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Description of the Tous Dam break case study (Spain)
Description du cas test relatif à la rupture de barrage de Tous (Espagne)

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ABSTRACT

A description of the Tous Dam break as a case study for flood model development and validation purposes is presented. The corresponding data set was put together during a joint European project named Investigation of extreMe flood Processes And unCerTainty (IMPACT) with the aim of testing numerical models of flood propagation, including the treatment of urban areas. The case study is based upon the failure of Tous Dam in Spain and the flooding of Sumacárcel, a small town located 5 km downstream. Tous Dam broke due to overtopping on October 20, 1982. This event exemplifies the failure of a major flood control structure with considerable risk for population and damage to properties. The paper describes Tous Dam, the event that led to its breaching, the effects of the flood downstream and the inundation of the town of Sumacárcel. The information provided together with the referenced data set allows for mathematical modelling of the breaching and flooding processes, including the town, and can be used for validation of mathematical models against real-life data.

RÉSUMÉ

Cet article décrit la rupture du barrage de Tous (Espagne) en tant que cas test pour le développement de modèles de propagation de crues et pour leur validation. Les données ont été rassemblées dans le cadre du projet européen IMPACT (Investigation of extreMe flood Processes And unCerTainty) dans le but de tester des modèles numériques de propagation de crues, en y incluant le traitement de zones urbaines. Ce cas test est basé sur la rupture du barrage de Tous et sur l'inondation de Sumacárcel, une petite ville située 5 km à l'aval du barrage. Le barrage de Tous s'est rompu par submersion le 20 octobre 1982. Cet événement constitue un exemple de rupture d'un ouvrage majeur destiné à contrôler les crues, rupture entraînant des risques considérables pour les populations et pour les biens à l'aval. Le barrage de Tous, l'événement conduisant à sa rupture, les effets de l'onde de submersion ainsi que l'inondation de Sumacárcel sont décrits dans le texte. Les informations et données fournies avec ce cas test permettent de tester la modélisation mathématique de la formation de brèche et d'une rupture progressive, ainsi que de propagation des crues. Ces données peuvent donc être utilisées pour la validation de modèles numériques incluant les zones urbanisées à partir d'un cas réel.

Keywords: Dam break; flood; urban flooding; dam breach; real life data; mathematical model validation.

1 Introduction

In order to gain confidence in the forecasts of mathematical models it is needed to confront them with real life data. However these are difficult to obtain because flooding usually takes place unexpectedly and, above all, because during flood events the resources are mobilised to help affected people and mitigate the disaster and not to acquire reliable field data.

The main purpose of this paper and the related data set is the description of the Tous Dam break and subsequent flooding event so that it can be used as a case study for testing and validation of flood propagation and dam breaching mathematical models, including the treatment of urban areas.

Tous Dam is the last flood control structure of the Júcar River basin that covers some 21,600 km^2 of hinterland in the central part of the Mediterranean coast of Spain. The Tous dam catchment corresponds to 17,820 km^2. Meteorological conditions in the area, of Mediterranean character, are prone to extreme rainfall events issued from high solar radiation and proximity to warm sea waters. These characteristics are accentuated in the lower part of the basin, closer to the Mediterranean Sea. Further, two mountain ranges (Sistema Ibérico running NW–SE and Sistema Bético running SW–NE) come together in the area producing a converging channelling effect (Estrela, 1999).

During 20 and 21 October 1982 a particular meteorological condition consisting of a cold, high-altitude depression surrounded by warm air with high moisture content led to extremely heavy rainfall in the hinterland of the central Mediterranean coast of Spain. Average rain intensities over 500 mm in 24 h were recorded in wide areas. As a result the Júcar River basin, directly affected by the rains, suffered flooding all along. Particularly dramatic was the flooding of the downstream part of the basin that is densely populated, with towns such as Alcira or Algemesí and the city of Valencia. Tous Dam is located only several kilometres upstream of the two aforementioned towns and failed on October 20, at about 19 : 00 with devastating effects downstream.

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Table 1 General characteristics of Tous Dam

Crest elevation	98.5 m (MSL)
Water elevation at normal operation	84 m (MSL)
Reservoir capacity at normal operation	52×10^6 m^3
Reservoir capacity at crest elevation	122×10^6 m^3
Spillway elevation (gates closed)	87.5 m (MSL)
Spillway elevation (gates open)	77 m (MSL)

MSL stands for Mean Sea Level.

The old Tous Dam (i.e. the one that failed, since a new, larger dam is presently in operation in the same place and with the same name) was of the rock-fill type, leaning against concrete blocks on both banks. The main data regarding the old Tous Dam and corresponding reservoir are listed in Table 1.

Rain started to fall in the lower Júcar basin during the late night of October 19 and early morning of October 20 but the strongest rain intensity took place during the morning and around noon on October 20 (from 8 : 00 to 14 : 00) with other peaks later in the afternoon.

Total rainfall volume over the basin reached almost 600×10^6 m^3, largely exceeding the capacity of old Tous reservoir (120×10^6 m^3), that bore an estimated peak inflow hydrograph of 9900 m^{3}s^{-1} (see Section 7). As a result, water level in the reservoir rose steadily, soon exceeding the Normal Operation elevation (84 m) of the dam. Early in the morning of October 20 the water started to spill over the gates of the spillway that had remained closed (closed gate elevation 87.5 m) but water level continued to increase. The crest elevation (98.5 m) was reached at about 17 : 30 h the same day and about 15 min later spilling over the crest started, beginning the erosion process. It seems that water elevation in the reservoir never exceeded 99.5 m (MSL) and that by 23 : 30 on October 20 the level in the reservoir had dropped to 81 m.

Dam failure was a progressive process as it usually happens with loose material dams. However it can be said that collapse took place at about 19 : 15 h, when a significant part of the dam fell, including the leftmost gate and rig, and was swept away by the stream. A picture of the remains of Tous Dam can be seen in Fig. 1. The outflow hydrograph is discussed in Section 3.

The effects of the flood downstream of Tous Dam were catastrophic: 300 km^2 of inhabited land, including many towns and villages were severely flooded, affecting some 200,000 people of which 100,000 had to be evacuated, totalling eight casualties.

Figure 1 The remains of Tous Dam after the failure looking upstream (from Estrela, 1999).

The first affected town was Sumacárcel (population 1500), about 5 km downstream of Tous Dam, lying at the toe of a hill on the right bank of Júcar river (see Fig. 2). The terrain is moderately mountainous and most of the buildings lie on a slope what protected them from the flood. The ancient part of the village, however, is located closer to the river course and was completely flooded, with high water marks reaching between 6 and 7 m. A sight of the town before and after the flood is shown in Figs 3 and 4, respectively.

It is worth noting that some of the pictures and graphs shown in this paper are included in electronic format in the joint data set DVD-ROM, together with data files and additional graphical material (see the Appendix). The resolution of the electronic format is much higher than the one shown here providing much more accurate information.

