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Thematic set:
Keeping lessons alive in engineering geology

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Geology, Engineering and Humanities: three sciences behind the Malpasset dam failure (France, 2 December 1959)

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Abstract: On 2 December 1959, the Malpasset arch dam in SE France suddenly failed, flooding the valley down to the sea, causing huge destruction and more than 400 deaths. Built from 1952 to 1954 for water supply and irrigation, filling of the reservoir was delayed 5 years and the failure occurred following a flash flood of the river the dam was closing. Post-failure studies and expertise during a trial revealed poor field investigations on a micaschist rock foundation crisscrossed by faults, and poor management of construction of the structure. The failure was ascribed to uplift, which moved a rock dihedron defined by a conspicuous fault and a tear along foliation. This paper shows that, in addition to the many traps listed by previous investigations (mostly geological and geotechnical), the human and organizational factors can also shed a new light on this catastrophe. Keeping lessons from Malpasset alive and increasing the knowledge about this case is relevant, as worldwide, after the catastrophe, not only did new regulations on dams appear but also the new fields of geological engineering and rock mechanics were developed. Thus, consciously or not, every geological engineer or rock mechanics specialist is somehow a descendant of this case.

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> If anyone be too lazy to keep his dam in proper condition, and does not so keep it; if then the dam breaks and all the fields be flooded, then shall he pay for any damages (extract from the Hammurabi Code, ancient Mesopotamia, 1750 BC).

After World War II, cities and resorts of the celebrated Côte d'Azur, along the Mediterranean Sea, developed very rapidly, thus requiring ever more water. The Var Department, located in this area, searched for a reservoir site able to store enough winter rain to cover summer needs, including agricultural ones. Var was to become the owner of the Malpasset arch dam near the city of Fréjus. Five years after its construction, on 2 December 1959, the Malpasset dam failed and a huge wave swept down the valley to the Mediterranean Sea, causing more than 400 deaths. This catastrophic event led governments worldwide to introduce new regulations on dam safety and can be considered as one of the main initiators of two new disciplines: geological engineering and rock mechanics. Well known by the members of the dam community, lessons of this case are worth sharing with a wider audience as they show that several traps can interact, as will be demonstrated in this paper. The Malpasset dam failure has long been regarded as a technical failure predominantly involving geological and engineering issues. Although partly true, this statement ignores some important aspects of the catastrophe. In fact, although the failure mechanism may have been technical, most of the root causes must be sought in the human and organizational aspects of the project. Therefore, this paper explores the relevance of examining the case on the basis of the organizational accidents theory developed in the 1980s and 1990s (e.g. Reason 1997). The first part of the paper describes the site, the project and the operation of the reservoir up to the failure; the second part details the post-failure observations, measurements, testing and analyses, and the proposed mode of failure; and the third part briefly presents the organizational accidents theory and details the human and organizational failures that eventually led to the collapse of the dam.

Dam site and dam project

> De tous les ouvrages faits de main d'homme, les grands barrages sont parmi les plus meurtriers, lorsqu'ils se retournent contre lui (Coyne 1943).

(This quotation is taken from Coyne's lesson on dams at the French Ecole Nationale des Ponts et Chaussées in 1943 (personal documentation); it could be translated as follows: 'Among all manmade works, dams are the most deadly when they turn against mankind'.)

This section provides some elements of the construction site and the reasons why it was chosen, and then reflects on the genesis of the Malpasset dam project and its construction phase. It finally describes the reservoir filling from 1954 until the dam failure in 1959.

Site

The Reyran is a small river flowing in a rather wide valley carved in a sand and siltstone syncline (coal measures) in gneissic hills. At 12 km upstream of Fréjus city (formerly a harbour founded by the Romans), the valley narrows when crossing a small gneiss horst. This section looked convenient for siting a rather economical dam retaining a useful reservoir.

Dam project

Geological investigations established the watertightness of the reservoir site; a few boreholes checked the alluvium thickness below the river bed, which was less than 4 m; on both valley sides the rock appeared throughout the site to be a gneiss crisscrossed with pegmatite lenses and dykes, which was thought to be strong enough to form a dam foundation. The design was contracted with the prominent dam engineer André Coyne together with his Bureau.

