The failure of the Fonte Santa mine tailing dam (Northeast Portugal)

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ABSTRACT: The Fonte Santa mine tailing dam situated in the Northeast of Portugal failed on the 27th November 2006 due to a combination of hazards, an extraordinary rainfall and an eventual clogging of the spillway. The dam was an earthfill embankment about 25 m high and with a crest length of roughly 35 m. After the overtopping of the crest, which originated the breaching process and consequent failure, the dam was completely washed away with a fraction of the mud retained in the reservoir. The present paper constitutes a preliminary report of the accident describing the dam breaching process and the morphodynamic changes on the downstream valley. The breach geometry is characterized and estimates of the water and mud releases are presented. The geomorphic changes in the valley are described, including deposition volumes of the dam material and eroded volumes from the riverbed.

1 INTRODUCTION

The consequences of such flood events as the ones resulting from the collapse of a dam include economic losses related to lost project benefits and potential damage to property in the inundated area, loss of confidence in the dam owner and operators, alteration of the habitat and environment, social impacts on the local community and, most important of all, loss of lives. These consequences make dam break accidents amongst the most feared flood hazards. Within the dam safety context, tailing dams from abandoned mines present added risk given the lack of surveying and maintenance. The contamination levels of the sub-products resulting from mining processes make this specific type of dams highly hazardous to the environment, which is demonstrated by the impact of the tailing dam failure of the Los Frailes lead-zinc mine at Aznalcóllar in the Doñana National Park (van Geen & Chase 1998 and Achterberg et al. 1999).

Being a rare event, the documentation of dam break accidents, including the breaching process and the downstream flood propagation, is of extreme importance to help assessing the phenomena and providing clues to further development of predicting models. In the past several authors have compiled important information related to accidents with natural and manmade dams, namely Babb & Mermel (1968), Johnson & Illes (1976), Combelles (1979), Serafim (1981), Ponce (1982), MacDonald & Monopolis (1984), Serafim & Coutinho-Rodrigues (1989), Lempérière (1993), Santos (1995) and Singh (1996), Franca & Almeida (2004), among others. Important contributions to the research on dam break floods were made with the detailed descriptions of such specific accidents as the Ha! Ha! lake flood (Lapointe et al. 1998) and the Tous dam break (Alcrudo & Mulet 2005). Both served as benchmark cases within the IMPACT Project (IMPACT 2005). Nevertheless, the phenomenology on the dam breach evolution in earthen dams is not sufficiently understood, as emphasized by Wahl (2001). When possible, field data provide variables describing the breach evolution, the extension of inundation areas, the magnitude of morphologic impacts and the celerity with which the dam-break wave progresses.

This paper documents preliminarily a tailing dam break occurred in November 2006 in a remote area of Northeast Portugal. We intend to document the causes associated to the accident as well as the breaching process and the effect of the passage of the flood wave through the downstream valley. The results are based on field visits, adequate topographic surveys and local meteorological records. Herein we describe the meteorological event, the dam breaching and the effect on the downstream valley. The breach geometry is characterized and estimates of the water and mud releases are presented. The topography changes in the valley are referred to, including alterations due to deposition of the dam material and due to riverbed erosion. Estimates of erosion and accretion rates in the downstream valley were assessed locally. A detailed field survey of the valley was made within the reach where geomorphic changes occurred.

2 CHARACTERIZATION OF THE DAM AND RESERVOIR

The Fonte Santa tailing dam is situated on the municipality of Freixo de Espada à Cinta (Bragança), on the creek Ribeiro da Ponte (Fig. 1; actually the creek changes its name in he dam section, upstream the dam it is called Ribeiro das Caravelas). It belonged to a mining complex abandoned for more than 30 years ago and its main function is to retain the mud resulting from the washing process of the extracted minerals. Fonte Santa tailing dam was an earthfill embankment about 25 m high and with a crest length of roughly 35 m. The crest elevation was at 505.0 m asl. It was not object of a special design; the construction was made progressively with coarse and fine material from the mining works. The material used to construct the dam was fine gravel ("tout-venant"). The shape of the dam was quite irregular, with a large amount of the fine gravel spreading downstream along the valley banks. The total volume of the dam embankment is estimated to be of 4 500 m^3. The mud deposited in the reservoir, with D_{50} of 0.0186 mm, contributed to keep the dam body impermeable along the years.

