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Investigation of extreMe flood Processes And unCerTainty – IMPACT

IMPACT is a major three-year European research project looking at the failure of flood defence embankments and embankment dams co-ordinated by IAHR Corporate Member HR Wallingford. More information on page 29

Breaching a 6m high embankment in Norway (Oct. 2002)

IMPORTANT NOTE:

The NOVATECH 2004 abstracts submission deadline (see leaflet within this mailing) has been extended to April 28th, 2003 for IAHR Members, instead of March 28th, 2003 as indicated in the leaflet.

Roman aqueducts

Dr. P.-L. Viollet and Dr. H. Chanson review the history of aqueducts in the section 'Chronicles on the history of hydraulics' on page 26

Arches of the Anio Novus aqueduct, in its upstream course, between Tivoli and Subiaco (photo: P.L. Viollet)

Keep up-to-date with the latest Congress news. Continues on page 21

International Journal of River Basin Management JRBM

A new Journal, JRBM - the International Journal of River Basin Management - will be launched at the Third World Water Forum in 2003 with a specific role to provide a forum for the scientific community to adopt a more cross-sectoral approach to research and practice in river basin management. The new Journal will be published by IAHR in collaboration with other leading international associations. See page 20 for further information on this new Journal.

Chronicles on the History of Hydraulics

Are YOU interested in the history of hydraulics? Is there any study or report in this area that YOU would like to publish in our new newsletter section 'Chronicles on the history of hydraulics'? Please don't hesitate to contact Dr. Pierre-Louis Viollet at: pierre-louis.viollet@edf.fr

Aqueducts : a short history

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What is an aqueduct? It can be defined as "an artificial channel or conduit aimed at delivering water to human settlements for domestic or industrial purposes". This definition excludes irrigation and navigation canals, and implies that water is delivered with a sufficient head for feeding a distribution network or producing energy.

In the birthplaces of the oldest civilisations, ancient Egypt and the fertile plain of lower Mesopotamia, the building of aqueducts was not possible because no water resources were available in that altitude. The oldest aqueducts are located in the eastern Mediterranean area where springs or streams are found in mountains or hills above the cities. By 2000 BC The palace of Cnossos in Crete had a water distribution system, and there were also terracotta or wood aqueducts in Mycenaean Greece (1600 – 1200 BC), for instance in the palace of Pylos (see Chronicle n°2 in Newsletter 6, 2002). In classical Greece (VIth to IVth centuries BC), terracotta aqueducts used to follow the level of the ground, in which there were buried, in order to protect them against accidental damages and to hide them from the eyes of enemies: they were made with elements 60 cm to 1 m long, and 11 to 22 cm inside diameter. By 530 BC on the island of Samos, a 1200 m long tunnel had been drilled in order to allow such a terracotta aqueduct to pass through a mountain and to reach the city; this tunnel is said to have been drilled by a man from Megara called Eupalinos, and was considered by the Greek historian Herodotes as one of the three most impressive civil engineering works of Greece.

All these old aqueducts used gravity flow only, following the ground level with a gentle slope. By the IIIrd century BC, the effect of pressure in fluids became better known, thanks to the works of a number of philosophers and mathematicians orbiting around the famous Alexandria Library and Museum -the most illustrious one being Archimedes (287 – 212 BC) who lived in Syracusa but had visited Alexandria and used to correspond with the mathematician Erathostenes of Cyrene, director of the Alexandria Library. By that time, pressure conduits made of stone-carved elements began to be used, allowing aqueducts to descend a valley and rise a hill using the principle of the so-called "siphon". This technique was not developed in Greece but in Hellenistic Anatolia (modern Turkey). In Pergamon, the astounding Mandradag aqueduct was probably built under king Eumenes II (197 – 159 BC). It consisted of a 40 km upstream section with 3 parallel terracotta pipes, followed by a siphon made of a single lead pipe. The siphon started from a cistern facing the Pergamon acropolis (fed by the aqueduct's upstream section), went down in a valley to an altitude 200 m lower than the reservoir, and then up 175 m to the Pergamon acropolis. The outside diameter of this pipe was 30 cm, (probably 20 cm inside), and it was about 3 km long.