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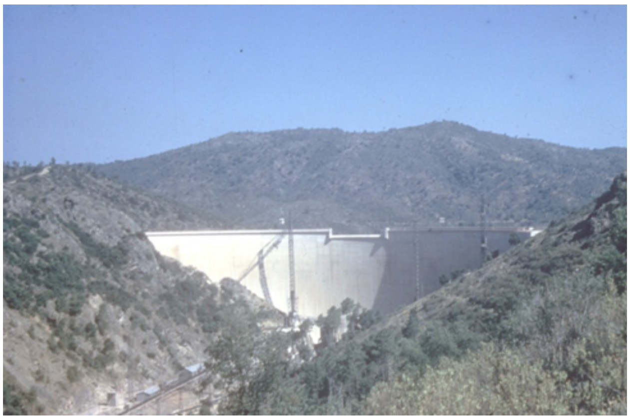

Fig. 1. Downstream view of Malpasset dam close to end of construction: the thrust block appears at right (on the left bank), the spillway weir in the centre (photograph COB, summer 1954).

Coyne had a long experience and expertise in dam design since his involvement with the Marèges dam in central France, 20 years before, and then the Castillon and Tignes dams, each being one after the other the highest arch dams in Europe. Between 1946 and 1952 he had been president of ICOLD (International Commission on Large Dams). When opening a symposium on arch dams (Coyne 1956) he stressed the fact that no failure of an arch dam had ever been reported, in contrast to all other dam types, which had been subject to many failures.

Instead of the gravity dam first considered, Coyne designed a thin double curvature arch dam (Figs 1–3 and Table 1), looking like many similar dams built at this time. He chose the exact position of it based on an examination of minute topographic details of the valley sides; for example, on the left side the crest abutted on a thrust block that was protected from water thrust by a wing wall.

Dam construction

The construction was awarded to a renowned dam contractor, Entreprise Léon Ballot, which had built the Marèges dam with André Coyne 20 years before and many other dams since. The dam was built in partnership with a local contractor. All grouting works were awarded to Bachy (which later became (and is still) Solétanche-Bachy), a well-known specialist in boring and grouting

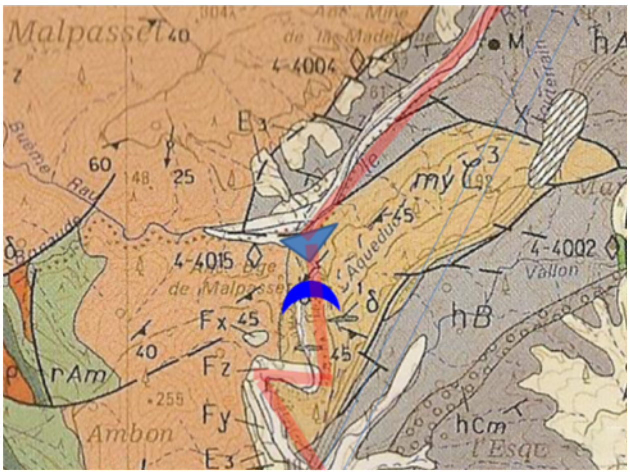

Fig. 2. From geological map of France, sheet Cannes: position of two dam projects, either gravity dam at the gorge entrance, or arch dam close downstream (the river, coloured in red, flows north–south) (gneiss brown; sediments grey). Map Data: BRGM http://infoterre.brgm.fr

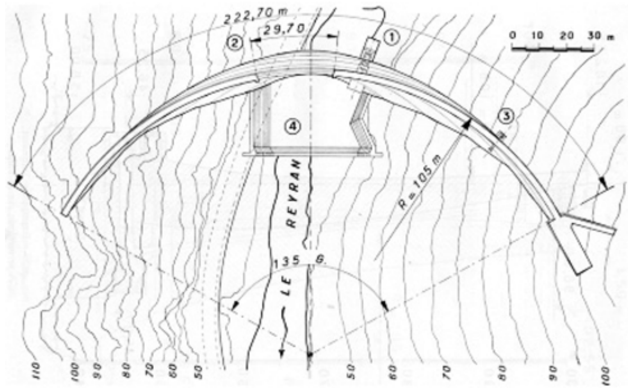

Fig. 3. Layout of the arch dam; its right end abuts on a thrust block protected against water by a wing wall.

dam foundations. As happens on most dam sites, the excavations were to be deepened at some places. (Excavations have the function of finding the right foundation rock. Because the initial estimate of depth is often optimistic, further digging is necessary.)