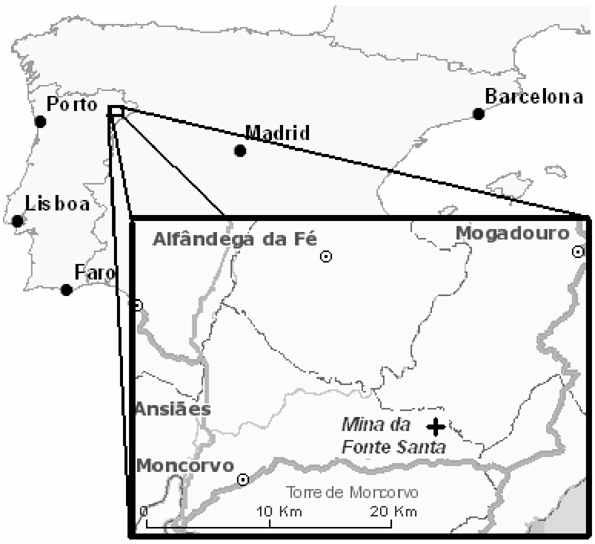

Figure 1. General location of the mining complex of the Fonte Santa. It is situated at the Northeast Portugal, north from the Douro river.

The dam is located in a section of the valley where a rock formation exists (Fig. 2). The flood discharge was made through an uncontrolled spillway excavated in the rock in an adjacent valley, with the upstream section at the level 504.4 m asl and a 3.5 m diameter roughly circular section. Eventually the upstream section of the spillway was clogged with rock material and its discharge was drastically reduced. The reservoir has approximately a maximum volume of 22.9 hm^3 for a water elevation of 505.0 m asl (crest elevation) and volume of 21.3 hm^3 for a water elevation of 504.4 m asl (spillway entrance). About 12.5 hm^3 of the reservoir is filled with the waste mud (Fig. 3).

Figure 2. General view of the Fonte Santa tailing dam after the dam break. Almost the totality of the dam body was eroded. The dam is located in a rocky and very stable section of the valley. The mud deposited in the reservoir was released leaving a scar which is visible in this picture from downstream.

On the 24th November 2006, an extraordinary rainfall occurred in the region. The continuous feeding of the reservoir for three days, combined with the clogging of the spillway, lead to the overtopping of the Fonte Santa dam crest originating breaching and subsequent total failure. The dam was completely washed with a small portion of the mud retained in the reservoir (Fig. 2). The immediate consequences of the accident were mainly loss of low density crops and eventual soil contamination.

Figure 3. Reservoir where 1.5 hm^3 of the volume is filled with waste mud from the mining processes. After the accident, a temporary solution constituted by an embankment (visible in the photograph) was made to stop the downstream mud release.

The mud deposited in the reservoir was released leaving a scar which is visible in this picture from upstream.

Local contractors exploited illegitimately the embankment material (fine gravel used as a construction material) excavating directly from the downstream dam toe. These actions may have contributed to a destabilization of the dam body and may be in the origin of the complete washout of the dam.

3 CHARACTERIZATION OF THE DOWNSTREAM VALLEY

The creek Ribeiro da Ponte flows into Sabor river, a major tributary of Douro river (Fig. 4). From the dam section until the downstream section of the creek, no major infrastructures or habitation exists within the floodplain. 1 800 m downstream the dam, a bridge exists from a secondary road linking two small towns. The main activity developed in the margins of the creek is low density agriculture for local subsistence; some cattle are breed in the floodplain of the creek. Abandoned structures such as mills and abandoned peasant villages exist.

Immediately downstream the dam, and roughly within the first 350 m after the dam, the creek section is very narrow and its bottom and banks are rocky thus stable. The access to the informal gravel exploitation referred previously was made through the downstream valley; for this purpose an embankment road was built in the valley providing access to the dam toe. This road was made with dam material and, after the break was washed away providing a good method to infer the erosion potential of the flood. This road was present in the first 400 m of the downstream valley and it still possible to see its remains. Downstream, the valley presents both, alluvial and fixed bed sections. A field survey allowed the identification of these different areas and an evaluation of the deposition and erosion within the valley.

