Construction History Vol. 10. 1994

The Failure of the Bouzey Dam in 1895

NORMAN A.F. SMITH

"Thank you for the copy of "Cassier" with your interesting article on the Bouzey Dam. It must have been an awfully jerry-built affair if the vertical bond was so wholly absent that it looked as if the mass filling the gap had slid and if the mortar joints, including the vertical bond, wouldn't stand such a paltry pull as 20 lbs. per sq. in. – about twice as much as a little boy's sucker!" (letter from Sir Benjamin Baker to Prof. W.C. Unwin in 1896)

Introduction

The Bouzey dam near Epinal in Eastern France failed almost exactly 100 years ago, on Saturday 27th April 1895 at 5-45 in the morning (Fig. 1). The ensuing flood-wave, pouring northwards along the valley of the Avière (Fig. 2) to the Moselle, drowned 85 people and extensively damaged canal works, railway structures, bridges, villages and farms. By the standards of dam disasters it was a serious accident although not so destructive of life as the Dale Dyke dam failure[1] near Sheffield in March 1864, which killed 244 people, and nothing like as terrible as the death-toll of over 2200 in Johnstown, Pennsylvania when the South Fork dam collapsed in May 1889[2]. For comparison, 75 people were killed in the famous Tay Bridge railway disaster of 1878.

There was another aspect of the gravity of the Bouzey failure, in the wider context of engineering safety and designer responsibility of great significance. The Bouzey dam, it was believed, had been designed rationally by the reasoned application of mathematics to a

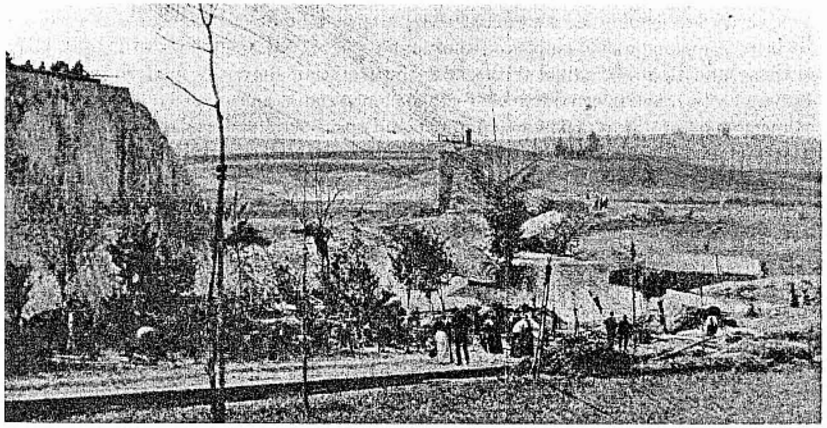

Fig 1: A general view of the breach looking southwest and into the reservoir (from Louis Geisler, 15 Vues Photographiques de la Vallée de l'Avière après la Catastrophe de Bouzey, Roan-l'Etape, 1895)

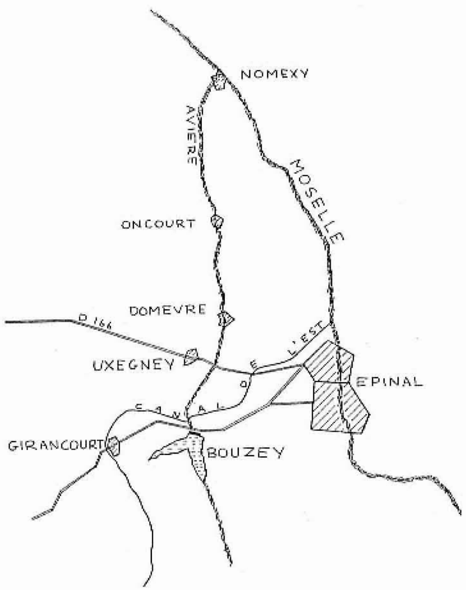

Fig 2: The Bouzey Dam and its environs

structural problem. Those engineers in France, Britain, Germany and the United States who had pioneered this first era of dam design were confident that new standards in safety of performance and economy of construction were now to hand. That they were astounded and alarmed when a dam of the new age went so badly wrong 100 years ago is hardly surprising.

This is not to be a "disaster" paper. It is about design and construction and why structures fail. Therefore, to begin with, it is necessary to examine, at least briefly, the background to the Bouzey dam's short life.

The Background

Masonry dams – gravity, arch, arched and buttressed – have been built from early times while the European tradition has clearly defined and well attested origins in the Roman period[3]. Some Roman dams are still in use as are Medieval structures, albeit with the aid, in most cases, of considerable repairs and reconstructions. There are big dams of the sixteenth century and later which, so far as trouble-free service is concerned, have much better records, indeed enviable. Some Spanish dams of the sixteenth and seventeenth centuries are a particularly impressive testimony to what could be achieved, and there are numerous examples of thoroughly successful dams built in France, Italy, Germany and Central Europe throughout the whole of the early modern period, the beginnings of a tradition carried on well into the nineteenth century.

I mention all of this to make the point, which if space permitted would bear considerable elaboration, that even in an era before dams could be designed rationally, they could still be designed very well. The old methods (pre-1850) of proportioning dams, whatever those methods comprised, were not unsafe even though they were undoubtedly uneconomic.

Even in the eighteenth century there was an emerging interest in calculating the ability of a masonry wall to resist overturning when loaded by some horizontal force. Charles Coulomb had applied himself to the particular problem of retaining walls bearing earth pressure, while B.F.de Belidor addressed the essence of the dam problem in his consideration of the behaviour of the walls of navigation locks.[4] Belidor examines the stability of a rectangular wall of height **b** and width **y**, to be determined, when resisting a depth of water **a**, less than **b** (Fig. 3). It is assumed that masonry is 5/3 times as heavy as water. By equating the overturning moment due to the water pressure, **P**, and the restoring moment developed by the weight of the wall, **W**, Belidor shows that y^2 must be at least $a^3/5b$ and in addition, to achieve a safety factor of 1.5, he shows that y^2 has to be $3a^3/10b$.

How far such rudimentary calculations were applied to practical dam-building in the late eighteenth and early nineteenth centuries has so far been impossible to establish. Serge Leliavsky[5] maintained that dams of the period *were* designed by Belidor's concepts, to which was added the requirement that the ratio of pressure to weight must not exceed the coefficient of friction appropriate to the masonry itself and the connection between the dam and its foundation. What *can* be said is that a number of French canal dams of the period – e.g. Lampy on the Canal du Midi; Vioreau, Bosméléac and Glomel on the Canal de Nantes à Brest; and Chazilly and Grosbois on the Canal de Bourgogne, ranging in date from the 1780s to the 1840s[6] – have profiles which are certainly not at odds with the "no-overturning" rule but that may be no more than coincidental.

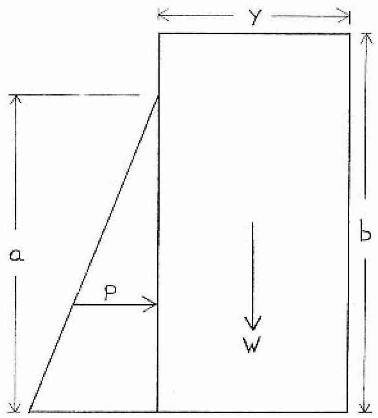

Fig 3: Belidor's problem

In 1853 came a decisive step. J.A.T.de Sazilly published his pioneering study of dam design, "Sur un profile d'égale résistance proposé pour les murs de réservoirs d'eau".[7] This long and complex paper was a further French contribution to the study of retaining walls generally and was based on previous work in the strength of materials by, for example, C.L.M.H. Navier and J.B. Bélanger. De Sazilly's ideas can be followed, in their essentials, by referring to Fig. 4.