The dam was made of 16 cantilevers separated by 15 joints. The thrust block was composed of two more monoliths. To leave a passage for the river flow during the construction works, the base of a joint was widened; a bottom valve was provided to control the reservoir's level through the central cantilever (Fig. 4).

The concrete used a crushed aggregate from a nearby rhyolite quarry, and the quality was regularly inspected by the laboratory of Toulon Marine Arsenal. The construction works proceeded for 2 years without any problem.

During summer 1954, the stilling basin under the spillway chute was concreted and the tower cranes were removed. Probably for budgetary reasons (lack of funds or search for savings), the designer was not entrusted with any other contracts for survey or maintenance of the project. A concrete irrigation pipe was laid towards Fréjus, but owing to the lack of money, the distribution network was never completed (this is considered further in the section 'Budget: an external factor with internal effects' below).

Reservoir filling and dam failure

The widened joint was closed on 22 April 1954, thus starting the filling of the dam. Figure 5 shows the evolution of the reservoir level from this time. Delays in buying some upstream land and the torrential regime of the Reyran prevented a total filling of the reservoir, thus only a temporary acceptance of the work was made in August 1956. The reservoir level rose a little every autumn up to November 1959, when huge exceptional rains made it rise dramatically fast. In mid-November leaks appeared in the right bank (7 m below the operating level); the bottom valve was kept closed, so as not to disturb the building site of a motorway bridge on the river that was located about 1 km downstream of the dam. The

Table 1. *Main data for Malpasset dam*

Owner	Var Department
Designer	Coyne et Bellier
Contractor	Entreprise Léon Ballot
Height on foundation rock	65 m
Height on river level	60 m
Crest length	222 m + thrust block 20 m
Maximum/minimum thickness	9 m/1.5 m
Concrete volume	48 000 m^3
Reservoir volume	50 hm^3
Construction years/failure date	1952–1954/2 December 1959

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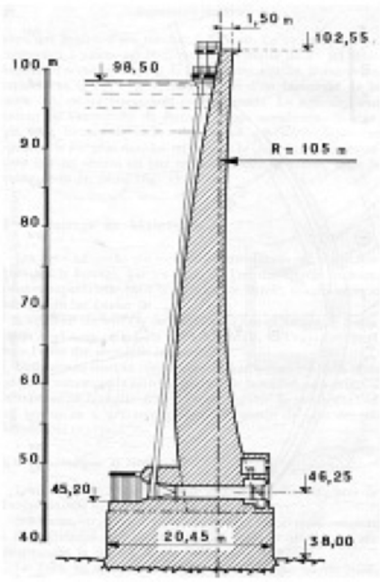

Fig. 4. Vertical section of the dam along cantilever IJ; the foundation block is thicker to encase the conduit of the bottom valve and its control cabinet downstream (at right).

last 3 m of the reservoir were filled in less than a day. At around 6 p.m. on 2 December, the bottom valve was finally opened after discussion between the people in charge of the dam and of the bridge, just before the dam overtopped; but it was too late and the dam broke at 9:14 pm.

The human toll of the disaster was 423 fatalities and many missing, with about the same number injured. In addition to the human victims there were about a thousand head of cattle lost, and thousands of damaged or destroyed buildings, cars and trucks. The Malpasset dam failure is the most deadly industrial accident in France in the twentieth century, after the dust explosion in the Courrières coal mine in 1902.