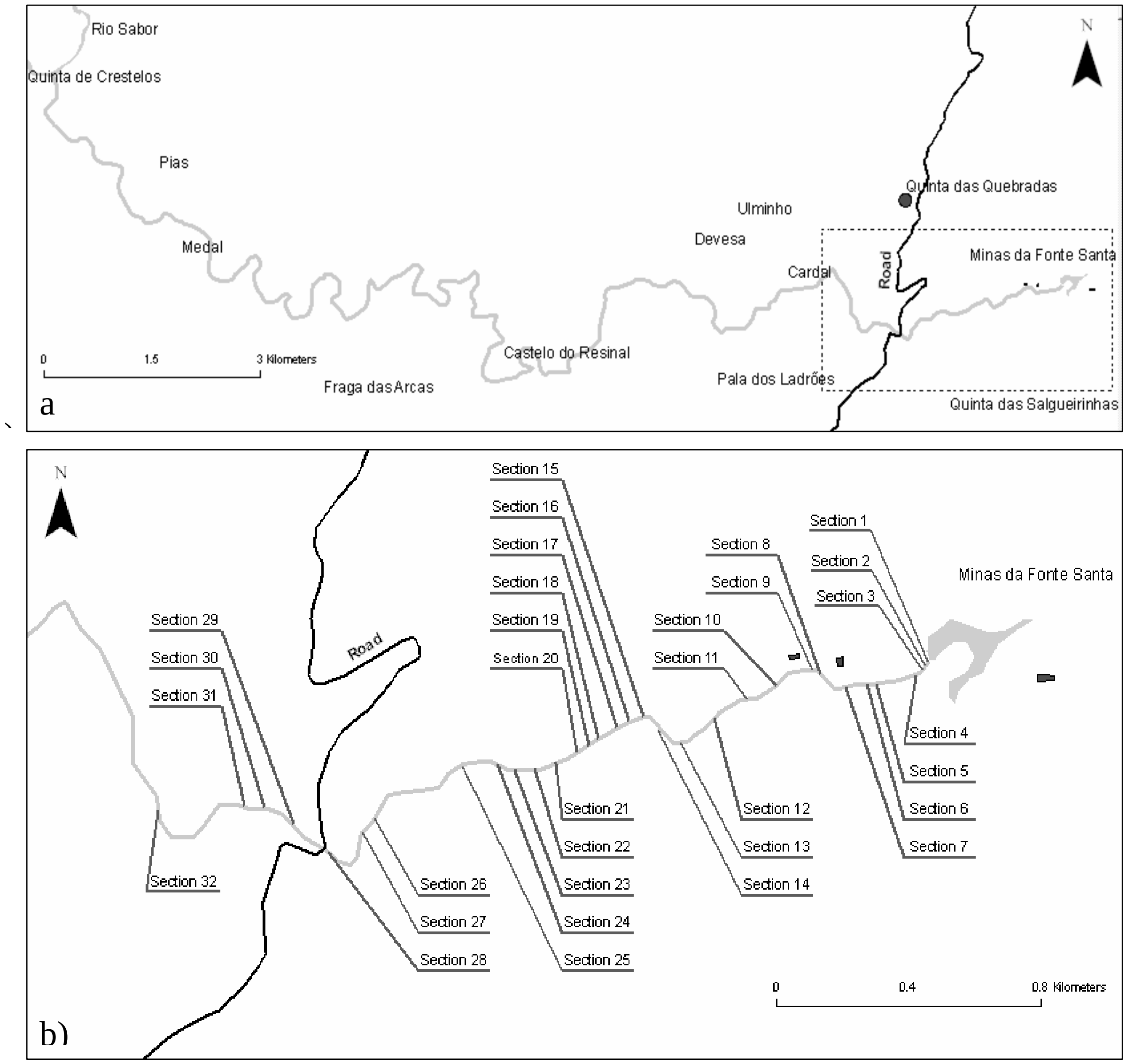

Figure 4. a) The valley of the creek Ribeiro da Ponte, between the dam section and the confluence with Sabor river (a major Portuguese river, one of the main tributaries of Douro river). Adjacent roads and towns are indicated; b) detail of the downstream valley with the sections where a detailed survey of the morphodynamic impact of the dam break event was made.

4 HYDROLOGY OF THE EVENT

4.1 *River basin*

The dam of Fonte Santa creates a river basin of approximately 14,0 km^2 and its main watercourse is the Ribeiro das Caravelas (Fig. 5) which has about 7.9 km and can be qualified as torrential, attending to its longitudinal profile. The concentration time of this brook is about 3h and the basin area soil occupation is characterized by a curve number of 90, considering the most humid antecedent conditions (AMCIII). This parameter was obtained from the CN (AMCII) that was estimated in ARC-GIS with the Soil Hydrologic Characteristics Map that is available on www.snirh.pt.