It was assumed that a straight gravity dam could be visualised as a series of separate slices of unit thickness, and that any one could be treated independently of all the others. The limitations to these assumptions are considerable and obvious. The height of a dam varies across a valley and, particularly near the abutments, slices interact with each other and provide additional resistance. However, the most critical case can be covered by analysing the tallest slice and assuming it to be unsupported by its neighbours.

De Sazilly stated in full the two requirements mentioned above: that it should be impossible for the section of dam above **XY** to slide relative to the part below and that the line of thrust representing **W** and **P** should be contained within **XY** so that the piece **ABYX** could not overturn. A huge

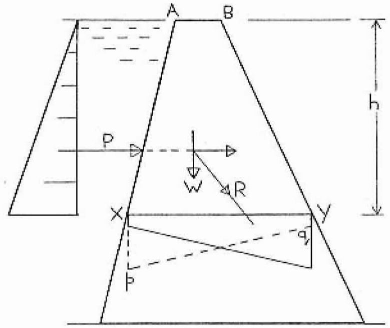

Fig 4: De Sailly's profile of equal resistance'; the vertical component of water pressure is ignored

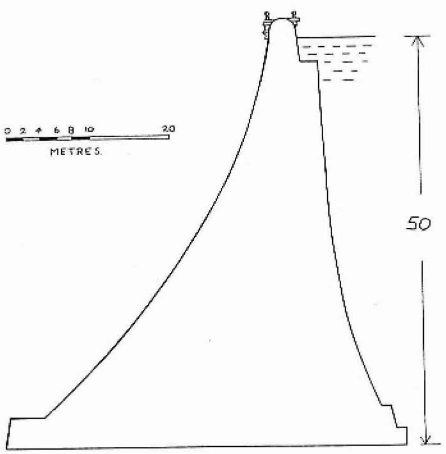

Fig 5: The Furens Dam, 1866

advance was de Sazilly's consideration of stresses. In effect he was extending the ideas of Navier and Bélanger to dams by treating each slice as a heavy vertical cantilever and assuming a linear distribution of stress on any horizontal section. When the reservoir is empty the self-weight **W** is taken to inducé a trapezoidal compressive stress diagram **XYqp** whose maximum is at the water-face. With the dam loaded the maximum stress will occur at the air-face since the imposition of **P** induces bending stresses across **XY** to add to the direct stress due to **W**. In other words, the line of thrust moves from left to right as **P** increases.

The calculation of these states of stress was, for de Sazilly, perfectly straightforward and in order to maximise the masonry's performance and economise on construction costs he set a condition. He specified that throughout the dam on every section, at the point **X** reservoir empty, and at the point **Y** reservoir full, the maximum compressive stress that the material could withstand should be realised. Hence the term "profile of equal resistance" used in his title. It means, of course, that the two compressive stress diagrams, reservoir full and reservoir empty, are mirror images of each other. It also means that in Fig. 4 every horizontal section is subjected only to compression, never to tension; the shape of the profile and de Sazilly's conditions see to that.

De Sazilly's propositions were applied immediately. The Furens dam near St. Etienne, generally reckoned to be the first "modern" dam, was designed and built between 1858 and 1866 (Fig. 5). Its designer, F.X.P. Emile Delocre, in his discussion[8] of dam design follows de Sazilly exactly and their concepts were adopted immediately as the basis of European and American practice for half a century.

The next important advance in the theory of dams came from Professor W.J.M. Rankine. In 1870 he was consulted over the design of the Tansa dam in India. In a famous paper of 1872 – one of the last and one of the best of his publications[9] – he found in favour of the basic de Sazillian ideas but added new and crucial considerations. Two were particularly critical and for brevity we will confine ourselves to them here.

Rankine stated firmly that nowhere on any horizontal section of a dam should tension be allowed to develop, either at the air-face, reservoir empty, or at the water-face, reservoir full. It is essential to re-emphasise here that in de Sazilly's profile of equal resistance, for the style of cross-section shown in Figure 4, the "no-tension" condition is, in fact, met. However, neither de Sazilly nor his disciples positively spell out the need to avoid tension. They recognised that it could occur and indeed, following the earlier works of Navier, Méry and Bélanger, knew full well that according to their theories, if the force **R**, the resultant of **P** and **W**, cut the section **XY** outside the "middle-third" – i.e. acted with an eccentricity of greater than **XY/6** – then tension was inevitable.

In de Sazilly's paper thère is a remark, at one and the same time chilling and portentous,

which states, apropos tensile stresses, that it is allowable to neglect "the force of cohesion in the mortar, which is unfavourable to resistance".[10] The opinion is repeated verbatim by Delocre. In short, the de Sazilly-Delocre view of tension in a masonry dam was not that it should be avoided, but rather that its contribution to structural strength *should simply be discounted*. Rankine knew better. And so it was that he brought into gravity dam design a new imperative: that there must be a strict observance of the so-called "middle-third rule".

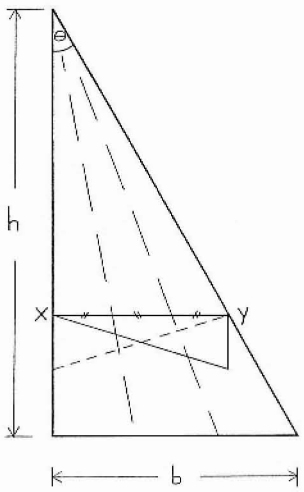

Fig 6: The basic triangular profile

The other of Rankine's observations challenged the assumption that maximum stresses did, in fact, occur on horizontal planes. Rankine puts it thus:

"The direction in which the pressure is exerted amongst the particles close to either face of the masonry is necessarily that of a tangent to that face; and, unless the face is vertical, the vertical pressure found by means of the ordinary formula is not the whole pressure, but only its vertical component; and the whole pressure exceeds the vertical pressure in a ratio which becomes the greater, the greater the "batter", or deviation of the face from the vertical".[11]

True, and quite correctly sensed here is that maximum *principal* stresses occur in directions parallel to those of zero shear. The face of a dam, by definition, is not subject to any shearing stress and therefore the *maximum direct* stress at the face of a dam must be on a plane at right-angles to that face. Moreover, its magnitude must exceed that of the associated vertical stress. Following Rankine's paper, a number of contributors to the theory of dams introduced variations on his criteria and by degrees the complexities of stress within a dam, including the role of shear, began to be assessed.[12]

As background to the Bouzey dam's design, which began in 1876, to its demise 20 years later, we can simplify the essential design concepts prevailing by considering the most basic of all dam profiles, the triangular one shown in Fig. 6. It is defined by the relationship $h^2=b^2w$, where **w** is the specific gravity of the masonry.