It was around that time that the Romans came along -the most famous aqueduct builders of all times- and in the article on page 27, Dr. H. Chanson discusses some aspects of their hydrology.

The Romans used tunnels, bridges, cascades, arches, and siphons -all techniques allowing to cross hills and valleys. Rather than terracotta, they used masonry channels with more or less rectangular shapes allowing larger cross-sections and thus higher flow rates than older aqueducts. The first aqueduct of the city of Rome, *Aqua Appia*, was built by 312 BC, and was mostly a subterranean simple channel. Between 312 BC and 226 AC, 11 aqueducts were built for the city of Rome, the longest ones being about 90 km long: *Aqua Marcia* (144 BC), the first one to use a siphon allowing water to pass from Caelius to Aventin hills inside Rome, and *Aqua Anio Novus* (52 AC), issuing from a dam on the river Anio. The amount of water supplied to Roman cities reached a peak: 1 cubic meter per day and per person for the city of Rome.

The Romans built aqueducts all around their empire. The longest ones are the aqueducts of Apamea (Syria, 116 AC), 150 km long, and of Carthage (Tunisia, 162 AC), 118 km long in its longest branch, and with wonderful arches in the valley of Oued Milliane. In Europe, the longest aqueducts outside Rome are found in Koln, 98 km long, and Lyon with the aqueducts of Gier and Brevenne which are more than 70 km long. The most impressive roman bridges are in Nîmes (see the photo by Chanson in the following article), Segovia and Tarragona. The highest and most sophisticated siphons are probably those of the 4 roman aqueducts of Lyon: the Gier aqueducts had four siphons which were between 575 m and 2660 m long, and between 30 m and 114 m high. Each siphon consisted of an upstream and a downstream reservoir at each side of the valley, and about 10 parallel lead pipes (outside diameter between 20-25 cm) descending down the valley, crossing the river on a low bridge, and climbing back up the slope to the downstream reservoir. Some of these reservoirs can still be seen, including some of the holes from where the lead pipes departed (see picture).

When the Roman empire collapsed in the West, the aqueducts slowly deteriorated, through lack of maintenance (see the table in the following article by Chanson); only in Rome, the Popes used to maintain some of the aqueducts for the needs of waterwheels. In the Western middle ages, people in cities returned to the rivers for their domestic needs, and many hygiene problems followed. In the Arabic world, the Roman idea of water in the city remained: for instance Samarkand kept its aqueduct systems operating until the city was attacked by the Mongols in 1219. Furthermore, in the XIIth century, Fes (Morocco) is known to have had conduits delivering pure water to all houses of the al-Qarawwiyyin town area, as reported by the medieval geographer al-Idrissi.

Bibliography.

ARGYROPOULOS P. A., "Ancient Greek hydraulic engineering experience and technique", IAHR Congress, Cagliari, Sept 1979
CHANSON, H., "Hydraulics of Roman aqueducts : steep chutes, cascades and dropshafts", *American Journal of Archeology,* 104, p 47-72, 2000
GARBRECHT, G. H., "Die Entwicklung der Wasserwirtschaft Pergamons bis zur Romischen Kaiserzeit", *Journées d'Etude sur les Aqueducs Romains,* Les Belles Lettres, 1983
HODGE, A.T., *Roman aqueducts and water supply,* Duckworth, 1995
VIOLLET, P.L., *L'Hydraulique dans les civilisations anciennes,* Presses des Ponts et Chaussées, 2000

The upstream reservoir of a siphon of the Gier aqueduct: of the ten holes from where the lead pipes departed, four can be seen on this picture. The white arrows show the direction of the flow (photo P.L. Viollet).

Roman aqueducts: hydrology Vs. hydraulics !?

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Roman aqueducts supplied water to cities for public baths and toilets in addition to public fountains (HODGE 1992, FABRE et al. 2000). They were long subterranean conduits, following contour lines (Fig. 1 & 2). Numerous aqueducts were used for centuries and some are still in use (e.g. Carthage, Mons). Their construction was a huge task, often performed by the army under the guidance of military hydraulic engineers. Their cost was extra-ordinary considering the real flow rate (less than 400 l/s) : i.e., about 1 to 3 million sesterces per kilometre on average (FEVRIER 1979, LEVEAU 1991). Today this would represent about 20 to 60 million US$ per km. For comparison, the construction of the Tarong water pipeline (Australia, 70 km long, $Q = 0.9$ m^3/s) costed about 100,000 US$ per km in 1994.