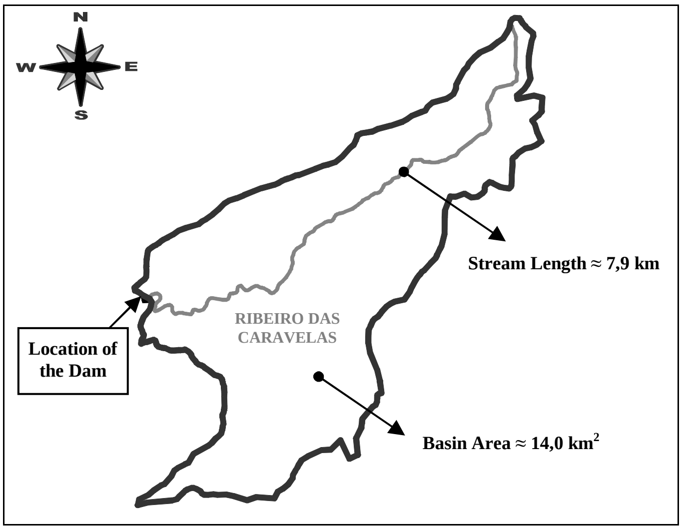

Figure 5 – River basin determined at the section of the Fonte Santa dam.

4.2 *Extreme flood on the day of the event*

On 20th November, 2006 a large low-pressure system was centered in the Atlantic North near Iceland. From the 20th till the 24th of November this system moved towards the west coast of Ireland affecting the Portuguese territory as well. In the area of the Fonte Santa dam basin, a sea level pressure drop of approximately 25 mbar was observed between the days 20th and 24th of November (Fig. 6). After the 24th the system moved away from the Ireland west coast, causing a pressure ascent in all Portuguese territory. The 25 mbar pressure drop observed along those four days on the basin's area was the cause of the extreme precipitation occurred on the 24th of November.

The flood hydrograph presented in Fig. 7 was obtained with HEC-HMS 3.1.0, a software developed by the U.S. Army Corps of Engineers, adequate to simulate precipitation-runoff processes of watersheds systems using, as input data, the above mentioned river basin characteristics and a pre-defined meteorological model. In the present case, observed hyetographs were used. These were measured at a meteorological station located in Mogadouro, a village distancing 12.5 km from Fonte Santa dam. This station was the only located on the interest area with precipitation registers useful in the characterization of the hydrology of the event. The meteorological data was kindly provided by the Portuguese Instituto de Meteorologia I.P..

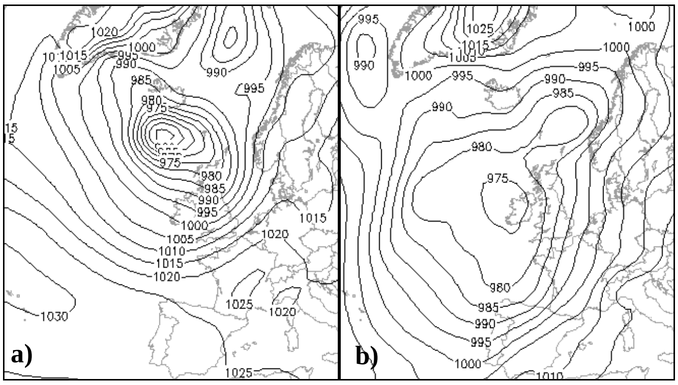

Figure 6 – Low-pressure system formed in the Atlantic North on the days a) 20th of November and b) 24th of November.

According to the meteorological information, between the 23rd and the 25th of November 2006, a total rainfall of about 115 mm occurred on the basin area. 63% of this precipitation took place on the 24th, having the remaining precipitation occurred equally distributed between the 23 and 25th November. The peak flow of the hydrograph (20.4 m^3/s) at the Fonte Santa dam was obtained on the 24th of November at 8:30 am (Fig. 7). The total volume of water inflowing into the reservoir for the three days of rain was of 1 300 m^3.

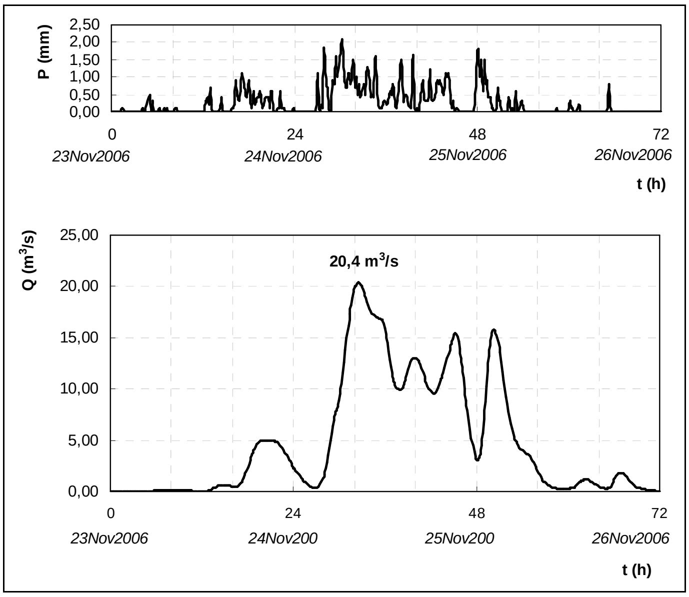

Figure 7 – Reconstructed hydrograph at the section of the Fonte Santa dam and Mogadouro precipitation hyetograph with a acquisition period of 10 min, for the 23, 24 and 25th of November.