Post-failure analyses: towards an accepted failure mode

> Il n'y a pas d'ouvrage qui tienne davantage au sol qu'un barrage; il y tient par le fond et par les flancs. Autrement dit, un barrage se compose de deux parties, le barrage artificiel, fait de main d'homme, et le barrage naturel qui le prolonge, qui l'entoure, et sur lequel il est fondé; le plus important des deux, c'est le second, celui qu'on ne remarque pas (Coyne 1943).

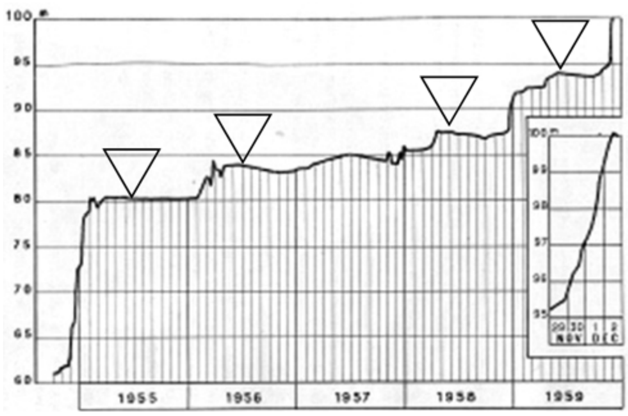

Fig. 5. Graph of the reservoir level from end of construction up to the failure; the window enlarges the three last days; triangles mark dates of measurements.

(This quotation is taken from the opening course on dams given by André Coyne at the French École Nationale des Ponts et Chaussées (Paris) in 1933; it could be translated as follows: 'There is no work holding more on the ground than a dam; it holds by the bottom and the flanks. In other words, a dam consists of two parts, the manmade artificial structure, and the natural dam which extends it, which surrounds it, and on which it is founded; the most important of the two is the latter, the one nobody notices.')

This section is dedicated to the post-failure observations, and measurements and tests that helped the birth of rock mechanics as an autonomous field of expertise and research, and allowed the experts to understand the technical contingencies that led to the ruin of the dam.

On-site observations

Dam site

Today, only a part of the dam remains standing on the right bank, up to half of the cantilever JK, as giant stairs, cut along vertical construction joints and horizontal concrete layers (Fig. 6); conversely, on the left bank only one half of the thrust block remains and a deep excavation was opened in the rock at the foot of what had been the dam foundation (Fig. 6). (The father of the first author, Joseph Duffaut, was head of the Dams and Electricity department in the French ministry of public works; he worked on the catastrophe from the next day.)

This excavation is in the form of a dihedron (Fig. 7) between a downstream face along a fault (see below), and an upstream face torn off along foliation surfaces. At the downstream foot of the dam the concrete apron of the stilling basin has entirely disappeared.

On the right bank (Fig. 8), a wide crevice appeared between the concrete foundation and the rock mass behind the dam, making clear a displacement of the dam of up to 50 cm downstream (see the section 'Measurements and tests' below). Such a feature had never been reported before anywhere, even though it is mechanically

Fig. 6. Remains of the dam on right valley side and valley bottom; the rock appears crisscrossed with white pegmatite dykes; the arrow shows the main fault; the river flow passes through the outlet valve (two assembled photographs, J. Duffaut, 20 December 1959).

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Fig. 7. The 'dihedron', a deep excavation cut inside left valley side at the foot of the dam. The concrete block inside has fallen from the thrust block after the flow (photograph P. Duffaut, May 1960).

Fig. 9. The two main concrete blocks, 600 m downstream of the dam: on the overturned block, the foundation rock remains adhered to concrete (photograph J. Duffaut, 20 December 1959).

necessary: the dam structure moves forward under the water thrust and the rock mass upstream does not follow. The crevice's width depends on the modulus of the rock downstream. This will be measured a few years later at Vouglans dam as only a few millimetres instead of decimetres, within a far stronger rock mass. Thus Figure 8 appears even more important than Figure 7, as it defines the upstream face of the dihedron.

Valley banks and floor

Up to the previous reservoir level upstream of the dam and a little less downstream, the banks are deprived of any vegetation, loose soil, talus and weathered rock, so providing excellent conditions to see the rock mass after the incident, by far better than at any time before. The valley floor appears to have been completely modified, with alternating highs and lows looking like giant ripple marks. Most of the material on the valley floor was sand and gravel from the washed valley sides, with concrete blocks gathered in three main groups just before each bend of the valley.