2 Topographic data

The resolution of the available topographic data seems high enough to allow flood modelling. Two sets of data have been retrieved. The first one dates back to a few weeks after the disaster (1982 data) and the other was produced in 1998. Very unfortunately no data prior to the flood have been found, what would have allowed the study of sediment transport. Both sets are now in digital format as Digital Terrain Models (DTMs) that will be

Figure 2 Aerial view of the Júcar River reach from Tous Dam (left) to Sumacárcel (right) about one week after the flood.

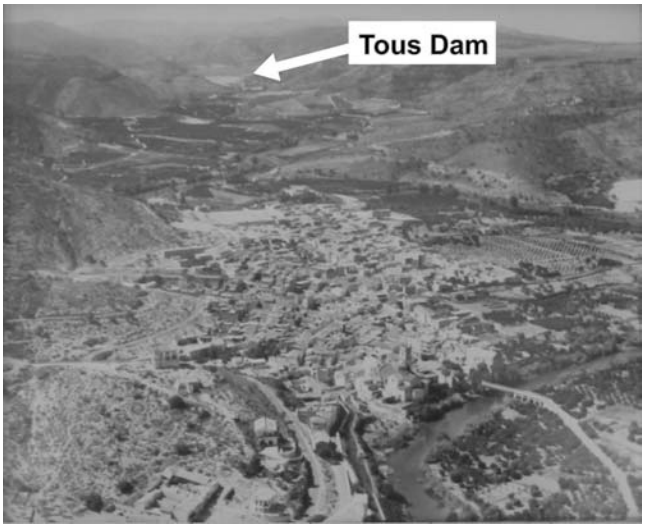

Figure 3 The town of Sumacárcel before the flood, looking upstream.

Figure 4 The town of Sumacárcel after the flood, looking upstream.

referred to as the 1982 DTM and the 1998 DTM in the rest of this paper.

Also a series of aerial cartographic pictures covering the Júcar river reach and Tous reservoir are available in digital format. There are two sets of photographs, one to a scale of 1 : 10000 and the other to a scale of 1 : 25000 taken a few days after the disaster. These were found at *Diputación Provincial de Valencia* (Local Government of Valencia) in the form of plates and were digitised with the highest possible resolution.

2.1 The 1982 DTM

The 1982 DTM has been generated by CESI (Italy) from paper maps at scale 1 : 5000 owned by CEDEX[a] with terrain elevation contours drawn every 1 m. The remains of the dam and evidence of the sediment movement process that took place during the flood can be clearly observed in the map. However sediment transport is very difficult to quantify.

The paper maps were first digitised with high enough resolution so that elevation contours could be easily identified. Then the contours were digitised into an AutoCAD file and from these, the DTM model was generated with a spatial resolution of 5 m.

The data structure of the DTM and other data files is explained in the accompanying DVD-ROM, in a document named `Data_explanation.doc`.

2.2 The 1998 DTM

The 1998 DTM was generated by CEDEX from cartographic data of 1998 with the new Tous Dam (considerably taller and larger than the old one) already built and in operation by that time. The upstream part of the DTM features the new Tous Dam, finished in 1995, that can easily be seen in a plot of the terrain. Also, the 1998 DTM covers a considerably longer reach of the river than the 1982 one. In order to save computational resources for flood modelling, the 1998 DTM can be cut short downstream the town of Sumacárcel at the discretion of the modeller.

2.2.1 Differences between both DTMs

Some remarkable differences can be found between the two DTMs available. They regard mainly the river bed and to a lesser extent the upstream part of the valley where construction works for the new Tous Dam have been performed. The main reason for the differences in river bed is the dredging that took place for conditioning of the reach during construction of the new Tous Dam. Also considerable amount of sediment transport took place during the 1982 flooding that in some places exceeded 2 m of sediment deposition. The 1982 DTM shows this sediment in place. As an example, the river bed at the section by the town of Sumacárcel after the flood was reported to be about 1.25 m above the original bed. Minor differences in bottom elevation might also have arisen because of the different cartographic sources and processing techniques used.

2.3 Buildings and town topographic data

A listing of the buildings present in the area (the town of Sumacárcel and some dispersed buildings in the valley) with their shape and co-ordinates of the vertices including rooftop elevation were provided by CEDEX to the authors. Additional documentation was drawn from the *Catastro Provincial de Valencia* (Land Registry of Valencia). The data were corrected to the time of the flood with the aid of local paper maps and discussions with citizens of Sumacárcel. A precise description of the buildings shape and position is enclosed in the DVD-ROM, in file `Buildings.dat` (see Appendix and `Data_explanation.doc` file). Further two additional DTMs (one for the each of the terrain DTMs) with building coverage were generated with a higher spatial resolution of about 0.5m. They can be found in files `Town_1982.dat` and `Town_1998.dat`. Due to the high resolution provided only the town area is included in these files.

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3 Initial and boundary conditions

3.1 Upstream boundary condition

The upstream boundary condition for use in Flood Propagation modelling is the outflow hydrograph from Tous Dam. This hydrograph is synthetic and has been computed by CEDEX (CEDEX, 1984, 1989a) since no actual discharge records exist. It has been obtained from a consistent blend of observations, measurements at a reduced scale (1 : 50) physical model of Tous Dam and downstream reach, and hydrologic and hydraulic calculations.

The outflow hydrograph can be divided into three parts: the first one goes up to the time when water spills over the dam crest at about 17 : 30 h on October 20. The second one, from 17 : 30 to the early morning of October 21, corresponds to the progressive erosion process. The third part of the hydrograph starts about 02 : 00 October 21 when the remains of the dam no longer present an obstruction to the flow. The discharge was computed differently for each of the three phases.

The hydraulic characteristics of Tous Dam and Reservoir that are needed for some of the calculations are described in Section 7 of this paper (Fig. 22 and the following). A 1 : 50 scale physical model of Tous Dam was set up at CEDEX long before the accident for dam characterization studies, among others to obtain the reservoir rating curve in different configurations of the discharge facilities.

To compute the first part of the hydrograph, water elevation records (Fig. 24) together with the usual reservoir rating curves with closed sluice gates were used. When water started to spill over the dam crest, the reservoir rating curve was supplemented with a broad crested weir equation.

For the second, and most difficult part of the hydrograph (the dam erosion phase) several concurrent strategies were used. Tests were first made with the fixed bed physical model, what led to an initial peak outflow estimate of 17,000 m^3s^{-1} in order to match the river banks high water marks. In a second tests series, the dam physical model was made mobile (only the rock fill was represented) with a prescribed target breach shape and the core was replaced by a plastic fabric that fell freely once the supporting rock fill had been swept. It included a device to manually simulate the collapse of the leftmost gate and its cage at 19 : 15 h. This model was also calibrated against the left and right bank high water marks leading to a corrected estimate of 15,000 m^3s^{-1} for the peak outflow figure. The differences between the first and second peak outflow estimates were assumed to be due to the effect of sediment transport.