5 DAM BREACHING

5.1 *Breaching process*

The understanding of the rupture process and the subsequent evaluation of the outflow hydrograph resulting from a dam failure is of primary importance as it constitutes an internal boundary condition for dam break flood models used for the risk management in valleys (Almeida et al. 2003). Several approaches are possible to estimate the breaching outflow hydrograph: (i) using historical dam failures data and regression approximations (cf. Wahl 2001); (ii) using semi-analytical methods established from the physical laws of breach progress and of reservoir depletion (cf. Singh 1996); and (iii) stochastic models (cf. Kast & Bieberstein 1997). However, uncertainties of about 50% in the estimate of the maximum discharge are still dominant on the results from existent models (CADAM 2000).

In the present case it is not clear how the breaking process occurred. As we may observe from the precipitation data, an extraordinary rainfall event took place in the region in the days 23rd and 24th November 2006. The meteorological information shows us that an 18 hourts of continuous precipitation took place on the 24th of November. However, local accounts confirm the dam breaking event on the 27th November 2006; the description of a loud sound heard at a distance of more than 1 000 m suggests a rather sudden wave travelling the valley. Two situations may have occurred: 1) the dam body may have been overtopped for a period of three days and a sudden destabilization of the body occurred finally on the 27th; 2) the spillway discharged the incoming flood efficiently and eventually got clogged on the 27th which induced the overflowing of the reservoir and consequent overtopping of the dam.

5.2 *Breach geometry*

Knowledge on the breach final configuration provides information for the calibration and validation breaching models (Singh 1996). Wahl (1997) affirmed that the characteristic parameters of the dam breach in embankment dams are the width, the depth the lateral bank slope and the formation time – see the overview by Singh (1996). The breach geometry was inferred in the field by adequate topography instrumentation. Locally we observed that the total volume of what used to be the informal dam body was washed away (80 to 90% of the 4 500 m^3, cf. Fig. 2) contributing to the large gravel accretion verified in the downstream valley. Fonte Santa breach has nearly a trapezoidal shape (Fig. 8). The dam breach reached the valley bottom, thus the erosion depth was about 25 m. Fonte Santa dam breach geometric parameters are presented in Table 1.

Table 1. Breach final geometry.

Top width (m)	35 m
Bottom width	11 m
Height	25 m
Right riverbank slope (angle with the horizontal)	50º
Left riverbank slope (angle with the horizontal)	45º

The presence of fine mud elements within the gravel composing the dam provided enough cohesion to hold such high average lateral slopes of the breach banks; locally the breach walls are nearly vertical. The deposition of the breach material was made along approximately 2500 m of the valley.

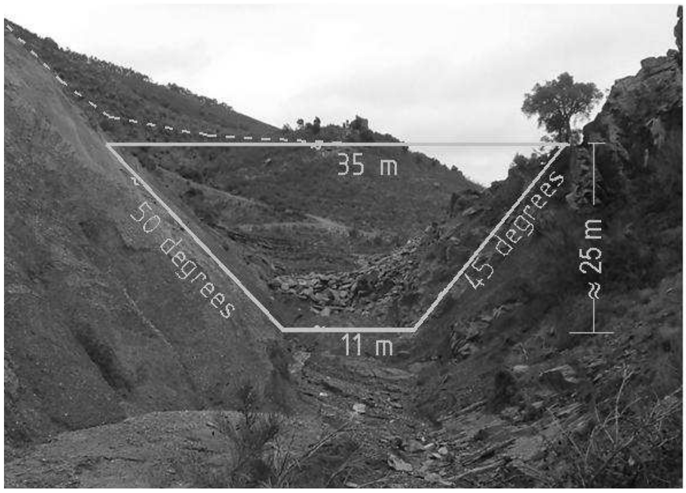

Figure 8. Final configuration of the dam breach. In the figure, a reconstruction of what could be initially the geometry of the dam crest is represented in dashed; the crest was not horizontal. The mud deposited in the reservoir was released leaving a scar visible in the picture. The figure is not scaled and the dimensions are not proportional. In the picture one may see works undertaken by the dam owner to stop the mud and water release.