It is elementary to establish a number of properties of this particular form of profile. For example, it can be shown that on the typical section **XY**, reservoir empty, the compressive stress diagram is itself triangular. If the same maximum compressive vertical stress is developed at **Y**, when the reservoir is full, then the same triangular stress distribution, reversed, will obtain, as shown. This will be true at every level, and in a sense what we have here is *a* profile of equal resistance. However, and this is crucial, it is not, and cannot be, *the* profile of equal resistance because the *maximum* working stress of the masonry cannot be realised at every level. Approaching the crest of a dam, up to and above maximum water level, stresses decrease progressively so that de Sazilly's theoretical profile is, to that extent, unattainable. On the other hand, the triangular profile automatically meets Rankine's middle-third condition because the lines of pressure, full and empty, pass through the two mid-third points, respectively, at every level. Thus we have here *the* most straightforward

Maximum Principal Stress kg/cm^2	Specific Gravity of Masonry		
	2.0	2.25	2.5
	H E I G H T - metres		
5.00	16.7	15.4	14.3
10.00	33.3	30.8	28.6
15.00	50.0	46.2	42.9
20.00	66.7	61.5	57.1

Fig 7: Limiting heights of triangular dams for various specific gravities and different maximum principal stresses

profile for a gravity dam. For the air-face, maximum principal stresses are easily calculated as being equal to **p**sec$^2\theta$ where **p** is the maximum vertical compressive stress and θ the angle of the face. Now this basic shape, and its behaviour when loaded, are susceptible to variations in at least four parameters, all of which can have a bearing on the design process and a dam's safe operation.

Firstly, the density of masonry is a variable. Generally it was not usual to use a stone whose specific gravity was less than 2, while in the case of a really heavy specimen, it could be as high as 2.5 or a shade more; the masonry of the Vyrnwy dam in Wales was particularly dense at 2.6. Interestingly enough, between these extremes of density, a triangular profile is not required to change all that much, only from about 32 to 35 in the angle of the dam.

Secondly, and much more significant, is the masonry's compressive strength, be it measured or estimated. The latter was a real enough approach. To get started on designs French engineers, such as Auguste Graeff, applied their analyses to historic Spanish dams and determined the prevailing maximum stresses.[13] The answers were pretty mixed; from as low as 6.5kg/cm^2 to as high as 14.5kg/cm^2. In the early days, and to be safe, the lower limits were chosen; the Furens dam is stressed to 6.5kg/cm^2. There was a bonus to this cautious approach to maximum stresses. Because it leads to a relatively wide dam profile – and not a particularly economic one – the middle-third rule is, fortuitously, likely to be met. However, in their determination to build more highly stressed dams, and hence ones which made more economic use of material, as well as satisfying a certain ambition to achieve "proper" design, European engineers generally were inclined, over the years, to allow higher compressive stresses in

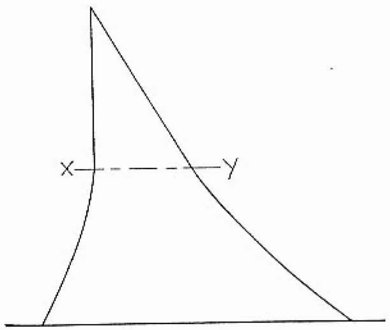

Fig 8: Below XY the profile must widen to restrict stress levels

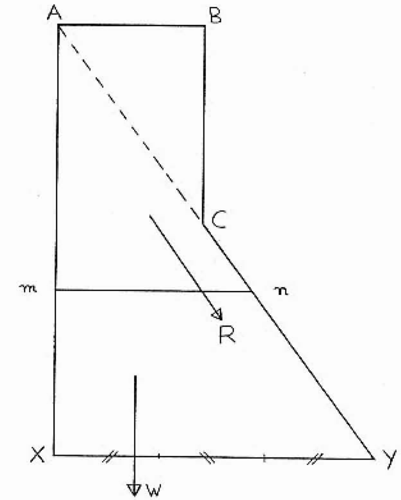

Fig 9: Dam with widened crest

increasingly slender profiles. Hence the risk of tension was increased; tension, remember, which in some quarters there was a willingness to discount.

The maximum stresses allowed have a marked effect on a dam's profile and the height to which it can retain the simplified triangular shape we have been visualising. It reaches its limits according to the range of numbers given in the Table in Fig. 7. To have a higher dam not stressed, front of back, beyond the prescribed limits requires a base of increasing width, and thus the more familiar shape of a high dam begins to emerge, as in Fig. 8.

This need to modify the basic triangular profile is compounded by another requirement, very relevant to Bouzey as we shall see shortly. A dam with a pointed crest is not a very practical proposition: it is difficult to build, vulnerable in use, and in any case fails to provide a roadway for maintenance, access or traffic across the structure.

As soon as the crest of gravity dam has some useful width, lines of thrust move and middle-third requirements are affected. Consider a width of road added to the top of a triangular profile as in Fig. 9. It is evident that when the reservoir is empty the mass of the piece **ABCYX**, will, below a certain level, **XY** say, shift the line of thrust *forward* and violate the middle-third rule *on the air-face*. This is very unlikely to be a problem but it is a fact. On the other hand, a very real issue arises when the reservoir is full. The fact that the top of the dam now has width means that above a section such as **mn**, the centroid of the profile is in any case much nearer the air-face. Therefore the possibility of generating tension at the water-face, at a point such as **m**, is greatly increased when the reservoir is full. In other words, on the section mn, the line of thrust, **R**, is forced to the right by the addition of **ABC**.

So it emerges that an unexpected property of a *practical* profile is that it is particularly susceptible to unfavourable stress distributions *near the top*. In the old days it was too easy to be unaware of this, the not unnatural assumption being that dams are vulnerable only in the depths where pressures are high. For a number of nineteenth century gravity dams – and Bouzey was a tragically outstanding example – it is elementary to show that the middle-third rule was nearly or *actually violated only near the crest*. It was a dangerous situation all too readily compounded by the fourth factor we are considering.

Inevitably designers and users alike assume that a reservoir's maximum water-level is known, predictable and controllable. However, a potential danger for any dam is that insufficient spillway capacity, or exceptionally rapid reservoir filling, or both, can produce an overload. It was especially true a century or so ago. Reservoir behaviour was, in its way, as problematical as dam behaviour. Indeed, the rates at which reservoirs filled, and overflowed, were as revealing of rainfall statistics and catchment area runoff as vice versa. So it is not difficult to appreciate that many a spillway was seriously under designed, and that a dam which was already stressed to the limit near its crest at *normal* maximum level,

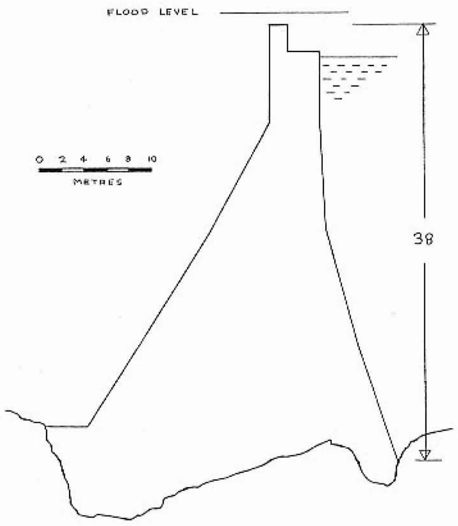

Fig 10: The Habre Dam

as discussed, was in a dire condition if an inadequate spillway allowed the water level to rise even higher.