The peak outflow figure obtained by the method above was also cross checked with the high water marks measured at three consecutive actual river cross sections 1.3 km downstream of Tous Dam. An iterative procedure based upon the application of the (steady) energy equation to the three selected cross sections yields an average value of the Manning roughness and the corresponding peak discharge. The uncertainty in water level records taken from the river banks leads to a peak outflow interval between 14,000 and 17,000 m^3s^{-1} by this method. The proposed peak discharge of 15,000 m^3s^{-1} obtained by means of the physical and mathematical models falls in between those figures. The details of the calculations can be found in the original reports (CEDEX, 1984, 1989a). The three consecutive river cross sections used in the computations can be seen in Fig. 5.

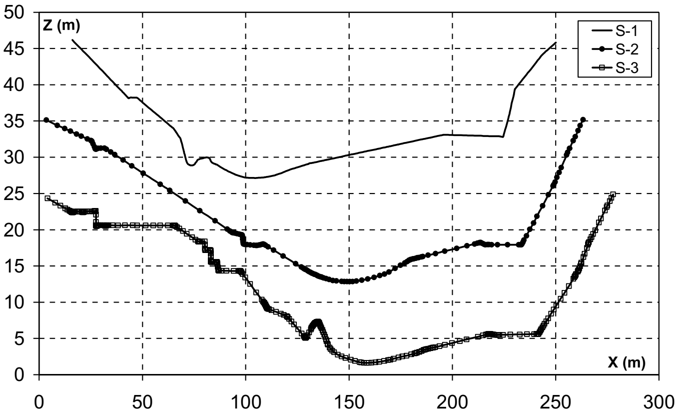

Figure 5 The three consecutive cross sections of Júcar River used for peak outflow estimation. Left of figure corresponds to left bank.

Finally, a simple mathematical model of the dam erosion process was set up. It considered the dam divided into 20 sections and applied a broad crested weir equation for the outflow and a simple relation between the tangential stress and the erosion rate. Breach evolution was manually adjusted to represent the sudden collapse of the leftmost gate and cage at 19 : 15. The reservoir volume-elevation curve and the available inflow hydrograph (Figs 22 and 26) were also needed. The mathematical model was calibrated to match peak outflow figures and the water level in the reservoir at 23 : 30 of October 20 that was reported to be 81 m. The final overall breach size and shape was comparable to the actual one.

The hydrograph curve during the dam failure phase was obtained from the mathematical model. For the third part, when the dam is already destroyed, the outflow hydrograph is assumed to be equal to the inflow one.

The Tous Dam outflow hydrograph thereby produced by CEDEX represents the best approximation available to the actual discharge from Tous Reservoir during the accident. However there is some evidence that its timing could be slightly erroneous: Peak outflow occurs at 20:00 h, with an abrupt rise in discharge between 19:00 and 20:00. However maximum water depths in the town were registered at 19:40 h by a (pendulum) clock that stalled upon arrival of water to the first floor room of a house where the clock was placed. It seems reasonable that peak flooding levels occur after peak outflow discharge and not the opposite.

Hence, the outflow hydrograph proposed for modelling is the one shown in Fig. 6 that has been advanced in time by half an hour with respect to the original CEDEX curve. The numeric data are provided in a Microsoft Excel file named `Outflow.xls` in the accompanying data set.

The area below the curve of Fig. 6 yields 550 × 10^6 m^3 for the total amount of water that passed through the dam during the event.

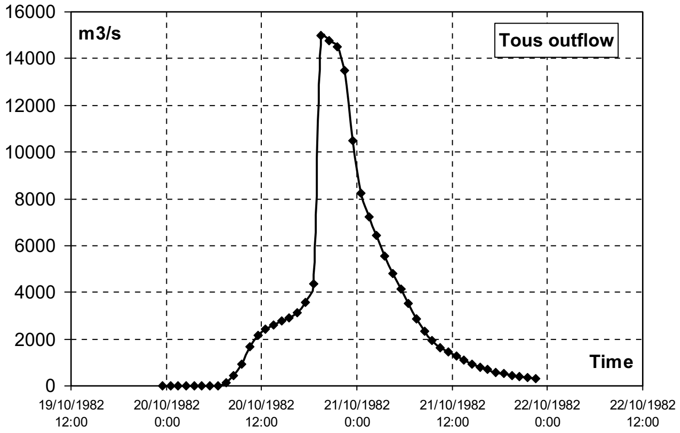

Figure 6 Tous Dam outflow hydrograph.

For flood propagation modelling, the Tous outflow hydrograph should be imposed as an inflow boundary condition at the upstream section of the river reach considered. Since the upstream section of any of the two DTM files includes either the breached old Tous Dam (1982) or the new Tous Dam (1998) several options are left open for modelling: either impose the hydrograph flowing over the dam (in case of the 1998 DTM), or across the breach (in case of the 1982 DTM), or just start the simulations immediately downstream of the dam location.

It should be noticed that in the outflow hydrograph of Fig. 6 nothing happens until about 7 : 00, October 20 (i.e. 25,200 s starting at 0 : 00 October 20). Hence considerable computer effort can be saved by starting the modelling process at 7 : 00 h of October 20.

Also it is worth pointing out that the flood duration is very long (almost 2 days). This fact, combined with the need for adequately resolving the flow in the town area, can lead to very expensive computations. Hence good judgement has to be exercised in order to find a compromise between spatial resolution and computational effort.

3.2 Downstream boundary condition

The river reach considered extends about 1 km downstream the location of Sumacárcel in the 1982 DTM and further in the 1998 DTM. There are no data regarding the flow state at the last section. Simulations show that the main stream is not supercritical, but a free outflow or a critical flow condition, although not exact, have proven successful in the runs performed by the authors and other researchers involved in IMPACT project. It must be borne in mind that the way the boundary conditions are implemented in a particular computational model plays an important role in the outcome of the simulation. In general, the influence of the boundary treatment is more noticeable the closer the downstream section is placed with respect to the region under scrutiny, in this case the town of Sumacárcel. In this respect the 1998 DTM, being longer, leaves more room for the placement of the downstream boundary, but reasonable agreement between simulation and field data have been found with both topographies.

3.3 Initial condition

The initial depth of water in the river reach is unknown prior to the rain events. The normal flow of Júcar River is roughly 50 m^3s^{-1} which is totally negligible in comparison with the scale of Tous outflow hydrograph.

Since Tous Dam spillway gates remained closed until the dam failure, the flow in the river was only due to the river base discharge plus the surface runoff coming from the partial basin covering the reach. The surface runoff until spilling started can be inferred from the fact that an estimated 100 mm rain had fallen until 8 : 00 h of 20 October. An additional 100 mm fell during the rest of October 20 and 21.

Given the huge volume of water represented by Tous outflow hydrograph, calculations can be started with a dry bed as a first approximation.

4 Roughness coefficient

Given the diversity of soils, vegetation coverage and crop fields present in the river reach, it is clear that the friction levels vary substantially all over the area. As a simple approximation a constant base Manning coefficient can be used all over the reach but main features of the flow can be lost. Table 2 shows Manning coefficients used during calibration of mathematical models (one dimensional) of the Tous event by CEDEX. Crop field or vegetation distribution can be found from the aerial pictures of the reach.