Despite superb ruins, little is known of the hydraulic engineering of the Roman aqueducts. What was the flow rate? How did they operate? How were they designed? In this note, it is argued that the hydraulics of the aqueducts was limited by their catchment hydrology. Four aqueduct systems are discussed and the results demonstrate severe hydrological limitations during dry periods, implying needs for some form of dynamic regulation.

Hydrology and operation of some Roman aqueducts

The hydrology of some catchment areas supplying Roman aqueducts were recently studied (CHANSON 2002), the "source de l'Eure" at Uzés supplying the Nîmes aqueduct; the "source de Gorze" feeding the Gorze aqueduct (Metz); the "source du Thou" and "ruisseau d'Arches" supplying the Mont d'Or aqueduct (Lyon); and the "sources de la Siagnole" feeding the Mons aqueduct (Fréjus), which are all in use today (Table 1). The comparison between the Gorze and Nîmes aqueducts is particularly relevant, considering that they were among the largest aqueducts in Roman Germany and Gaul respectively, and that they had similar characteristics. Both were supplied by a natural spring with a catchment area between 45 and 60 km^2, and the aqueducts were equipped with a massive aqueduct bridge (Fig. 1).

Overall, recent hydrological data show large variations in streamflow (Table 1). During dry periods, the daily flow was on average less than 10% of the maximum discharge. In a month, the daily spring flowrate varied on average within 35% of the mean at Gorze, but these variations were greater during dry periods: e.g. between 40% and 200% of the average daily flowrate at Gorze, and the spring outflow was zero more than once at Mons. While the flowrates during Roman times are unknown, it is plausible that hydrological variations were similar to present trends. This suggests that the aqueducts conveyed relatively low flows during dry periods. In turn, the operation of the aqueduct and the water distribution in the Roman city had to be adjusted, possibly with a dynamic regulation.

Aqueduct flow regulation?

Several aqueducts were equipped with regulation basins installed along the canal. For example at Ars-sur-Moselle (Metz); at the Vallée de l'Eure, upstream of Pont-du-Gard, at Lafoux along the Nîmes aqueduct; at Segovia upstream of the aqueduct bridge. Most regulation basins were equipped with a series of gates and an overflow system. Basic hydraulic considerations imply that undershoot gates were used to regulate the aqueduct flow while overshoot gates were used for the overflow discharge (CHANSON 2002). Hydraulic calculations were conducted for two large regulation basins on the Gorze and Nîmes aqueducts. The results demonstrated that the undershoot gate openings had to be small: i.e., between 2 and 10 cm at Gorze, and between 3 and 12 cm at Nîmes. This type of operation implied fine gate opening adjustment systems to enable precise flow regulation.

What type of flow regulation was used? Water supply operation can be based upon two different techniques; i.e. On/Off (100% or 0%), or a dynamic flow regulation. In the former case, the gates were open constantly, and the waters flowed to the cities without further regulation than the force balance between gravity and flow resistance (e.g. HENDERSON 1966, CHANSON 1999). The gates and valves were used to stop the flow for repairs, maintenance and cleaning. Dynamic flow regulation is commonly used in modern times and it involves a system operation to respond constantly to the users' demand. In Roman times, this type of operation would have required an engineer in charge of the regulation, gangs of workmen operating the gates and a good communication system along the aqueduct canal. CHANSON (2002) discussed some implications. It is plausible that several aqueduct systems (e.g. Gorze, Nîmes, Mons) were controlled dynamically: e.g. gates were possibly operated twice per day to store water in the canal at night.