A famous failure of this type befell the Habra dam (Fig. 10) in Algeria in 1881[14]. Massive runoff after storms and huge flood flows produced an overflow at the dam of, at its maximum, as much as 5000m^3/sec. Not only was the spillway, such as it was, overwhelmed, but so too was the dam itself. The crest was overtopped to a depth of nearly 1m and the normal operational reservoir level was exceeded by about 4m. Proportionately, the increase in water pressure was not all that significant near the base of the dam, but it most certainly was at the top. At a depth of some 10m below the crest the horizontal section was being subjected to *twice* the designed thrust. Consequently, tensile stresses must have developed at the water-face and the masonry presumed to have cracked. Such cracking would have allowed the penetration of water as a result of which a new force came into action. It was an uplift force acting vertically within the crack. In effect, it augmented the horizontal water pressure in overturning the dam section above crack level.

As we shall see, the mechanism of failure at Bouzey was to be precisely the same, and to that extent Habra should have been a warning to be heeded. But apparently it was not. In fact, there seems to be no evidence that the Habra failure was considered even in the deliberations which *followed* the Bouzey accident, never mind those that went before.

There are three general observations to be made about the theory of dams in the period of Bouzey's original design, and during the years of maintenance and extensive reconstruction which preceded the final failure.

1). Following the work of de Sazilly, Delocre, Rankine and others, the sound design and construction of high, masonry, gravity dams was perfectly possible. It was achieved regularly in several countries, and the structures created continue to serve well to this day.
2). French engineers, pursuing rational design in the interests of economy, adopted maximum compressive stresses and the associated concept of the "profile of equal resistance" as the essentials of design. But "no tension" was not a design imperative. Observance of Rankine's "middle-third rule" was very often achieved but only as a consequence of other decisions, not as an object in itself.
3). Any theory of dams can be applied to two quite different problems and proper distinctions must be drawn. It is one thing – and relatively straightforward – to analyse an existing profile for stability and stress levels; it is quite a different matter to design a safe profile from scratch for a given situation. De Sazilly and Delocre attempted a generalised mathematical solution to the problem but had to give best to some prodigious equations; a close reading of their work is not for the faint-hearted or the mathematically inept. Rankine, by making concessions and being realistic, was more successful in realising a general solution, but ultimately it was relatively crude step-by-step design procedures, judiciously modified in the light of experience and common sense, which won the day. They usually do.

The Bouzey Dam

France continued to undertake major canal building long after the railways had won the argument in Great Britain. The Canal de l'Est was a particularly important project which was begun in 1872 following France's loss of north-south navigation along the Moselle-Rhine system as a consequence of the Franco-Prussian War. The Canal de l'Est consisted of two distinct parts: a northern section, essentially a canalised River Meuse, from Givet to Troussey; and a southern section from Toul to Corre on the River SÉone. The two were connected west of Toul by utilising 20km of the already built Canal de la Marne au Rhin. The summit-level of the southern section of the Canal de l'Est is situated just to the west of Epinal; it runs for 10km between the D166 road bridge and the village of Girancourt (Fig. 2). It was to supply this summit that the Bouzey reservoir was created by damming the River Avière.[15]

Originally, in 1876, the intended dam was to have held about 20m of water. Reservoirs, however, are subject to a tempting law of increasing returns. A nominal increase in the height of a dam can often realise a huge increase in reservoir capacity. The Canal de l'Est's engineers recognised this possibility at Bouzey and in September 1880 permission was obtained to add 2m to the dam's final height. This decision by the Ministre des Travaux Publics did not have the approval of the Conseil Général des Ponts et Chaussées which was unconvinced that canal traffic, at least at that stage, needed so much water, or that the dam, at least initially, should be subjected to so much pressure, as events were to prove, it is the case that the extra 2m of water did nothing to enhance the security of what turned out to be a very poor design indeed.

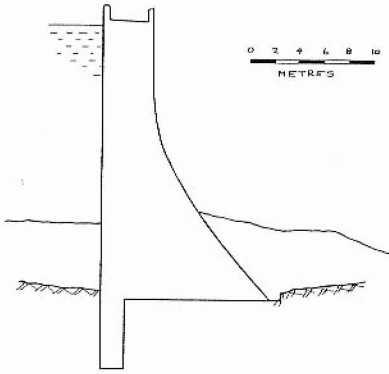

Fig 11: The Bouzey Dam as built

The Bouzey dam was completed right at the end of 1880 and filling of the reservoir began late in 1881. The reservoir's capacity was 7 million cubic metres, it covered 128 hectares, and could feed something of the order of 45,000m^3 of water to the canal each day. The dam itself was straight, quite long at 525m, but not exceptionally high at 22.7m. The masonry and mortar used to build the dam had an overall specific gravity of 2, a low value but not of itself a cause for concern. In order to counter the fissured nature of the foundations, a cut-off wall was built reaching down as much as 5m below the base of the dam on the upstream side. As built the Bouzey dam's cross-section was the one shown in Fig. 11.

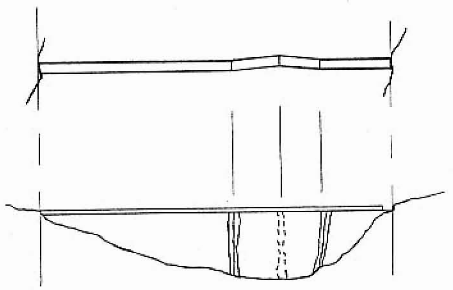

Fig 12: Plan and elevation of the failure of 1884 (not to scale)

Top water level was at 371.5m above datum or 22.1m above the foundation level.

As the reservoir began to fill, so the dam began to leak; even at water depth of less than 15m the leakage was up to 65 l/sec. In December of 1882 two fissures materialised to add to the leakage. They were put down to longitudinal contraction of the structure in cold weather. Come December 1883 the reservoir level had reached 15.5m, that is to say about two-thirds the maximum, and at this moment the water-supply to the reservoir was augmented very substantially by the completion of a 43km-long aqueduct bringing Moselle water from Remiremont. By March 1884 the reservoir was 18.6m deep; the leaks had grown only a fraction to 70 l/sec. The level rose a further 80cm. And then, on the 14th of March, just before noon, 135m of the dam slipped forward into the V-formation indicated in Fig. 12. The maximum displacement was 35cm and the break occurred at foundation level (Fig. 13).[16]

By any reckoning this was a serious situation and yet the astonishing thing is that not only were no precautions taken, the reservoir level was actually allowed to rise a further 20cm, to 19.6m of depth. In this condition, for over 18 months, the Bouzey dam continued in use with water pouring through cracks at the rate of 232 l/sec.

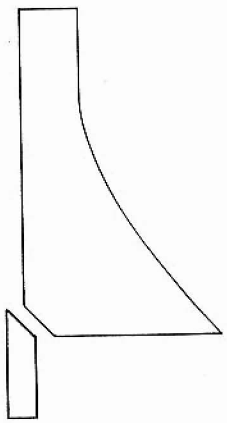

Fig 13: The nature of the fracture

The reservoir was drained in the autumn of 1885. Not surprisingly groups of vertical cracks were found at each end of the displaced section and at its centre. They, quite evidently, were the result of bending fractures, tension cracks in a broken "horizontal beam". Underneath the dam it was found that the cut-off wall had no means protected the poor rock immediately under the structure. Fissured and permeable beds reaching well into the reservoir area had not been sealed by the cut-off wall, and the formations under the dam were dislocated and saturated to a depth of 2-3m. Something which all the pioneer analysts of dams had thought about but never really believed could happen, in fact had. A dam had slid on its foundations, an effect probably exacerbated by a considerable uplift pressure under the dam, although that factor was not fully debated until a later date.