Especially important for the flooding of Sumacárcel are the orange tree orchards that surround the town. They had a strong impact on the flood characteristics, particularly in steering the flood into the town by means of the increased flow resistance that dammed water up. After witnesses, the flood was directed towards the river bank opposite to the one where the town lies due to the topography (see aerial pictures). However that bank was covered with very tall orange trees (5–6 m high) that dammed up water leading to a lateral flooding of Sumacárcel.

As a suggestion a base Manning of 0.030 can be used for the whole river reach and then take into account the orange tree orchards as zones of increased Manning coefficient. In particular, two dense orange tree orchards can be remarked from the pictures. These can be described as two four-sided polygons and the coordinates of their vertices are given in Table 3. From the size and density of the trees, the maximum value of the span for

Table 2 Estimated Manning coefficients for different land use (from CEDEX, 1989b)

Soil type	Friction coefficient (Manning)
River bed	0.025 – 0.045
Lined river bed	0.014 – 0.017
Orange tree orchard	0.05 – 0.1
Ricefield	0.02 – 0.025
Vegetable garden	0.025 – 0.04

Table 3 Vertices of the polygons covered by orange trees (authors' estimation)

Vertex points	Zone 1		Zone 2	
	X (m)	Y (m)	X (m)	Y (m)
P1	2025	4040	2430	3250
P2	2500	3500	2730	2810
P3	2675	3800	3030	3120
P4	2130	4200	2770	3725

the Manning roughness should be selected from Table 2, thus yielding a value of $n = 0.100$.

5 Observed data

The data provided in this paper and the accompanying data set DVD-ROM for flood propagation and breach model validation are based upon three sources of information:

1. Official reports issued by the governmental bodies CEDEX and *Confederación Hidrográfica del Júcar* (CHJ, Júcar River Basin Authority).
2. The two series of aerial cartographic pictures taken shortly after the disaster mentioned in Section 2.
3. Field observations and measurements taken by the authors around and in the streets of Sumacárcel with the help of eye witnesses of the flood.

5.1 Official reports accessed

The 1982 flood has been studied extensively by CEDEX and by CHJ. In most studies both organisations worked in close communication because they report to the same Ministry of Public Works. The conclusions are collected in several reports of which those cited in the references under CEDEX (1984, 1989a, 1989b) could be accessed by the authors of this paper.

The first one, CEDEX (1984), provides a thorough description of the event, including recorded measurements and statements of eye witnesses and citizens mostly in populated areas and hot spots (dams, power stations) all around the Júcar river basin. Hydrologic data given were used to determine inflow hydrograph to Tous Reservoir. Hydraulic parameters concerning Júcar River were used to determine Tous Reservoir outflow hydrograph (see Section 3.1). A sequence of events explaining Tous Dam failure can also be found there.

Five years later the second report issued (CEDEX, 1989a) is a revision of the first one refining some figures according to work carried out at the CEDEX hydraulics laboratory in a physical model of Tous Dam, and corrected hydrologic calculations. In this work, assistance was sought from external institutions (Laboratorio Nacional de Engenheria Civil of Portugal and the U.S. Soil Conservation Service) to assess the CEDEX figures and conclusions.

The reports include some data regarding the flooding of Sumacárcel.

5.2 Aerial cartographic pictures

The two series of cartographic pictures mentioned in Section 2, were taken a few days and a couple of weeks after the flood and provide very good resolution of the area. They were located at Diputación General de Valencia and digitised with the highest practicable resolution. They show quite clearly the envelope of water elevation along the banks of the Júcar River reach, except in the urban area of Sumacárcel due to the presence of houses. A. Zuccalá at Centro Elettrotecnico Sperimentale Italiano (CESI, Italy) analysed the plates and prepared an AutoCAD file displaying the shore line envelope during the flood along the river banks. The shore line envelope can be seen in Fig. 2 (with very low resolution in comparison with the digital files provided). The plates themselves provide information concerning sediment transport (deposition) also, but are difficult to work with because of their size (between 100 and 250 Mbyte each).

5.3 Field observations

As regards hydraulic data concerning the flooding of the town of Sumacárcel, and besides the information included in the reports by CEDEX, a field study was carried out. A visit to the town was made by the authors of this paper during 26–29 March 2003 and later on in November. Several eye witnesses of the flood were interviewed, including a member of the local police with whom all the streets flooded were visited and data regarding high water marks and timing of the flood were taken as far as possible. These data were translated onto a paper map of the town. Regarding the issue of timing of the flood, it must be borne in mind that the town was evacuated, hence a very limited set of data could be recorded.

Maximum water elevation marks were recorded at 21 locations within or very close to Sumacárcel. These will be called probes or gauging points in the rest of this paper. In three places a rough evolution of water depth with time could also be estimated. It is important to note that the ground in the town area was fully paved with concrete and the flood did not erode it. Hence there is no concern about topography uncertainties due to sediment movement in the town area. Table 4 lists the position (X, Y) of the selected points in the co-ordinates consistent with those of the topography files, together with the corresponding maximum water depth records. Figure 7 shows the location of the gauging points in a plot of the DTM.

As can be seen from Table 4 some gauges (numbers 5, 9, 15, 17, 18 and 21) show no flooding (zero or near zero maximum water depth). These correspond to locations just barely attained by the waters and represent a sort of shore line of the flood within the town. This can provide a useful test for mathematical model output.

Figure 8 depicts water depth evolution at gauging point number 1 (bridge) according to two different sources. The corresponding river cross section is displayed in Fig. 9. As can be seen from both figures water largely overflowed the river banks flooding the town. According to witnesses and statements quoted in the reports, the town was already flooded before the dam break due to the intense rain and river flow. At about 18 : 00 on October 20

Table 4 Probe locations

Gauge	*X* (m)	*Y* (m)	Estimated maximum water depth (m)	Comments
1	2410	3290	17.5–19	River bed at bridge (rough time evolution available)
2	2400	3335	8.0–9.0	Cinema
3	2355	3315	7.0–8.0	Church street
4	2345	3380	7	Condes de Orgaz St.
5	2335	3175	0.2	Júcar Street
6	2335	3420	5.0–6.0	Proyecto C Street
7	2330	3365	6	Old city hall (rough time evolution available)
8	2315	3450	5	Pendulum Clock house (rough time evolution available)
9	2310	3590	0	Era Square
10	2303	3255	4	Júcar Street
11	2285	3425	2	Stairs Street
12	2285	3500	5.0–6.0	Condes de Orgaz St.
13	2280	3280	2.5–3.0	Valencia Street
14	2266	3550	2	Pintor Sorolla Street
15	2265	3400	0	Valencia Street
16	2259	3530	3.0–4.0	Pintor Sorolla Street
17	2250	3440	0	Pallecer Street
18	2230	3525	0	Severo Ochoa Street
19	2205	3445	2.0–3.0	Virgen Street
20	2195	3440	2	Virgen Street
21	2190	3485	0	West Avenue

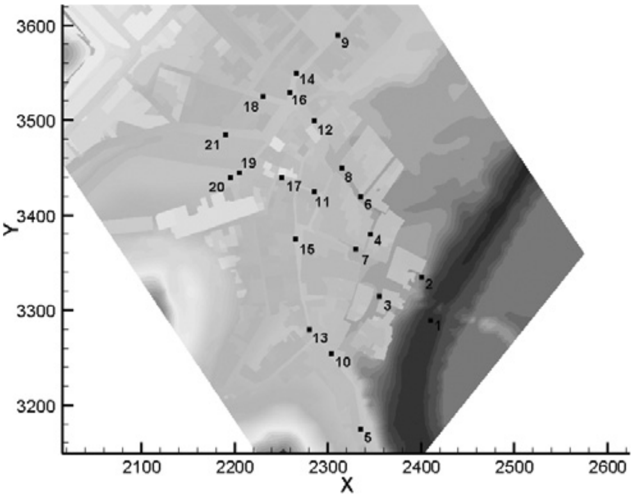

Figure 7 Probe locations in the streets of Sumacárcel.