Website

This note is complemented by the following website : http://www.uq.edu.au/~e2hchans/rom_aq.ht

CHANSON, H. (2002). "Some Hydraulics of Roman Aqueducts. Myths, Fables, Realities. A Hydraulician's Perspective." *Internet resource*

Acknowledgments

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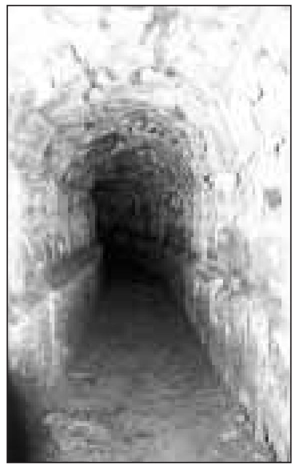


Fig. 2 - Brévenne aqueduct (Lyon, Fra.) at Biternay - Inside view of the subterranean conduit, looking upstream

References

BURDY, J. (2002). "Les Aqueducs Romains de Lyon." Presses Universitaires de Lyon, Lyon, France, 204 pages.

CHANSON, H. (1999). "The Hydraulics of Open Channel Flows : An Introduction." Butterworth-Heinemann, Oxford, UK, 512 pages. (already translated into Spanish and Chinese)

CHANSON, H. (2002). "Certains Aspects de la Conception hydrauliques des Aqueducs Romains." ('Some Aspect on the Hydraulic Design of Roman Aqueducts.') Jl La Houille Blanche, No. 6/7 (in French).

FABRE, G., FICHES, J.L., and PAILLET, J.L. (1991). "Interdisciplinary Research on the Aqueduct of Nîmes and the Pont du Gard." Jl of Roman Archaeology, Vol. 4, pp. 63-88.

FABRE, G., FICHES, J.L., LEVEAU, P., and PAILLET, J.L. (1992). "The Pont du Gard. Water and the Roman Town." Presses du CNRS, Caisse Nationale des Monuments Historiques et des Sites, Collection Patrimoine au Présent, Paris, France, 127 pages.

FABRE, G., FICHES, J.L., and PAILLET, J.L. (2000). "L'Aqueduc de Nîmes et le Pont du Gard. Archéologie, Géosystème, Histoire." CNRS Editions, CRA Monographies Hors Série, Paris, France, 483 pages & 16 plates.

FEVRIER, P.A. (1979). "L'Armée Romaine et la Construction des Aqueducs." Dossiers de l'Archéologie, Séries Les Aqueducs Romains, Vol. 38, Oct./Nov., pp. 88-93.

HENDERSON, F.M. (1966). "Open Channel Flow." MacMillan Company, New York, USA.

HODGE, A.T. (1992). "Roman Aqueducts & Water Supply." Duckworth, London, UK, 504 pages.

LEFEBVRE, C. (1996). "L'aqueduc Antique de Gorze à Metz." ('The Antic Aqueduct of Gorze at Metz.') Itinéraire du Patrimoine No. 119, Direction Régionale des Affaires Culturelles de la Lorraine, Nancy (in French).

LEVEAU, P. (1991). "Research on Roman Aqueducts in the past Ten Years." Future Currents in Aqueduct Studies, Leeds, UK, T. HODGE ed., pp. 149-162.

VALENTI, V. (1995a). "Aqueduc Romain de Mons à Fréjus. 1. Etude Descriptive et Technique. Son Tracé, son Profil, son Assise, sa Source ..." Research Report, Fréjus, France, 97 pages.

VALENTI, V. (1995b). "Aqueduc Romain de Mons à Fréjus. 2. Etude Hydraulique. Son Débit ... de sa Mise en Service à son Déclin." Research Report, Fréjus, France, 123 pages.