It was easy to recognize where in the dam the biggest blocks came from: the first heap was about 300 m from the dam and it comprised concrete blocks from the left cantilevers and a few smaller rock blocks (of the large dihedron volume, about 30 000 m^3, only a few small blocks had survived; a proof of its low strength). Before the second bend in the valley, the bases of cantilevers KL and LM are the biggest blocks present, with volumes of about 700 m^3 weighing close to 2000 t (Fig. 9). Two huge blocks went over the motorway crossing and smaller ones went farther downstream. This distribution testifies to the power of the first flow under the maximum water head.

One critical observation was made on the foundation blocks: their lower surface was coated with a slice of rock, proving that a failure had happened within the rock mass, just below the concrete structure and not at the interface or within the concrete.

The main fault

Revealed by the dihedron, the main fault had never been suspected before; only when one knows it do the contours in Figure 1 suggest its path on the left valley side (Fig. 5). Its fresh surface was described as very characteristic of a fault, and a cross-section of it appeared at the lower part of the right bank and below the overturned concrete block. Its strike being perpendicular to the river, it was easy to find it on the opposite bank although there no topographic indication on the contour lines, but the cross-section was made visible by the stripping effect of the flow. Its dip, at about 45° north, makes it cross the valley below the stilling basin and pass about 15 m below the dam foundation. Its thickness was about 1 m. It comprises two bands of finely crushed rock on either side, 3–5 cm thick, with less crushed material between them (Fig. 10). On the left side of the valley, at the foot of the dihedron, the borders had been eroded and the core looked more like a kind of conglomerate, preserving cobble-sized pieces of rock.

Fig. 8. A conspicuous open crevice separates the dam concrete from the rock mass upstream (photograph J. Duffaut , 20 December 1959).

Fig. 10. Close-up on the fault cross-section at the foot of right bank; the finely crushed layers are clearly visible on both sides of the fault material (photograph P. Duffaut, May 1960).

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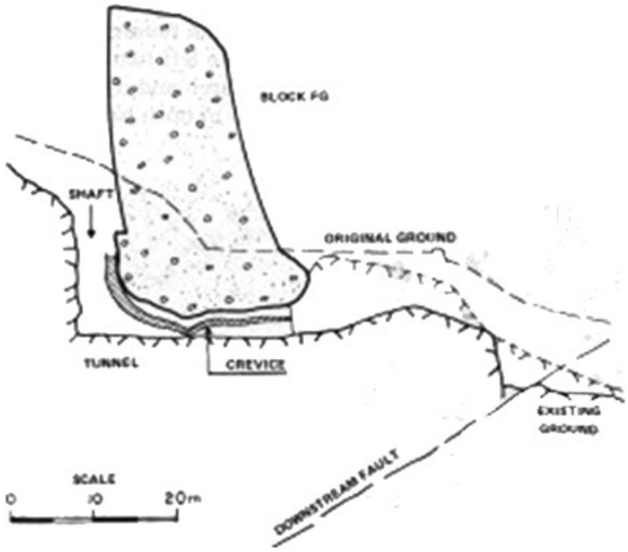

Fig. 11. Cross-section of the base of cantilever FG showing the investigations performed in late spring 1960 and the discovered crevice; the downstream fault appears also below the dam (from Mary 1968; the length scale is faulty).

Geology

The first experts commissioned by the ministry called for a geological survey by Jean Goguel (report published in 2010; Goguel 2010). Goguel spent a few days on site and chose samples for accurate petrological description. A few of the samples close to the dihedron showed sericite, a type of mica suspected to cause the rock to have a higher deformability and lower strength. Goguel stressed the high heterogeneity, from massive augen gneisses to very micaceous ones, and the anisotropies through schistosity and foliation. Goguel described fissures, fractures and faults, mentioning that the scatter of their attitudes defied any statistical presentation: ‘The examination of the rock cleaned by the flow (and of the highway trenches) brought to light an extraordinary density of faults and diaclases in any scale, challenging the structural description, and confirmed by the fact that the digging of the gallery on left bank did not supply blocks of considerable size’ (Goguel 2010).