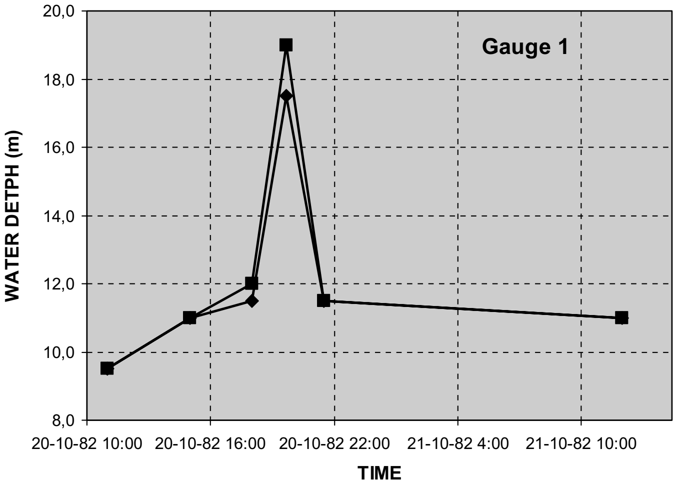

Figure 8 Estimation of water depth evolution at Gauge 1 (riverbed at the bridge).

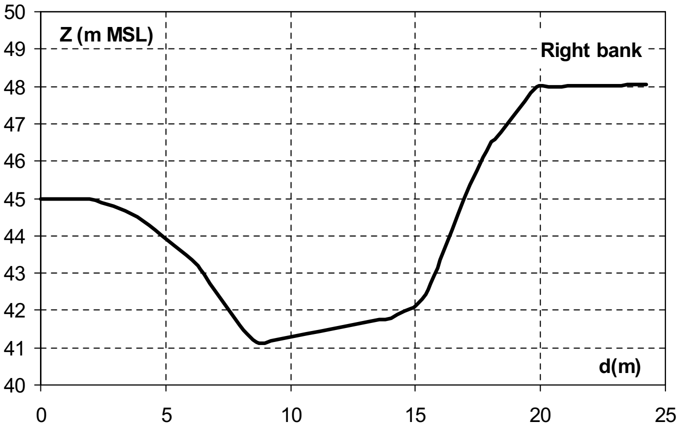

Figure 9 River cross section at Gauge 1 (bridge). November 1982 data.

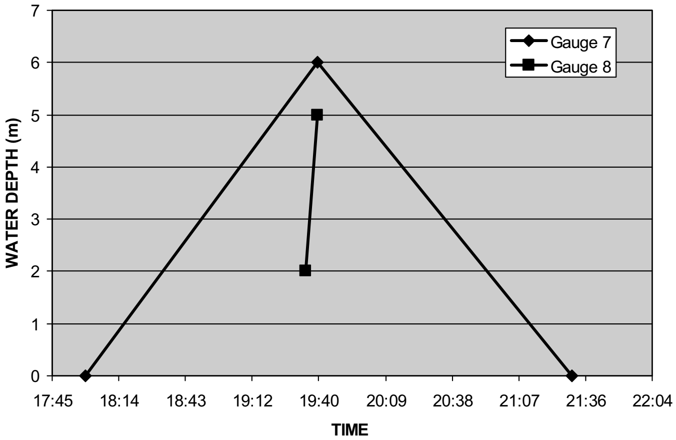

Figure 10 Estimated water depth evolution at Gauges 7 and 8.

water reached the old city hall (Gauge 7) and the town was evacuated. Somewhere after 19 : 30 the flood wave caused by Tous Dam failure arrived at the town but no one stayed there to watch it. It seems that water rose very quickly but no front or surge formed. Animations obtained from the numerical simulations do not show a wave front either, but rather a quick rise of water level. Because of the topography, the town itself was flooded laterally from the river bank inland and hence the velocity of the main stream was tangential to the town limits.

Figure 10 shows estimated water depth evolution at gauges 7 and 8 according to a single source (local police officer).

The following series of pictures (Figs 11–18) helps giving an impression of the places where the gauges are located and the corresponding maximum water elevation attained during the flood.

Figure 11 Present day view of Gauge 1 location (riverbed at the bridge) looking upstream.

Figure 12 A view of Sumacárcel main square from its access across the bridge.

Figure 13 Probe 3. The man behind the car marks 2 m elevation above the ground.

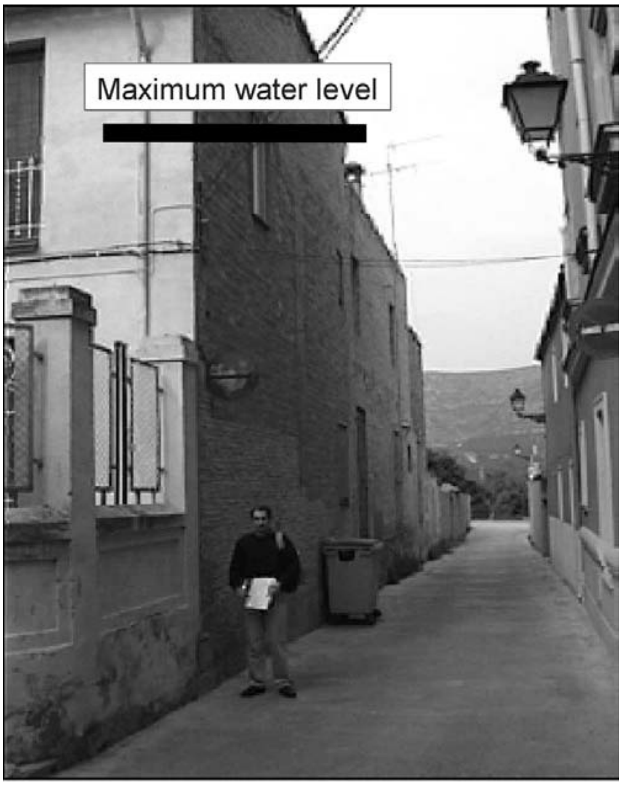

Figure 14 Probe 6.

Figure 15 Probe 7.

Figure 16 View of the location of Probe 8.