Fig. 1 - Pont du Gard, Nîmes aqueduct in June 1998 - Looking from the right bank

Table 1 - Hydrological and hydraulic characteristics of four Roman aqueducts

	Gorze (Metz, Fra.)	Nîmes (France)	Mons (Fréjus, Fra.)	Mont d'Or (Lyon, Fra.)	Remarks
Hydrology Catchment area (km2) :	58	45-50	130		
Spring(s) :	source des Bouillons (Gorze)	Eure (Uzés)	sources de la Siagnole (Mons)	(1) source du Thou (2) ruisseau d'Arches	
Study period of the springs :	1/1997 to 12/1998	7/1967 to 5/1968 & 1/1976 to 12/1978	1/1981 to 12/1993	end of 20th century	
Spring average discharge (m3/day) :	8,050 (*)	29,600	97,200	(1) 400 (2) 1,000	Average daily data. (*) include overtoppings.
Standard deviation (m3/day) :	2,950	--	--	--	Modern data.
Maximum daily discharge (m3/day) :	10,980 (*)	143,400	1,550,000	(1) 1,500 (2) 3,000	Modern data based upon daily data. (*) include overtoppings.
Minimum daily discharge (m3/day) :	1,100	10,800	0	(1) 100 (2) 150	Modern data.
Hydraulics Aqueduct length (m) :	22,300	49,800	39,400	26,000	
Total drop in invert elevation (m):	14.19	17	481	372	
Channel (internal) width (m) :	1.1 2 * 0.85 (*)	1.2	0.60	0.5	Main channel. (*) aqueduct-bridge.
Estimated maximum discharge capacity (m3/day):	15,000	35,000	52,500	10,000	Estimates (?).
Maximum water depth (m):	0.92	1.0	possible transition to pipe flow in some sections	0.65	Corresponding to the height of the waterproof mortar (enduit de mortier de tuileau).
Storage volume in the aqueduct (m3) :	21,200	58,800	--	--	Excluding the aqueduct-bridge.
Aqueduct-bridge River :	Moselle	Gardon	--	--	
Bridge height (m) :	30	48.3	--	--	Pont sur la Moselle and Pont-du-Gard respectively.
Bridge length (m) :	1,300	360	--	--	
Channel invert slope (S_o=sinq):	3.9 E-3	7 E-5	--	--	
Internal width of channel (m) :	2 * 0.85	1.2	--	--	
Upstream regulation basin - Volume (m3) :	18.0	4.0	--	--	Banks full.
Downstream dissipation structure - Volume (m3) :	4.24	N/A	--	--	Banks full.
Aqueduct usage Start :	AD 100/200	AD 40/80	BC 31/AD 70	BC 20	Estimates (?).
End :	AD 450/500	AD 350/500	AD 370/470	--	Estimates (?).

References : FABRE et al. (1991,1992,2000), VALENTI (1995a,b), LEFEBVRE (1996), BURDY (2002), CHANSON (2002).

Making an IMPACT

If you visited UK IAHR Institution Member HR Wallingford in September 2002 you might have seen engineers building what looked like giant sandcastles in a test flume. In fact these were carefully scaled and instrumented model dams. The exercise was part of **IMPACT** (**I**nvestigation of extre**M**e flood **P**rocesses **A**nd un**C**er**T**ainty) a major three-year European research project looking at the failure of flood defence embankments and embankment dams.

Supported by the European Commission under its Fifth Framework Programme, **IMPACT** is contributing towards implementation of the Generic Activity on 'Natural and Technological Hazards' within the Energy, Environment & Sustainable Development programme. It is also supported by the UK's Department for Environment Food and Rural Affairs/Environment Agency and feeds into a current R&D project entitled 'Reducing the Risk of Embankment Failure under Extreme Conditions'. **IMPACT** involves eleven main collaborators[1] and is co-ordinated by HR Wallingford.

Embankment and dam failure can cause catastrophic flooding and loss of life. The **IMPACT** work programme investigates three related 'extreme' flood process areas:
breach formation
flood propagation
sediment movement

A fourth area comprises geophysical techniques and data collection whilst a fifth crosscutting theme addresses the issues of uncertainty associated with prediction of each of these processes.

Breach formation

Breach research has involved both laboratory and field tests. Large scale field work was carried out last autumn near Lake Røssvatnet in northern Norway, where specially built 6m high embankments were failed under controlled conditions. Three further tests are planned during 2003. Laboratory investigations have also been conducted at Wallingford. Data from both laboratory and field work is being used to test and validate existing numerical breach models, as well as in the development of new models.

Statkraft Grøner and HR Wallingford will also undertake research to look at factors contributing to breach location. This has particular applications in flood defence management.