Several features of the 1884 accident and its aftermath are intriguing. That the broken dam was expected to carry on for 18 months cannot, surely, have been a decision of engineers. It must reflect the Canal de l'Est's paramount need for water to sustain traffic.[17] And yet once the reservoir was drained, progress was very leisurely. Exploration of the foundations occupied the years 1885 and 1886; reports were prepared and discussed in 1887 and 1889. There were conflicting opinions as to what had happened and what to do next. Oddly, the

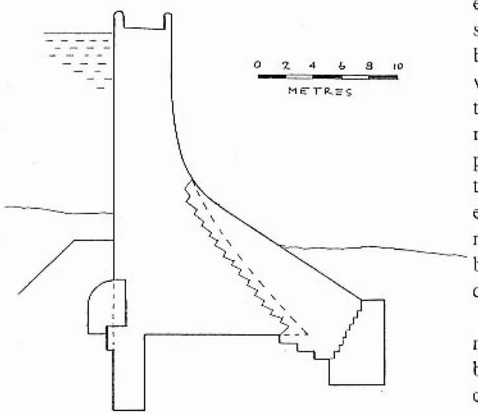

Fig 14: The Bouzey Dam rebuilt (the old dam is shown by the broken line)

one thing which was never agreed – surprisingly given how much time elapsed – was to demolish this ill-starred structure and start again.[18] The best chance to ensure the dam's future was missed. One detects here, though the issue is never broached in the relevant literature, profound economic problems. It was a post-war period and the Canal de l'Est was new and expensive. The urge to use the navigation and make it pay must have been powerful. Therefore the Bouzey dam was repaired.

On the upstream side at the base masonry was used to seal the gap between the body of the dam and the cut-off wall, the whole repair being generously covered with puddled-clay. For the downstream side there were several proposals. The most extraordinary was to construct an earthen bank to the full height of the dam; the best was for a series of tall buttresses in the manner of the measures taken at the dams of Grosbois and Chazilly.[19] In view of what was to happen in 1895 the decision *not* to build "contreforts" was another chance missed. In the event, the chosen solution was a massive buttress "toothed" into the original masonry and bearing against a deep level abutment. The intention was to prevent further sliding. But no strengthening was provided for the upper half of the dam and that was where the ultimate disaster was lurking. Drains were installed at the base of the dam to take away any water percolating underneath. The vertical cracks were filled with cement mortar or grout. The bore-hole used to investigate conditions on the lower side of the original dam was retained as a basis for monitoring water-pressures beneath the modified structure. The rebuilt cross-section is shown in Fig. 14.

On the 18th November 1889 the Bouzey reservoir began to refill. The level passed 19.4m, the depth at which the accident of 1884 occurred, in February 1890 and subsequently the water level was relentlessly increased. On 15th May it achieved a depth of 21.6m, just 50cm short of the maximum. In subsequent years the maximum level was always achieved. For 53 days in 1893 and for 167 in 1894 the water level fluctuated between 21.6m and 22.1m.

For the first half of the 1890s it must have seemed that all was well. The dam retained a high to full water level without mishap. Theodolite measurements[20] along the dam indicated a maximum deflection of 15mm; leakage was of the order of 70 l/sec., significant but not exceptional, especially by Bouzey standards; the piezometric levels were about 10m above foundation level. These various observations were not, as the years went by, maintained. The deflection measurements were given up in 1893 and replaced, totally unsatisfactorily, by visually sighting pegs. The piezometer proved itself very easily damaged by ice so that after the savage winter of 1894-5 it was removed. This same fearsome winter is supposed to have significantly opened vertical fissures in the dam as the wall contracted, a crack width of as much as 7mm being recorded.

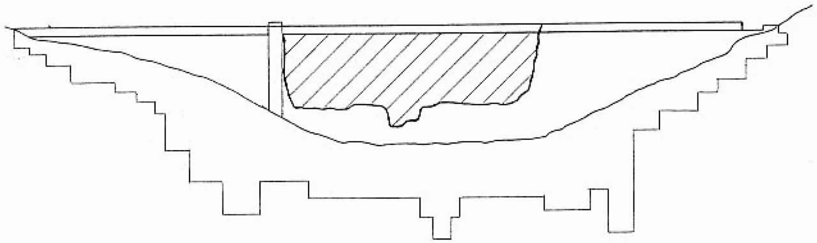

Fig 15: The failure of 1895, viewed from upstream. The vertical scale is 5x the horizontal; the stepped line shows, approximately, the bottom of the cut-off wall

To what extent accurate and frequent measurement might have predicted the final collapse will never be known. Several individuals claimed that towards the end a pronounced downstream curve of the dam developed which could be detected by the naked eye. If such could strike passers-by it surely would have registered officially had it been measured accurately. But it was not and the Bouzey dam failed.

The Failure

There were three witnesses to the collapse on the 27th April 1895. Early that morning a workman called Thiriat was crossing the dam and he stopped, 160m short of the spillway at the eastern end, the right bank, to talk to a mason working below. As they talked the dam began to break up. M. Thiriat had to jump over a 10cm crack in his dash to safety. The mason he had been chatting with was the first victim of the disaster. The third eyewitness was the innkeeper M. Gihin who was watering his horse in the village of Bouzey, 300m downstream. He was able to provide a useful account of the failure sequence which comprised two phases: an initial break near the crest in the middle of the structure over a length of 20m, followed by the main collapse of 180m of the dam to a depth of about 10m. Both Thiriat and Gihin commented on the noise. The failed dam is shown diagrammatically in Fig. 15.

Reactions to the disaster came at several levels. On behalf of an outraged public the popular press clamoured for explanation, redress and the names of those responsible. Louis Geisler was quickly into print with his "15 Vues Photographiques de la Vallée de l'Avière après la Catastrophe de Bouzey", a photographic collection in the style of the even better one covering the ruins of the Dale Dyke dam put together by the Manchester photographer, James Mudd. There was huge international coverage in the engineering press in France, Germany, Great Britain and the United States.[21] Of course there was an official enquiry, conducted by French engineers, and tours of inspection by other experts two of whom were Professor W.C. Unwin of Imperial College and Dr. G.F. Deacon, designer of the Vyrnwy dam in Wales. The latters' observations are among the most useful and objective certainly in English, that the historian can consult.[22] Not the least interesting feature of the deliberations which took place is the degree of disagreement as to what exactly had happened and how to explain it. It certainly was not enough to observe that the design of the dam was bad and that

it had bad foundations.[23] Moreover, agreed conclusions were paramount because, as pointed out at the beginning of this account, Bouzey was supposed to have been *designed*. And if dam design was to be trusted, it was vital to comprehend how and for what reasons it could go wrong with an unsafe structure the result.