Figure 17 Probe 10. The man marks 2 m elevation above the ground.

Figure 18 Probe 16.

6 Description of Tous Dam

This section describes old Tous Dam in greater detail for the purposes of breach modelling. The information regarding the old Tous Dam and its construction materials included here has been obtained from the excellent monograph by the Jucar River Basin Authority engineer Utrillas, *La Presa de Tous* (Utrillas, 2000), the cited CEDEX reports and some private conversations with engineers at CEDEX. Although the book by Utrillas is mainly devoted to the New Tous Dam, the project, construction and failure of Old Tous Dam is also reviewed. The first works to build a dam in Tous started in October 1958, with the idea to build a concrete dam about 80 m high above the river bed. During construction, geological conditions of the foundation terrain forced to interrupt the works in December 1964, after identification of two faults that delimit the river bed. The works were resumed in April 1974, resorting to a rock-fill dam with clay core between the concrete blocks previously built at both sides of the river bed. The project consisted of two phases of which only the first one, with a dam crest elevation to 98.5 m was completed. The second phase that would have brought the crest of the dam to 142 m was never started.

The old Tous Dam was of the rock-fill type, which is generally made up of three parts. From the inside out these are: The impervious core, the drainage layers and the rock-fill itself. The impervious core, usually made of clay, prevents seepage through the dam. The drainage layers, or filters, ensure that core material does not migrate by the effect of seepage forces. Finally the rock-fill protects the core from erosion and provides stability to the dam.

Figure 19 shows a sketch of a standard cross section of the old Tous Dam where the three parts in which it is divided are very clear: the clay core, the filters around the core and finally the rock-fill body that surrounds the other two zones. The slope in the upstream side of the core is uniform (1 : 5), but it changes in the downstream side at the elevation of 64 m (1 : 5 to 1 : 1). The crest level of the first phase was set at 98.5 m with a Normal Reservoir Operation level at 84 m. The berms in the downstream face of the dam are situated at two different elevations, 64.00 and 90.50 m.

A top view of the old Tous Dam can be seen in the Fig. 20. The surrounding terrain, the concrete blocks in both sides of the dam, the spillway, the berms and some important elevations are

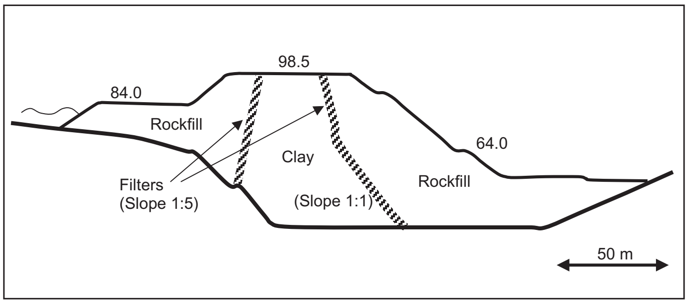

Figure 19 Tous Dam cross section. Vertical and horizontal scales are equal.

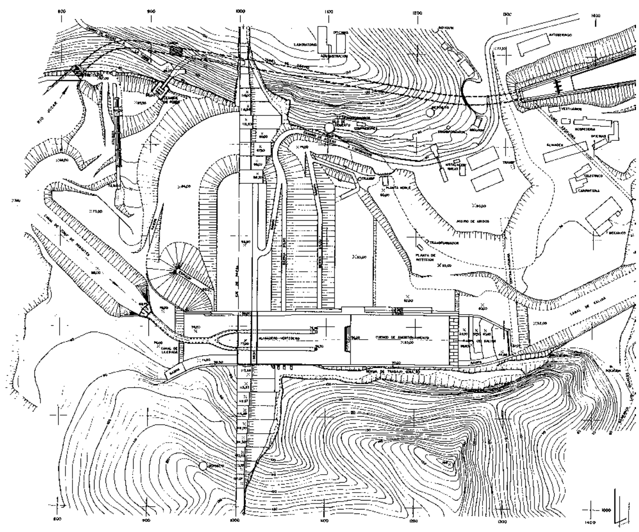

Figure 20 Tous Dam top view.

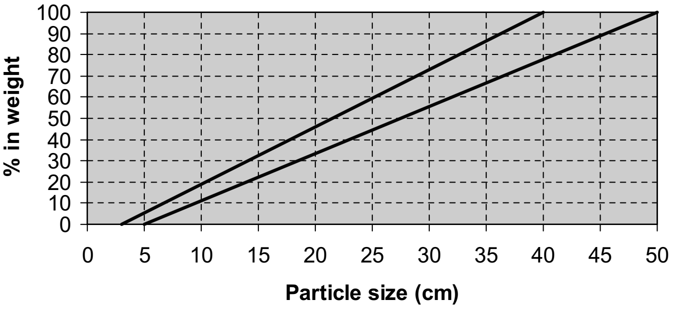

Figure 21 Rock-fill estimated size distribution during construction of old Tous dam.

indicated in this view that supplement the information on Tous Dam provided in Table 1. Figure 20 is reproduced in the joint DVD-ROM with very high resolution.

The materials used in the different zones of the dam are defined by means of their size distribution and other physical properties. The following sections describe the main characteristics of the rock-fill, the clay and the filters respectively.

6.1 Rock-fill

It can be assumed as a good approximation that the actual grading of the rock-fill of Tous Dam followed a uniform distribution between a particle size of 3–5 cm and a particle size of 40–50 cm. Figure 21 shows a plot of the two estimated boundaries of the rock-fill grading. It is supposed that the actual grading of the rock-fill falls between the two lines.

The estimated values for the specific weight, γ, and the friction angle, ϕ, of the rock-fill are:

$$\gamma(\mathrm{kN\,m^{-3}}) = 26.5$$

$$\phi(^\circ) = 30 - 40$$

The value for the friction angle given is the standard value for gravels with similar characteristics.

6.2 Clay core

The physical characteristics for the clay used in the old Tous dam core are described in terms of a hyperbolic model with the following properties:

Young Modulus number K = 400
Young Modulus number exponent $n = 0.8$
Poisson's ratio = 0.45
Cohesion c ($\mathrm{MPa\,m^{-2}}$) = 0.2
Friction angle ϕ (°) = 10
Failure ratio = 0.8
Lateral earth pressure coefficient at rest $K_o = 1$

Table 5 gives actual characteristics of the clay extracted from the quarry that was used for construction of both the old and new Tous Dam core.

Besides the grading, the clay plasticity must be defined. The liquid limit, the plastic limit and the plasticity index are detailed in Table 6.

Table 5 Actual clay characteristics

Percentage in weight	Grading (ASTM standard sieve)			
	1″ (25.4 mm)	N° 4 (4.75 mm)	N° 200 (0.075 mm)	$<5\mu$
Average	90.0	84.2	66.3	35.1
Standard deviation	7.4	9.3	11.4	9.8
Maximum	100.0	100.0	97.0	59.0
Minimum	51.7	33.9	15.0	3.0

Table 6 Clay plasticity

	Plasticity		
	Liquid limit	Plastic limit	Plasticity index
Average	29.5	13.5	16.1
Standard deviation	4.0	1.3	3.4
Maximum	50.7	19.6	31.3
Minimum	18.8	11.1	4.5

Table 7 Clay moisture content

	Natural moisture content (%)
Average	9.7
Standard deviation	1.7
Maximum	13.4
Minimum	4.7

Table 7 lists the available data on the natural moisture content of the clay obtained from the quarry used for construction of the core of the old Tous Dam.