Flood Propagation

It is extremely difficult to model complex flood flows in urban areas, yet these are the very areas that can be most affected by flooding after embankment failure or dambreak. **IMPACT** focuses on how best to produce and extend reliable modelling methods for the propagation of catastrophic flood flows. Partners from the Universidad de Zaragoza, CESI, the Université Catholique de Louvain and CEMAGREF aim to:
investigate flow behaviour in urban areas and identify the most appropriate techniques for simulating these conditions
identify dambreak flow behaviour in complex natural valleys and its interaction with infrastructure.

Work will involve a combination of physical modelling, numerical analysis and case study simulation.

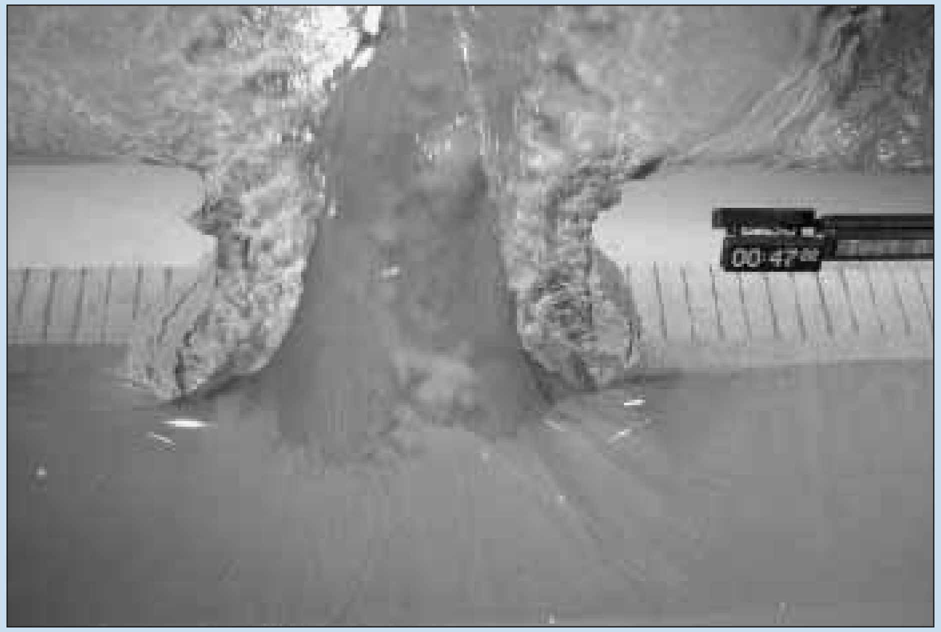
Sediment Movement

Experience in the USA has shown that significant quantities of sediment and debris can move during extreme floods. These can affect rates of flood wave propagation and influence floodwater level – sometimes by tens of metres - due to their effect on bed level. Within **IMPACT**, researchers from the Université Catholique de Louvain, Universitá de Trento, Statkraft Grøner and Instituto Superior Technico will use physical and numerical modelling to address issues of near- and far-field sediment flow during dambreak and extreme flood flows.

Risk and Uncertainty

The research that has already been outlined focuses on *processes.* One important aspect of any *process* that contributes towards an overall risk assessment (i.e. prediction of flood risk) is an understanding of the *uncertainty* associated with the prediction of that particular process. A further goal of **IMPACT** is to identify sources and magnitude of uncertainty associated with the prediction of *each process*, and to demonstrate these through application to a case study. Implications for the end users of such data – including asset managers and emergency services – will then be reviewed.

If you would like further information about the IMPACT project, or if you wish to contribute to the work in any way, please contact Mark Morris at HR Wallingford (01491 822283, email: m.morris@hrwallingford.co.uk). Further information is also available on the project website at www.impact-project.net.



Physical model undergoing laboratory testing at Wallingford

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[1] *The IMPACT project team comprises Universität Der Bundeswehr München (Germany), Université Catholique de Louvain (Belgium), CEMAGREF (France), Universitàdi Trento (Italy), Universidad de Zaragoza (Spain), CESI (Italy), Statkraft Grøner AS (Norway), Instituto Superior Technico (Portugal), The Geo Group (Czech Republic), H-EURaqua (Hungary) and HR Wallingford Ltd (UK).*