation with the RWL (Figure 11) and define a trough in the equipotential surface, suggesting flow towards the seepage zones and the drainage system of the dam (Figure 10B). Part of the leakage water most probably flows through the foundation beneath the dam body, as support the high grout absorption recorded in the two boreholes drilled 4 m SE of profile P1 in 2013 (Figure 4), and the anomalously high settlement measured by levelling in the crest of the dam around profile P1 (Figure 2).

At the right abutment, the equipotential lines suggest higher water loss through the grout curtain close to the edge of the dam and around borehole PZ1D (Figure 10A). Water levels in boreholes and the distribution of seepage zones indicate a main flow path towards the right margin of the valley. During the period when the RWL reached the maximum, significant water discharge occurred in the tributary drainage located downstream of the dam NW of borehole PZ22d, where a herringbone drainage system was constructed to prevent waterlogging in crop fields.

7. Evidence of active subsidence at the left abutment

In September 2011, a collapse sinkhole was detected on the left abutment just upstream of the dam body (sinkhole 1 in Figure 10). The collapse affected a slope covered by rip-rap. Probably the sinkhole was formed beneath the water sometime before and it passed unnoticed until it was exposed by the water level decline. On 27 March 2014 the circular sinkhole was 4.3 m wide and 1 m deep (Figure 12A).

Periodic levelling measurements are obtained along the crest of the dam. The settlement time series in most of the levelling points show the expectable gradual subsidence proportional to the dam height, with a decreasing temporal trend related to compaction. However, point N1 located on profile P1, and point N2 situated 25 m to the SE, show the opposite trend since September 2010 (Figure 13). On February 2014, cumulative settlement had reached around 0.08% of the dam height in all of the levelling points, except in N1 and N2 where it amounts 0.24% and 0.16%, respectively. The subsidence time series show that in points N1 and N2, the common attenuation of the deformation rate changed since September 2010 to a subsidence acceleration phase. The average subsidence rate measured in points N1 and N2 between June 2007 and September 2010 was 4.6 mm/yr and 5.6 mm/yr, respectively. Between September 2010 and February 2014 the vertical deformation rate increased to 13.8 mm/yr and 8.6 mm/yr in points N1 and N2, respectively.

By the end of March 2014, during a RWL decline, three new sinkholes or sinkhole clusters were detected in the left abutment upstream of the dam within a NNE–SSW band around 100 m long (see location in Figure 10). Sinkhole 2 was a small collapse 0.7 m long and 0.4 m deep located 18 m upstream of the base of the shoulder. Sinkhole cluster 3, located 25 m upstream of the dam, was also composed by two fresh collapses 1.5 m across and 4.5 m long. These sinkholes where embraced by open cracks with a subcircular pattern around 9 m across (Figure 12B).

Sinkhole cluster 4 comprised a circular and an elongated collapse 1.5 m across and 4 m long, respectively (Figure 12C). The overhanging edges of the depressions and the fresh cracks associated with them suggest that these sinkholes will keep on enlarging and coalescing.

All these data, consistent with the high grout absorption values recorded in the boreholes conducted in 2013, the gap detected in the waterproofing system, and the equipotential map, indicate that there is substantial water leakage at the left abutment next to and beneath the dam body. This water flow, as suggested by the increasing leakage discharge despite the declining RWL, is most probably enlarging conduits by dissolution and internal erosion, leading to the settlement of the dam body and the occurrence of sinkholes.
rate of over 110 l/s and is nearly saturated with respect to gypsum (Pearson, 1999).