Fig 16: A close-up view of the break (from a photograph by Profession W.C. Unwin)

The failed dam itself is the place to begin a brief account of what happened. Naturally there was a readiness to associate the final collapse with the accident of 1884 and the repairs of 1888-9. In reality no such connection could usefully be made. The great abutment had not yielded and appeared to have prevented all further movement of the base of the dam. And in any case the failure of 1895 did occur *entirely above* the level of the remedial works of six years before. In addition, the extremes of the failure of 1895 did not coincide with the vertical cracks at the limits of the movement of 1884 while the central group of fissures in the earlier accident were contained completely by the final collapse. As Unwin put it, "The fracture of 1895 seemed to avoid, rather than to depend on, the fissures of 1884."[24]

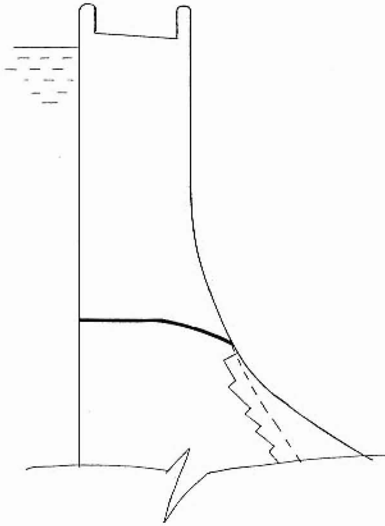

Fig 17: The typical shape and position of the failed section

The cross-section of the failed dam is instructive (Figs 15–17). The break runs horizontally through about half the section and then drops away. Unwin was struck by the fact that there was no evidence of failure by crushing, that "The mass was torn out along a nearly level plane of fracture ..... without any obvious cracking or splintering of the stones along the down-stream edge of the fracture. The mass filling the gap appeared rather to have slid or overturned."[25]

One school of thought was quite convinced of a shear failure. Of the three experts appointed to the tribunal of enquiry, two advanced this view and they were supported by the expert witness of the eminent M. Maurice Lévy.[26] In a sense they were probably correct. The mechanism of a dam's failure is a very complex affair, a whole series of effects occur in quick succession, and the one which starts the chain is not necessarily the one associated with the final moments of collapse. At Bouzey the final stage very likely was a shear

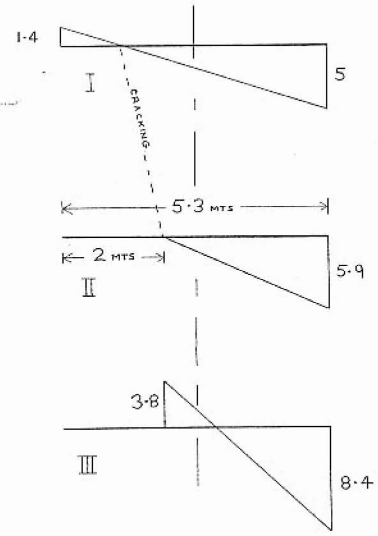

Fig 18: Successful sates of stress (in kg/cm²) and cracking across the critical section

failure on a surface sloping down towards the air-face. But the key question remains: what initiated the failure in the first place?

By applying the analytical techniques described earlier, the ones that were available to the engineers of the day, it is easily shown how completely the middle-third rule was violated in the upper part of the dam, and that the greatest deviation was at the level of the fracture. Actually the compressive stresses induced at the air-face were not destructive. The maximum vertical stress was about 5 kg/cm^2, the corresponding principal stress parallel to the air-face being of the order 6 kg/cm^2. Such compressions were well within the strength of the masonry used and relatively low compared with many other dams. By contrast the situation at the water-face, reservoir full, at a depth of 10m was fatal. Here the vertical *tensile* stress was about 1.4 kg/cm^2; a metre higher it was still 1.1 kg/cm^2.[27] It seems very probable that both the masonry and the mortar could have taken these stresses even though good design should not have required them to, particularly since neither was of first class quality. The crucial defect was that the bond between the masonry and mortar was very poor and should not have been relied upon in any case.[28] It was quite incapable of resisting the tension which developed with a full reservoir and so the Bouzey dam cracked.

Referring to the stress diagram I in Fig 18 we can show that if the tension of 1.4 kg/cm^2 was relieved by cracking, the crack would penetrate 2m and the next stress diagram, II, would then apply, the minimum stress now becoming zero and the new maximum being a compression of 5.9 kg/cm^2. So far the dam is still not over-stressed, exactly as de Sazilly, Delocre and their followers were willing to allow. However, as soon as water pressure penetrated the tension crack a new vertical force came into play, the uplift force we were considering in the case of the Habra dam, cracked in that case by a chronic hydraulic overload. The uplift U within the cracked Bouzey dam significantly increased the over-turning moment and the magnitude of the effect is readily calculated (Fig 19).

At a depth of 10 m of water we can now construct a third stress diagram, III (Fig 18); it applies to the surviving 3.3m length of the section and, of course, it includes a new element of tension – 3.8 kg/cm^2 at maximum – which, if it is relieved by cracking, allows an even larger uplift force and leaves a decreased length of section intact. It is hardly necessary to emphasise the progressive nature of the failure now underway, except to point out again that at the final stage, overturning about the downstream edge would most likely give way, if that is the phrase, to shear fracture. Such a fracture would be along a surface that falls away towards the air-face, as indeed the ruins of the dam confirmed (Fig 17). A similar surface of failure had been observed in the Habra dam.

Such then is the explanation as to why the Bouzey dam failed. And yet, given that its profile was so poor that tension *did* occur, one wonders not so much why it failed but how

on earth it lasted so long.[29] The explanation has a number of elements. Although the basic theory treats a dam as a series of thin vertical "slices", in practice it is not; the slices interact one beside the other in resisting deformation and so a crack has to extend to a considerable depth before *all* the resistance is finally overcome. The point is emphasised by the great length which gave way at Bouzey. Also, because Bouzey was a "leaker", its face was from time to time treated to a waterproof coating. Presumably, therefore, the percolating water was inhibited at intervals and sufficiently to prevent uplift pressures equal to the full head of water. And then again the reservoir was not always full. A canal which was busy in the summer presumably allowed the dam some seasonal respite.

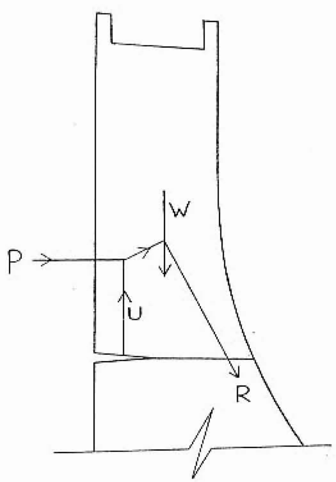

Fig 19: System of forces with uplift

The Puzzle

The question has not been answered. Why *did* the Bouzey dam have such inadequate shape and one that allowed so much tension? After all, the basic mechanics of dam design are straightforward and by 1876, when the project was begun, all the essential elements of the theory were in place including the middle-third rule.