5.3 *Estimate of the water and mud releases*

By the configuration of the valley and the final breach configuration, we assume that the water released from the reservoir during the dam break was stored above the mud accumulated behind the dam body (≈ 500 m asl). Taking into account the reservoir accumulation curve and the hydrograph in the dam section due to the extreme precipitation verified upon the accident, we estimate that the total amount of water released to the valley was roughly 230 000 m^3. According to Froehlich (1987) the maximum discharge may be estimated from the expression:

$$Q_M = 0.607 V_w^{\;0.295} h_w^{\;1.24} \qquad (1)$$

where V_w = initial water volume above the final breach bottom position (m^3); and h_w = the initial water height above the final breach bottom position (m). With expression (1), we obtain a estimation for the maximum discharge issued from the Fonte Santa breach of 3700 m^3/s, which seems rather an overestimation when regarding the inflow hydrograph and the reservoir volume. Froehlich's formula was empirically deduced using 22 documented dam accidents and it is widely used as a first approach. Subsequently, a breach model, calibrated with field data and the accounts of witnesses, will be used by the authors to simulate the reservoir routing during the event and to estimate a hydrograph resulting from the dam breaching.

During the dam break event the mud deposited immediately upstream the dam lost its stability and was eroded downstream, as it is evidenced by a scar in the reservoir bottom (Figs. 2 and 3). Locally we could infer that a volume of 1600 m^3 was released and disseminated in the valley

6 MORPHODYNAMIC IMPACT ON THE DOWNSTREAM VALLEY

Dam break flood waves have a high erosive potential and are responsible for major geomorphic changes in the downstream valley as was demonstrated in the surveys made by Lapointe et al. (1998) and Alcrudo & Mulet (2005). The documentation of prototype dam break accidents are of extreme importance to test existent models as was made previously in INRS-Eau (1997) and Ferreira et al. (2005), among others.

An extensive field survey, supported by adequate topographic GPS-based surveying methods, was made along the downstream valley. GPS data was collected, in Fast Static Surveying, by a rover unit Leica-GS20. The minimal occupation time for each point was 3 minutes, with time intervals of 5 seconds. For the post-processing we used the Leica GISDataPro with a reference station based in Mirandela (coordinates in WGS84: Lat 41º31´00.41592´´N; Long 07º11´10.19545´´O; Ellipsoidal height 332.019 m; Mean Sea Level height 275.954 m). The reference station belongs to the GPS/GNSS network, managed by the Portuguese Geographic Institute. The results of the post Processing reveal a mean position and height quality of approximately 20 cm.

The detailed survey was realized between the dam position and the last section where morphodynamic changes were visible (erosion or deposition of the riverbed and banks), see Figure 4. The dispersion of the mud released from the reservoir however was observed until the creek outlet at the Sabor river (cf. Fig. 4), though with no significant impact on the river morphology.

On Figure 9, we define the width across the channel where morphodynamic impacts from the passage of the dam break flood are visible, erosion or deposition of material.

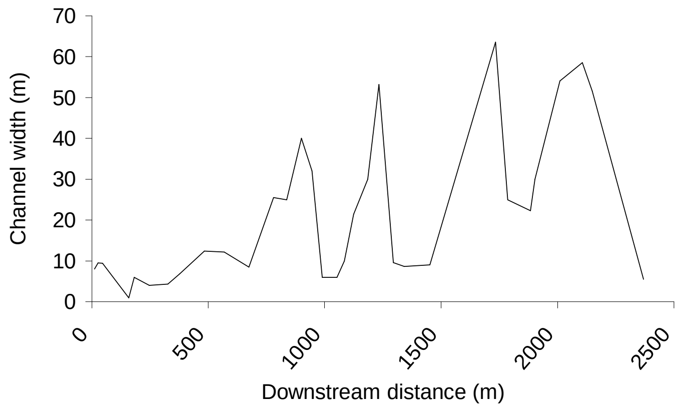

Figure 9 – Lateral extension of the morphological impacts of the flood passage.

When the field visit was made, flood marks corresponding to the maximum water levels occurred during the dam break flood were visible. This allowed the mapping of the flooded areas along the downstream valley. Figure 10 shows the maximum flood levels observed throughout the valley, caused by the dam break flood event.

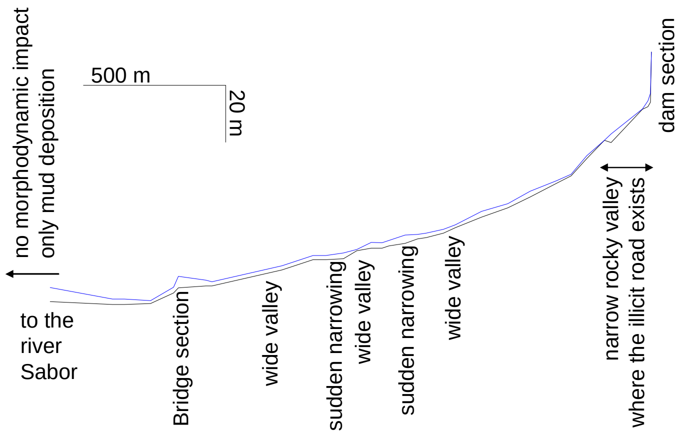

Figure 10 – Valley profile with the maximum flood levels observed in the field.