The impoundment of reservoirs involves creating unprecedented and unnatural high hydraulic gradients that may lead to water leakage through karstified rocks. Underground flows escaping from the reservoir may flush out the deposits that plug karst conduits and enlarge discontinuities and cavities by dissolution, with the consequent permeability increase in a self-accelerating process (James, 1992; Romanov et al., 2003; Milanovic, 2004; Johnson, 2008; Gutiérrez, 2010; Cooper and Gutiérrez, 2013). Moreover, impounded water in direct contact with evaporite outcrops may rapidly dissolve the karst rocks, with the consequent hydrochemical degradation of the stored water. In areas with steeply dipping sedimentary successions, karst rocks associated with dam sites and reservoirs commonly form restricted outcrops or bands. Many dam sites are located at valley constrictions related to dipping carbonate units striking perpendicularly or obliquely to the valley (Milanovic, 2004). In these situations, the spatial distribution of potential leakage zones and the layout of grout curtains may be constrained with confidence on the basis of geological data. However, in areas with subhorizontally-lying successions, the soluble rock units may occur along the whole perimeter of the reservoir basin. In the case of La Loteta Reservoir, there is a subhorizontal gypsum unit with limited thickness (11 m), but distributed all around the basin. Therefore, water has the potential to flow away from the reservoir through the gypsum unit along extensive sectors, especially at the NE margin of the reservoir where the dam is located. Although unlikely, there is also the possibility for the water to escape through the SE margin towards the adjacent El Bayo Stream (Figure 6). This channel is located 10 m below the maximum water level of the reservoir (288 m a.s.l.) and the distance between that contour line in the reservoir and the valley is 1.5 km. In this type of contexts, the design and construction of grout curtains face two significant problems: (1) a lack of a lateral boundary in the karstified unit with an impervious rock to establish the desirable edge of the curtain; and (2) the probable need of building long costly grout curtains to assure the watertightness of the reservoir.

Preferably, grout curtains should be oriented perpendicularly to the expected underground flow direction and should be built into impermeable rocks. In La Loteta Dam, 675 m and 255 m long grout curtains were built on the left and right abutments, respectively. These curtains penetrate into the clayey sediments underlying the gypsum unit, but it was not possible to tie their edges to impervious sediments due the lateral extension of the gypsum unit. The longer curtain at the left abutment, where the gypsum showed significantly more evidence of karstification, has a curved trace with a significant downstream deflection from the orientation of the dam. This geometry, conditioned by land ownership constraints, may limit the desirable performance of a grout curtain with such length.

The available data indicate that water leakage occurs through the 11 m thick gypsum unit II exposed in the dam site and along the NE margin of the basin. Fortunately, the highly soluble halite and glauberite unit located 70 m and 45 m below the dam body and the cut-off wall, respectively, does not seem to have been affected by water leakage from the reservoir. Remediation in such a scenario would be very difficult and uncertain due to the extremely high solubility of halite (360 g/l) and glauberite (118 g/l). The 80 m thick argillaceous unit III situated between that contour line in the reservoir and the valley is 1.5 km. In this sector, the solute hydrochemical degradation of the stored water may increase in a self-accelerating process (James, 1992; Romanov et al., 2003; Cooper and Gutiérrez, 2013). Moreover, impounded water in direct contact with evaporite outcrops may rapidly dissolve the karst rocks, with the consequent hydrochemical degradation of the stored water. In areas with steeply dipping sedimentary successions, karst rocks associated with dam sites and reservoirs commonly form restricted outcrops or bands. Many dam sites are located at valley constrictions related to dipping carbonate units striking perpendicularly or obliquely to the valley (Milanovic, 2004). In these situations, the spatial distribution of potential leakage zones and the layout of grout curtains may be constrained with confidence on the basis of geological data. However, in areas with subhorizontally-lying successions, the soluble rock units may occur along the whole perimeter of the reservoir basin. In the case of La Loteta Reservoir, there is a subhorizontal gypsum unit with limited thickness (11 m), but distributed all around the basin. Therefore, water has the potential to flow away from the reservoir through the gypsum unit along extensive sectors, especially at the NE margin of the reservoir where the dam is located. Although unlikely, there is also the possibility for the water to escape through the SE margin towards the adjacent El Bayo Stream (Figure 6). This channel is located 10 m below the maximum water level of the reservoir (288 m a.s.l.) and the distance between that contour line in the reservoir and the valley is 1.5 km. In this type of contexts, the design and construction of grout curtains face two significant problems: (1) a lack of a lateral boundary in the karstified unit with an impervious rock to establish the desirable edge of the curtain; and (2) the probable need of building long costly grout curtains to assure the watertightness of the reservoir.