Finally, the lower limit for the dry unit weight of the clay is set as: $\gamma_{\mathrm{dry}} = 17\mathrm{kN\,m^{-3}}$.

6.3 Filters

There are no data regarding the filter materials employed in the old Tous Dam, hence only the filter materials used in the new Tous Dam are quoted here as a reference. Actually, this hypothesis is not too relevant for dam breach modelling because the filter volume is very small in comparison with the core or the rock-fill.

The materials used in the filters of the new Tous Dam are divided into two types depending on the grading. The available data for the grading of both materials in the filters of the new Tous Dam according to Utrillas (2000) are described in Table 8.

The filters are situated in the inner part of the filter zone near the clay core whereas the drains are situated in the outer part of the filter zone, in transition to the rock-fill zone.

The physical properties of the filter material are detailed below:

$$\gamma_{\mathrm{dry}}(\mathrm{kN\,m^{-3}}) = 16.7$$

$$\gamma_{\mathrm{wet}}(\mathrm{kN\,m^{-3}}) = 21.0$$

$$\phi(^\circ) = 35$$

Table 8 Filter and drain size distribution

Sieve (ASTM standard)	Filter (% in weight)	Drain (% in weight)
3″	—	100
3/4”	—	60–100
N° 4	100	10–40
N° 10	70–100	0–17
N° 20	30–65	0–10
N° 40	15–35	—
N° 100	0–15	—
N° 200	0–5	0–5

where γ_{dry} and γ_{wet} stand for the specific gravity of the dry and water saturated filter material as sampled during construction. Correspondingly for the drain material:

$$\gamma_{\text{dry}}(\text{kN m}^{-3}) = 18.3$$

$$\gamma_{\text{wet}}(\text{kN m}^{-3}) = 21.5$$

$$\phi(°) = 35$$

Finally, the modulus of elasticity and the Poisson’s ratio for both materials can be taken as:

Modulus of elasticity (MPa) = 80
Poisson’s ratio = 0.3

7 Hydraulic characteristics of Tous Dam and Reservoir

This section describes some of the hydraulic characteristics of Tous Dam and Tous Reservoir (elevation-capacity curve, rating curves etc.) that may be needed for breach modelling of the failure. They have been obtained from the referenced CEDEX reports. Figure 22 shows the reservoir volume as a function of water level or elevation-capacity curve.

Figure 23 is a plot of the Tous Dam rating curve with sluice gates closed as they were in fact during the failure. It is to be remarked that as far as the water level does not overtop the crest (98.5 m), water flows only through the spillway over the closed gates. Once water level rises above the dam crest (98.5 m), water spills over the entire crest length, as well as across the spillway, between its upper bridge and the gates, hence acting now as a submerged structure. These data were obtained at CEDEX in a reduced scale model of the dam.

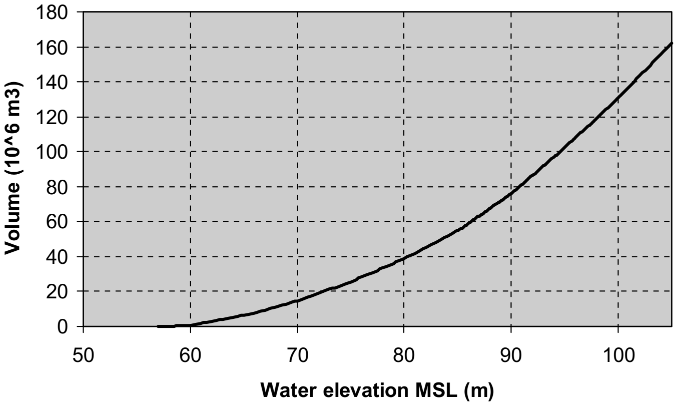

Figure 22 Water volume—Elevation curve for Tous Reservoir.

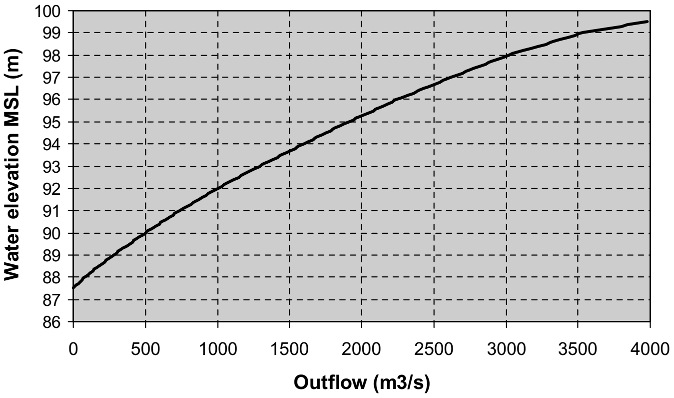

Figure 23 Reservoir rating curve with closed sluice gates (from CEDEX, 1984).

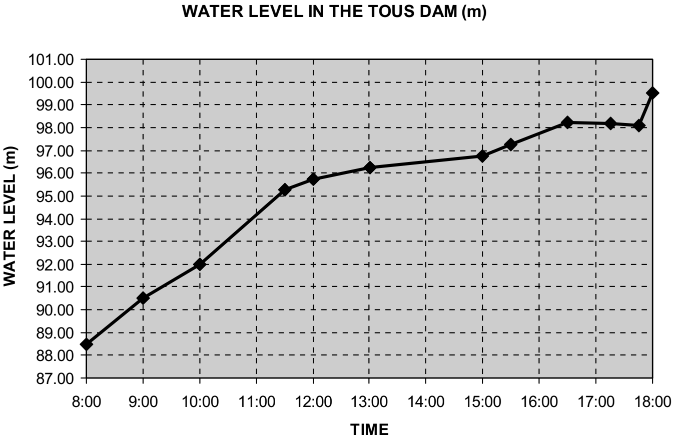

Figure 24 Water level recorded in Tous Dam during the event (from CEDEX, 1989a).

Figure 24 shows recorded water level in Tous reservoir until the dam failed by overtopping. As it has been mentioned before it appears that water elevation never exceeded 99.5 m (MSL). There is also evidence that the water elevation in the reservoir had dropped to 81 m at 23 : 30, October 20.

If a refined simulation of the two-dimensional lake flow is considered for breach modelling it may be interesting to know the hydrograph of the Escalona River into Tous reservoir. The Escalona River flows into the reservoir just upstream Tous Dam. The junction of the Escalona River can be seen in Fig. 25.

Figure 26 shows total inflow hydrograph into Tous Reservoir as estimated by CEDEX using hydrologic methods. It comprises both the inflow coming across the upstream section of Tous Reservoir plus the contribution at the Escalona River junction.