The maximum water depth verified with the passage of the flood is consequent with the channel geometry (cf. Fig. 9). Just after the dam, in the narrow reach of the valley, the water depths were as high as 5.5 m. Downstream, major elevation of the water depths occurred occasionally before river constrictions and in the bridge section which was overtopped over 0.5 m. Upstream the narrowing sections, the destruction was more evident on the vegetation, riverbed and occasional natural or manmade structures, due to the apparent formation of a hydraulic.

Figure 11 shows the estimates of deposition and erosion volumes on the riverbed, obtained from local assessment.

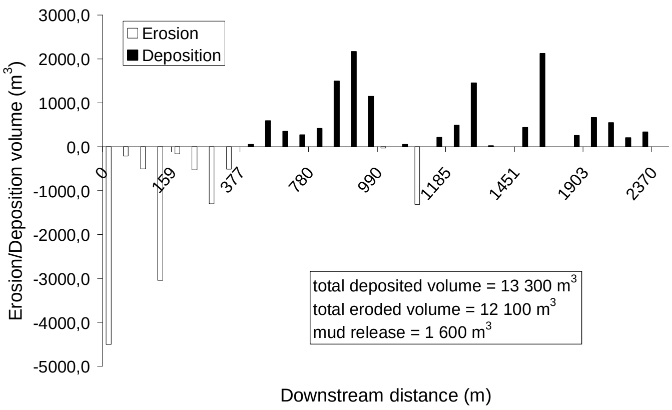

Figure 11 – Profile of the estimated erosion and deposition volumes of the river bed, throughout the downstream valley and based on the field survey.

The erosion peak observed at the upstream section corresponds to the erosion of the dam body (estimated in 4 500 m^3). The main erosion occurs immediately downstream the dam until roughly 380 m after the dam, where the valley was filled with the illicit road referred previously. Actually, for the sake of the morphodynamic impacts analysis, the existence of this structure was positive allowing a good estimation of the erosion power of the passage of the flood.

Downstream, mainly deposition of the dam material is verified due to the immense volume of fine gravel that composed the informal dam body (Fig. 12). Furthermore, part of the deposited material throughout the valley is originated from the gravel road embankment which is made from the same material of the dam body. The deposition occurred essentially in the river sections where the available flow area increased, allowing a reduction in the flow velocity and consequently the erosion capacity of the flow diminished (cf. Figs. 8 and 10).

Figure 12 – Deposition occurred on the riverbed, roughly 500 m downstream the dam section.

Local episodes of bed erosion in narrower sections or due to local singularities in the channel geometry are observed after the section 380 m. Bank erosion (Fig. 13), though not assessed on Figure 11, was observed as well in sudden reductions of the available flow area and where the bank material allowed higher erosion rates.

Figure 13 – Erosion occurred on the riverbank, roughly ??? m downstream the dam section.

The remaining downstream valley, beyond roughly 2 500 m after the dam, does not have important geometry changes; only a fine layer of mud is visible where the flood went through until the confluence with the Sabor river..

7 CONCLUDING REMARKS

As emphasized in the text, this paper constitutes a preliminary report on the dam break accident of the tailing dam belonging to the Fonte Santa mining complex.

The hydrologic extreme event conducting to an extraordinary inflow hydrograph in the reservoir is described. First estimates of the water and mud releases are presented. The maximum flood water depths as well as a calculation of the deposited and eroded volumes throughout the downstream valley are given. The eroded and deposited volumes throughout the area of the valley surveyed by the authors are in equilibrium, indicating that the main morphodynamic impacts produced by the flood wave are contained within this river reach.

The impact of such a flood wave as the one resulting from this event on the geomorphic characteristics of the valley was large. The quantification of this impact is of extreme importance calibration and validation of dam break flood propagation models. The first values herein presented give already useful information to be used by researchers and engineers working on the field. The work in progress on the documentation of this dam break event will produce a detailed report of the breaching process and geomorphic alterations within the downstream valley to be, hopefully, used as a benchmarking case.

At the moment the Fonte Santa dam is being reconstructed by the dam owner in order to sustain the remaining mud in the reservoir and to avoid future disasters and the spreading of the miming mud in the valley.