Preferably, grout curtains should be oriented perpendicularly to the expected underground flow direction and should be built into impermeable rocks. In La Loteta Dam, 675 m and 255 m long grout curtains were built on the left and right abutments, respectively. These curtains penetrate into the clayey sediments underlying the gypsum unit, but it was not possible to tie their edges to impervious sediments due the lateral extension of the gypsum unit. The longer curtain at the left abutment, where the gypsum showed significantly more evidence of karstification, has a curved trace with a significant downstream deflection from the orientation of the dam. This geometry, conditioned by land ownership constraints, may limit the desirable performance of a grout curtain with such length.

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8. Discussion and conclusions

La Loteta Reservoir is located in a unique geological setting; a large subsidence depression around 6 km long resulting from interstratal karstification of halite- and glauberite-bearing evaporites. The dam site corresponds to the water gap carved by the small drainage that captured the previously internally drained basin, covering around 20 km². This is the largest karst depression documented so far in the extensive evaporite terrains of the central sector of the Ebro Cenozoic Basin. Moreover, to our knowledge, La Loteta Reservoir, together with Carter Lake, Colorado, are the only artificial lakes placed on evaporite dissolution-induced basins reported in the literature. Carter Reservoir in the Colorado Front Range was built on an enclosed subsidence depression 3 km long and 1.5 km wide related to dissolution of Permian-Triassic gyspiferous strata. The natural lake used to drain underground feeding a spring outside the basin. At the present time, leakage water from the reservoir emerges in the former natural spring with a flow...
and the adjacent orthogonal borehole rows II and III (Figure 4). (5) More than 80% of the leakage water collected by the drainage system correspond to zones Z1 and Z2, and piezometric data indicate that the zone Z2 water is transferred from zone Z1, where the drainage pipe has a significant gradient (Figures 2 and 8). (6) Flow lines inferred from the equipotential map (Figure 10). (7) Accelerated subsidence with rates as high as 14 mm/yr has been measured at the left edge of the dam crest (Figures 2 and 13). (8) Several collapse sinkholes have formed within a band around 100 m long next and upstream of the left edge of the dam (Figures 10 and 12). Additional water leakage occurs through the grout curtain in the right and left abutments, in order of importance (Figures 10 and 11). Significant leakage at the right abutment is evidenced by a number of seepage points detected on the right margin of the valley, and a tight correlation between the RWL and the groundwater levels measured in boreholes downstream of the curtain. Most of this leakage is not collected by the drainage system of the dam and consequently its flow rate is uncertain. Borehole data and the equipotential map also indicate water leakage through the grout curtain in the left abutment. There is also the possibility of having water flow beyond the edge of the grout curtain in the right abutment, although the lack of borehole data precludes checking this option.

The aggressive reservoir water that flows through the gypsum unit at different sites is most probably enlarging joints and conduits at a considerable rate with the consequent permeability increase. Leakage water may rapidly wash out the deposits that fill cavities enlarging their carrying capacity and connectivity. Moreover, voids may grow rapidly by dissolution of high-solubility gypsum. Dissolution kinetics increases substantially when the size of the conduits reaches the threshold at which laminar flow changes into turbulent (breakthrough situation) (Jeschke et al., 2001; Romanov et al., 2003). Such enlargement of conduits and the short-term permeability increase in La Loteta is supported by increasing leakage discharge at the same RWL and the occurrence of sinkholes. In dams where leakage is associated with evaporites, remedial measures should be accomplished as soon as the occurrence of sinkholes. In dams where leakage is associated with evaporites, remedial measures should be accomplished as soon as (Figure 10).

References