To my knowledge the designer of the Bouzey dam is never named. That he could produce a profile which simply *looks* so appallingly inadequate is interesting in itself.[30] Earlier I noticed that it was easy to overlook the vulnerability of the gravity dam near its crest when the reservoir is full or, as Habra was, overfull. Conceivably Bouzey's proportions, long but not very high, were too readily regarded as ordinary, elementary to design and posing no significant risk in practice. The reason why French engineers pursued the design and construction of masonry dam so assiduously was because, to quote M.I. Auguste Graeff apropos the 50-m Furens dam, "We need not in this case consider earthen dams which are of very doubtful security at a height of 20 metres; at 50 metres they would, of course, be quite out of the question."[31] Always of concern was this question of height. But Bouzey was not a high dam and therefore if, for that very reason, the dam's designer was already complacent and if, in addition, he was prepared, like de Sazilly and Delocre, to allow tensile stresses and then discount them, either because he believed the material could withstand them or because it was assumed permissible to settle for a cracked section, as Fig 18, then Bouzey's design is explained. There is a telling paragraph in Langlois relating to the "calculs des ingénieurs de 1876". He says "No observations have come to light on the subject of upstream tension, of which there is no consideration, neither in the calculations of 1876 nor in those which preceded the reconstruction of 1888-9."[32]

There is one other feature of Bouzey's ill-judged design to consider. The dam was proportioned, apparently, by the method of M.Bouvier. His procedure was much in vogue at the end of the nineteenth century and in a French ministerial circular of 1897 was even specified as mandatory. But in reality Bouvier's method was never more than a device and its use at Bouzey may explain a good deal. Consider Fig 20. Bouvier, in an effort to allow that maximum stresses are not vertical ones, considers the resultant of **P** and **W**, the force **R**,

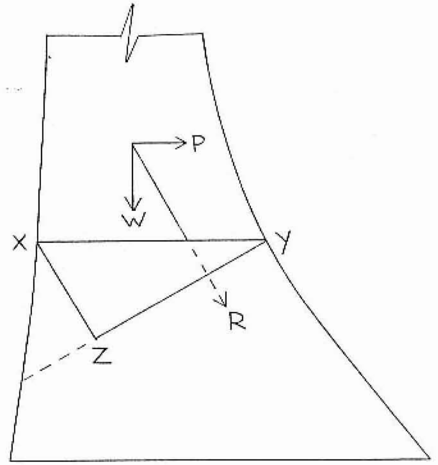

Fig 20: Bouvier's method

as acting on the plane **ZY** rather than **XY**. The stress distribution on **ZY**, at right angles to **R**, is assumed linear, as usual, but the calculated stresses are higher than those obtained by considering **W** acting on **XY**. It is a device which is plausible but without rationale. But what is crucial is that whereas Bouvier's method gives an augmented compressive stress value for the air-face point **Y**, as intended, it gives no stress value for the water-face at all, the point **Z** being in effect nowhere. As Langlois complained of Bouvier's method , "it does not determine anything about what happens on the air-face."[34] In short a designer relying on Bouvier's method will almost certainly design an adequate air-face at the same time as he ignores the water-face completely. The method is intrinsically a technique for determining a peak stress at a point, not a stress distribution between two points.

The Aftermath

Bouzey failed at a crucial time and strange though it may seem to say so, it was not altogether a bad thing: much good came out of this catastrophe.[35] For nearly half-a- century there had developed a growing confidence in dam design but considerable variations in how to do it, what assumptions could and should be made, and what criteria to apply. And this remember was in a period when dams were being built in increasing numbers world-wide, for public water-supply, irrigation and the newly developing application to hydro-electric power (the Bouzey dam's use for a canal was actually rather old fashioned). Moreover, dam-building was by no means the monopoly of European countries. Much, and often the most significant, was happening in North Africa, India, the United States and Australia. That is where one finds the very big dams, e.g. Aswan, and the emerging fashion for the thin arch dams, e.g. in California and New South Wales.

The need to fully understand the events at Bouzey was therefore of great importance and the audience awaiting enlightment was large and international. Close scrutiny of the failure and its full discussion disposed of a number of erroneous or unreliable propositions and established positively that for safe dam design (a) the no-tension condition was an imperative, (b) the middle-third rule was a correct concept, essential to observe, (c) a maximum compressive stress must not be exceeded and (d) a dam must not be able to slide. Not far behind came some instructive lessons to do with construction techniques and the quality of materials.

The Bouzey failure not only summed up the essential developments so far. It also helped to confirm the direction of future work. New design problems and attitudes to them, already it is true under consideration anyway, were given fresh illumination and a much sharper focus.

There was, for example, the matter of uplift and the difficulty of comprehending its behaviour in various circumstances. Some attention had already been given to uplift pressures in the design of such dams as Vyrnwy, in Wales, and Alfeld, in Alsace.[36] Avoiding uplift altogether was one possibility and in some quarters, following a much misunderstood French ministerial circular of 1897,[37] this led to dams being profiled so that the compressive stress at the water-face was greater than the water pressure, the belief being that the infiltration of cracks then became impossible. One result was some very broad profiles indeed.

In fact the 1897 instructions were *intended* to allow for uplift by reducing the effective density of the masonry. They also drew attention to the need to determine maximum compressive stresses on oblique joints, in effect maximum principal stresses, and to investigate the magnitude and danger of shear stresses, something about which the Bouzey failure had been instrumental in promoting discussion, as we have seen. Thus, and this is the point, Bouzey was central to the developing interest in the stress analysis of dams beyond the elementary concepts of de Sazilly and Rankine. In France, Maurice Lévy was prominent in pursing these increasingly sophisticated concepts while in England an equally mathematical approach succeeded in triggering a first class controversy in which the main protagonists were Professors Karl Pearson and W.C.Unwin.[38] And then, in attempt to throw light on these intractable problems, recourse was made to models utilising, in the early experiments, such rather unsuitable materials as plasticine, gelatine and India-rubber. Nevertheless, for all the crudeness of the techniques, it was the start of a very significant, and at times a crucial, trend in twentieth century dam design.[39]

The failure of the Bouzey dam, when all is said and done, stands at a cross-roads where the first phase of rational dam design ended, first of all in controversy but then in clarification. Most branches of civil engineering have their land-marks; for dam-building the Bouzey failure was truly a key one.[40]

Let me quickly finish the story of the dam itself. It was rebuilt twice more. The first reconstruction was a makeshift affair of 1901-2. According to Bellet[41] it was only 6.4m in height forming a reservoir of 1.5 million m^3 , useful to the Canal de l'Est no doubt, but a great reduction in capacity all the same. The present dam dates from 1939 and is of rock- fill construction, 27m high and 504m long. It occupies exactly the site of its ill-fated predecessor of which the only surviving part is the spillway.

Correspondence : Dr. N.A.F. Smith, 2 Pike Close, Marlow, Bucks SL7 2AX

References

1. Technical details are in G.M.Binnie, *Early Victorian Water Engineers* (1981), pp.263-277. A popular account is G. Amey, *The Collapse of the Dale Dyke Dam 1864* (1974).
2. A recent account is W. Frank, "The Cause of the Johnstown Flood", *Civil Engineering*, 58 (May 1988), pp.63-66.
3. Two general histories of dams are: N.A.F.Smith, *A History of Dams* (1971) and N. J. Schnitter, *A History of Dams* (Rotterdam, 1994).
4. B. F. de Belidor, *Architecture Hydraulique*, Vol.1, Part 2 (Paris 1750), pp.77-83.
5. In, for example , S. Leliavsky, *Irrigation and Hydraulic Design*, Vol. 3 (London 1960), pp.375-78.
6. These and other early French canal dams are covered in E. Wegmann, *The Design and*

Construction of Dams (New York 1907) and H. Bellet, *Barrages en Maçonnerie et Murs de Réservoirs* (Paris 1907).