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REFERENCES

Achterberg, E.P., Braungardt, C., Morley, N.H., Elbaz-Poulichet, F. & Leblanc, M. 1999. Impact of Los Frailes mine spill on riverine, estuarine and coastal waters in southern Spain. *Water Research* 33(16): 3387-3394.

Alcrudo, F. & Mulet, J. 2005. The Tous dam break case study. *Final Technical Report of the IMPACT project, Annex II, Part B WP3: Flood Propagation*, item XIX.

Almeida, A.B., Ramos, C.M., Santos M.A. & Viseu T. 2003. *Dam break flood risk management in Portugal*. Lisbon: Laboratório Nacional de Engenharia Civil.

Babb, A.O. & Mermel. T.W. 1968. *Catalog of Dam Disaster, Failures and Accidents*. Washington DC: Bureau of Reclamation.

CADAM 2000. *CADAM: Concerted Action on Dambreak Modelling*. CADAM Final Report.

Combelles, P. 1979. *Internal report.* Service de la Production Hydraulique – Electricité de France.

Ferreira, R.M.L., Leal, J.G.A.B. & Cardoso, A.H. 2005. Mathematical modelling of themorphodynamic aspects of the 1996 flood in the Ha! Ha! River. *XXXI IAHR Congress* Theme D: 3434-3445. Seoul.

Franca, M.J. & Almeida, A.B. 2004. A Computational Model of Rockfill Dam Breaching Caused by Overtopping (RoDaB). *Journal of Hydraulic Research* 42(2): 197-206.

Froehlich, D.C. 1987. Embankment-Dam Breach Parameters. *Proc. ASCE Conf. Hydr. Eng.*, Williamsburg (Virginia): 570-575

van Geen, A. & Chase, Z. 1998. Recent Mine Spill Adds to Contamination of Southern Spain. *Eos Transactions (AGU)* 79(38): 449-455.

IMPACT 2005. *IMPACT: Investigation of Extreme Flood Processes and Uncertainty*. IMPACT Final Technical Report.

INRS-Eau 1997. *Simulation hydrodynamique et bilan sédimentaire des rivières Chicoutimi et des Ha! Ha! suite aux crues exceptionnelles de julliet 1996 – Rapport INRS-Eau No. R487*. Quebec: Institut National de la Recherche Scientifique.

Johnson, F.A. & Illes, P. 1976. A Classification of Dam Failures. *Water Power and Dam Construction* 28(12): 43-45.

Kast, K. & Bieberstein, A. 1997. Detection and Assessment of Dambreak-Scenarios. In A.B. Almeida & T. Viseu (eds), *Dams and Safety Management at Downstream Valleys*, Rotterdam: A. A. Balkema.

Lapointe, M.F., Secretan, Y., Driscoll, S.N., Bergeron, N. & Leclerc, M. 1998. Response of the Ha! Ha! River to the flood of July 1996 in the Saguenay Region of Quebec: Large-scale avulsion in a glaciated valley. *Water Resources Research* 34(9): 2383-2392.

Lempérière, F. 1993. Dams that have failed by flooding: an analysis of 70 failures. *Water Power & Dam Construction* September/October (5): 19–24

MacDonald, T. C. & J. L. Monopolis 1984. Breaching Characteristics of Dam Failures. *Journal of Hydraulic Engineering* 110 (5): 567-586.

Ponce, V.M. 1982. *Documented cases of earth dam breaches: Civil Eng. Series No. 82149*. San Diego: San Diego State University.

Santos, S. 1995. Dam Break Events – Accidents and Wave Propagatin, In J. Marques & J. Lima (eds), *Hydroelectric Power Plants*, Universidade de Coimbra: Coimbra.

Serafim, J.L. 1981. Safety of Dams Judged from Failures. *Water Power and Dams Construction* December: 32-35.

Serafim, J.L., Coutinho-Rodrigues, J.M. 1989. Statistics of Dams Failures: A Preliminary Report. *Water Power and Dams Construction* 41(4):30-33.

Singh, V.P. 1996. *Dam Breaching Modeling Technology*. Dordrecht: Kluwer Academic Publishers.

Wahl, T. L. 1997. Predicting Embankment Dam Breach Parameters – A Needs Assessment, *Proceedings of Energy and Water: Sustainable Development*, São Francisco,

Wahl, T.L. 2001. The Uncertainty of Embankment Dam Breach Parameter Predictions Based on Dam Failure Case Studies, *Proceedings of USDA/FEMA Workshop on Issues - Resolutions and Research Needs Related to Dam Failure Analysis*. Oklahoma City (Ok).