In order to accurately model the flow in the lake it would be advisable to subtract the Escalona outflow hydrograph from the Tous inflow hydrograph, and then use both inflow hydrographs entering the reservoir at the appropriate locations: the Escalona outflow hydrograph should be imposed at the junction

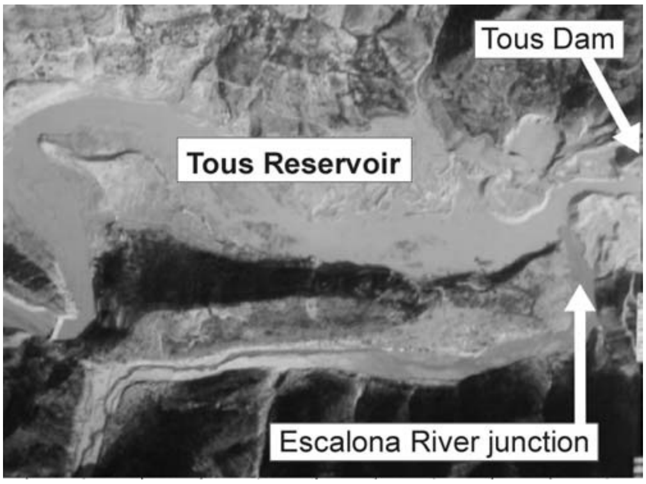

Figure 25 Location of the Escalona River junction.

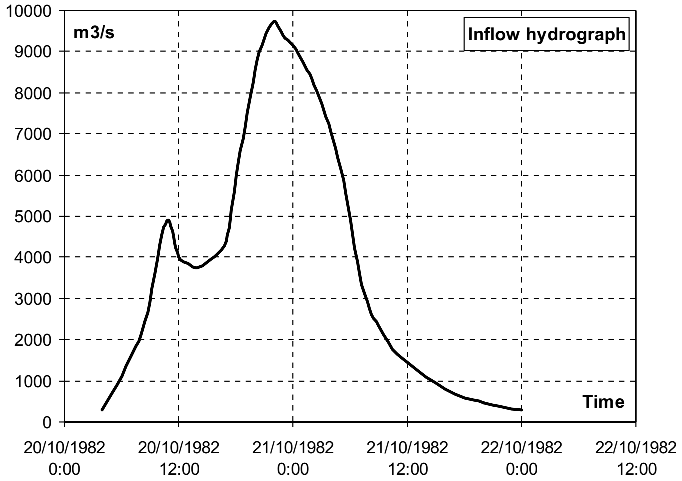

Figure 26 Estimated inflow hydrograph into Tous Reservoir during the flood (CEDEX, 1989a).

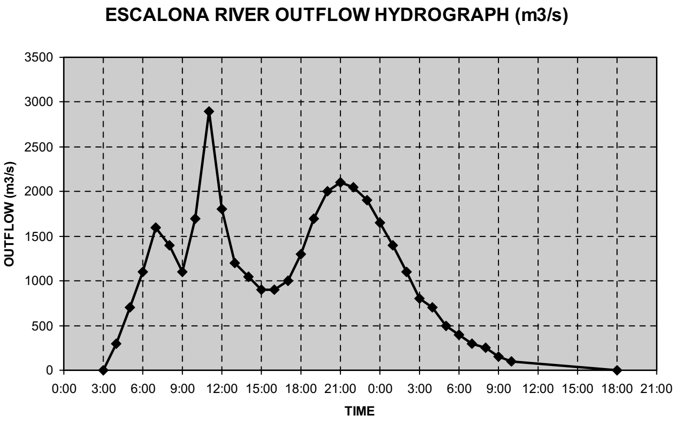

Figure 27 Escalona River outflow hydrograph.

of the Escalona river with Tous Reservoir, and the modified (subtracted) Tous inflow hydrograph should be imposed at the tail or upstream section of Tous Reservoir. The corresponding outflow hydrograph from the Escalona River into Tous Reservoir can be seen in Fig. 27.

8 Conclusions

This paper describes the Tous Dam break and the subsequent flooding of the town of Sumacárcel for flood and breach model validation purposes. The main value of the paper lies in that it describes a real life event and provides field data. The amount of information included is not outstanding but nevertheless it enables validation of dam breaching and flood propagation models separately or linked together. The output produced by breach models can be compared with the outflow hydrograph provided in Section 3 or fed directly into a flood propagation model and then compare its output with recorded flood levels in the river banks and the town.

The lack of a sufficiently accurate topography of the area prior to the dam break is a drawback for flood propagation modelling. In order to evaluate the uncertainties associated with the terrain description, two different topographies produced 16 years apart are provided. Running a flood propagation model on both and cross checking the predictions can give an idea of the errors incurred when the topography is not exactly known.

This set of data has been used by different modelling teams within IMPACT project for model validation and uncertainty estimation and it proved useful for the task. Some of the work performed can be accessed at the project website (IMPACT, 2004).

Acknowledgements

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Appendix: List of files available in the data set DVD-ROM for flood and breach modelling

`Data_explanation.doc:` Explanation of the accompanying files and their data structure, in particular DTM and building files.

`DTM_1982.dat:` The 1982 DTM topography (just after the event) prepared by the CESI team, with the format explained in file Data_explanation.doc.

`DTM_1998.dat:` This file is the 1998 DTM as explained in the text.

`Buildings.dat:` This file is a listing of the buildings, represented as polygons. The vertices of the polygons and the rooftop elevation are listed as explained in file Data_explanation.doc.

`Town_1982.dat:` This is a fine mesh covering the town with the buildings placed on top of the terrain represented by the 1982 DTM (for this, use has been made of Buildings.dat and DTM_1982.dat files)

`Town_1998.dat:` This is a fine mesh covering the town with the buildings placed on top of the terrain represented by the 1998 DTM (for this, use has been made of Buildings.dat and DTM_1998.dat files)

`Tous_water_levels.dwg:` AutoCAD file showing the envelope of the shoreline during the event on top of a series of aerial pictures covering the river reach. The picture files are listed below.

`1131_tagliata_ridotta.tif`
`1132_tagliata_ridotta.tif`
`1134_tagliata_ridotta.tif`
`1136_tagliata_ridotta.tif`

Important Notice: The five files listed above MUST be placed in the same directory in order that the AutoCAD program can find and display them appropriately. Furthermore their names MUST NOT be changed.

`Outflow.xls:` Numerical values of Tous Dam outflow hydrograph.

`Inflow.xls:` Numerical values of Tous Reservoir global inflow hydrograph.

`Escalona_outflow.xls:` Numerical values of Escalona river outflow into Tous Reservoir.

`Volume.xls:` Numerical values for the elevation-volume curve of Tous Reservoir (Fig. 22).

`Rating_curve.xls:` Numerical values for the Tous Reservoir rating curve with closed sluice gates (Fig. 23).

`Tous_levels.xls:` Water elevation recorded in Tous Reservoir prior to the dam break (Fig. 24).

`Tous_Dam_plan.gif:` High resolution plan view of Tous Dam (Fig. 20).

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