7. J.A.T.de Sazilly, "Sur un type de profil d'égale résistance proposé pour les murs de réservoirs d'eau", *Annales des Ponts et Chaussées*, 2 (1853), pp.191-222.
8. E. Delocre, "Sur la forme du profil à adopter pour les grands barrages en maáonnerie des rèservoirs", *Annales des Ponts et Chaussées*, 2e sem. (1866), pp.212-272.
9. W. J. M.Rankine, "Report on the Design and Construction of Masonry Dams", *The Engineer*, 33 (January, 1872), pp.1-2.
10. J.A.T.de Sazilly "Sur un type de profil d'égale résistance proposé pour les murs de réservoirs d'eau", p.193.
11. W.J.M. Rankine, "Design and Construction of Masonry Dams", p.1.
12. These developments are reviewed by E. Wegman, *Design and Construction of Dams* Chaps. II-IV and H. Bellet, *Barrages en Maçonnerie*, Chaps.V-VI.
13. A. Graeff, "Sur la forme et le mode de construction du barrage du gouffre d'Enfer, sur le Furens, et des grands barrages en général", *Annales des Ponts et Chaussées*, 2e sem. (1866), pp.207-211.
14. "La Rupture du Barrage de l'Habra, près de Perrégaux", *Le Génie Civil*, XCII (1928), No.11, pp.256-9; No.12, pp.283-5: the author – denoted by "A.C." – may be André Coyne. See also E. Wegmann, *Design and Construction of Dams* pp.94-8 and H. Bellet, *Barrages en Maçonnerie*, pp.54-6.
15. The most complete general account of the Bouzey dam is Léon Langlois, *Rupture du Barrage de Bouzey* (Paris 1898).
16. These and other details of the Bouzey dam's career are taken from, in particular, L.Langlois and the report of a special commission of the Corps des Ponts et Chaussées which was published in 1895. There is a copy in the library of the Institution of Civil Engineers. It was abstracted by A.W.Binnie, "Failure of the Bouzey Dam", *Proc. Inst. Civ. Eng.*, CXXV (1895-6), pp.461-466. This same report appears to be the basis of "Failure of the Great Dam at Bouzey", *The Engineer*, 17 January 1896, pp.50-1.
17. The pint is noticed in "Historic Accidents and Disasters: No.XVIII, The Bouzey Dam", *The Engineer*, 4 December 1942, p.452. Langlois, *Rupture du Barrage de Bouzey*, pp.93-4 deals with canal consumption and there is a lengthy comparative study of canals' water requirements in Maurice Lévy, *Observations sur la Catastrophe de Bouzey*, (Paris n.d, circa 1896).
18. *The Engineer*, 4 December 1942, p.453 notes this oversight but does not reflect on the practicality of rebuilding. The dam had after all only been displaced, not destroyed.
19. H.Bellet, *Barrages en Maconnerie*, pp.37-9. The Grosbois dam is the subject of M.Guenot, "La Stabilité des Digues du Réservoir et du Contre-Réservoir de Grosbois alimentant le Canal de Bourgogne", Annales des Ponts et Chaussées, .4 (1949), pp.467-91.
20. So far as I can determine the Bouzey dam is the earliest to be instrumented in this way.
21. The bibliography of the Bouzey failure is enormous, far too much to record here. Serge Leliavsky once referred to the many articles written as being "comparable to a sea of ink"; see his discussion to E.Gruner, "Dam Disasters", *Proc. Inst. Civ. Eng.*, 27 (1964), p.362. For an introduction to the bibliography of the failure there is ICOLD, *Lessons From Dam Incidents* (Paris, 1973), p.29 and A.O. Babb and T.W.Mermel, *Catalog of Dam Disasters, Failures and Accidents*, (Washington D.C., 1968), pp.31-2.
22. W.C.Unwin, "The Failure of the Masonry Dam at Bouzey, France" *Cassier's Magazine*, XI (1896-7), pp.9-19. G.F.Deacon , "Water Supply", *The Encyclopedia Britannica*, 13th Edition, Vol.28, p.403. Professor W.C.Unwin frequently raised the Bouzey dam issue at meetings of the Civils. See, for example, his discussion to G.F.Deacon, "The Vyrnwy Works for the Water-Supply of Liverpool", *Proc. Inst. Civ. Eng.*, CXXVI (1895-6), pp.93-7 and then to Sir John Ottley and A.W.Brightmore, "Experimental Investigations of the Stresses in Masonry Dams subjected to Water-Pressure", Proc. Inst. Civ. Eng., CLXXII (1907-8), pp.70-78.
23. Unwin is worth quoting on this: "It had been said that the design of the dam was bad, though it was not said in what respect; and also that it had a bad foundation. That was something like the mayor of a town in France who had seventeen reasons for not firing a royal salute, and the first was that there was no powder". W.C.Unwin discussion to Deacon, p.93.
24. W.C.Unwin, *Cassier's Magazine*, p.18.
25. W.C.Unwin, *Cassier's Magazine*, pp.18.
26. H.Bellet, *Barrages en Maçonnerie*, p.68. and Lévy, *Observations*, pp.10-23.
27. And it can be calculated that a zone of tension covered a height of about 6 mts above and below the facture.
28. Analyses of the accident are replete with discussions about the strength of the materials used: see Langlois, Rupture du Barrage de bouzey, and Lévy, Observations, pp.7-22. The author of "Historic Accidents and Disasters", *Engineer*, 4 December 1942, p.455 makes much of the use of lime rather than cement mortar.
29. Philip A.Morley Parker puts it in an interesting way when he says: "Nevertheless, these facts create a feeling not so much of astonishment at the disaster, as of confidence in a well designed dam. We have a dam violating in every possible manner all the present-day principles of sound construction. The foundation is bad, and the dam is not carried down far enough; yet it only partially fails." – Philip A.Morley Parker, *The Control of Water*, (1913), p.393.
30. Although one must be wary of hindsight here. In 1876, or thereabouts, the basis for appreciating a well proportioned dam was limited to only a decade or so's experience.
31. A.Graeff, "Sur la Forme et le mode de construction ....". p.196.
32. L.Langlois, *Rupture du Barrage de Bouzey*,. p.57.
33. M.Bouvier, "Calculs de résistance des grands barrages en maáonnerie", *Annales des Ponts et Chaussées*, 2 (1875), pp.173-205. Bouvier's method is assessed by H.Bellet, Barrages en Maçonnerie, pp.46-9.
34. L.Langlois, *Rupture du barrage de Bouzey*, p.56.
35. S.Leliavsky, discussion to E.Gruner, "Dam Disasters", pp.362-3.
36. For Vyrnwy see I.Davidson, "George Deacon (1843-1909) and the Vyrnwy Works", *Transactions of the Newcomen Society*, 59 (1987-88), pp.85-6. For Alfeld see S.Leliavsky, *Uplift in Gravity Dams*, (1958), pp.1-2.
37. "Circulaire du Ministère de l'Agriculture du 15 Juin 1897" is reproduced in H.Bellet, Barrages en Maconnerie, pp.293-302.
38. A.J.S.Pippard, "The Functions of Engineering Research in the University", *Jour. Inst. Civ. Eng.*, 33. (Feb.1950), pp.265-284.
39. And interestingly enough, the Bouzey dam itself was treated to an experimental investigation long after the events described; see V. de Belaevsky, "Note sur la rupture du barrage du Bouzey", *Le Génie Civil*, LXXXVI (March 1925), pp.239-40.
40. This is the theme of "Lessons Learnt from Dam Disasters", *Engineering*, 15 May 1964, p.683.
41. H.Bellet, *Barrages en Maçonnerie*, p.70.