Late observations

Owing to a very dry spring in 1962, the ponds around the dam base dried, giving access to the very foot of the shell; it was possible to bore a small gallery under cantilever FG (Fig. 11). A water flow below the dam had been suspected from bubbles on the day after the failure and a debris sill formed below the water level by a large discharge during the first days (Fig. 12). The gallery showed a wide crevice inside the rock mass, which explained the flow.

Measurements and tests

Geodetic measurements

The experts led by Goguel also asked for a geodetic check of the position of the dam’s remains. Geodetic measurements confirmed that the movement first developed from the crevice (Fig. 9). The whole concrete arch had rotated as one piece around the fixed right end of the dam, with displacements up to 60 cm, without any apparent disturbance inside the rock foundation. An exception was that the thrust block had moved about 2 m, two times more than that explained by the rotation.

A significant discovery also was made by a close examination of the results of the four geodetic surveys carried out during the construction of the dam (see Fig. 5 for dates of measurements and height of the reservoir). In Figure 13, segments AB show the displacements between the two first surveys (with a 1 year interval and a reservoir level 4 m higher), segments BC, those between the next 2 years (with a reservoir level 3.5 m higher), and segments CD, those of the last year (with a reservoir level 6.5 m higher). Although it seems normal that segments CD are far longer, apparently nobody noticed that segments CD also showed a clear tendency to move towards the left bank.

Fig. 12. The debris sill formed underwater by the flow below cantilever FG (photograph P. Duffaut, May 1960).

Field tests

EDF sent its rock mechanics expert, Joseph Talobre, whose team were used to making jack tests for assessing the rock elastic modulus

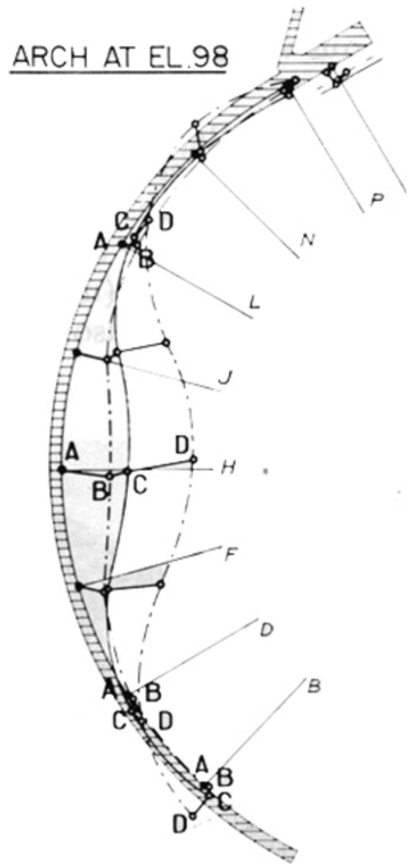

Fig. 13. Displacement measurements of the arch at elevation 98; bold letters ABCD mark dates of the measurements (four triangles in Fig. 5); the inclination towards the left bank of vectors CD is conspicuous.

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around underground penstocks. On dam sites, this practice had been reserved for soft rocks or conversely very hard ones but never applied to standard foundations. Some short shafts and a 30 m gallery were dug to perform the tests. As no basis was available for comparison, EDF ordered the same tests to be performed on seven dam sites at design or construction stage. The Malpasset site results were the lowest of all sites tested, around 1000 MPa, 10 times lower than many of the other sites.

A seismic survey was performed through parallel refraction profiles on the whole left bank, showing a high wave velocity at a depth over 10 m (5–6000 m s^{-1}), although this value was halved closer to the surface. Unfortunately, no data were available on the dihedron rock.

Laboratory tests

Rock samples were dispatched to many laboratories for mechanical tests. Standard testing methods were applied to concrete samples for deformability and strength. Creep had been suspected but was not found. The most comprehensive tests were made at École Polytechnique (LMS, laboratory of solid mechanics) under the supervision of Pierre Habib, and reported by Bernaix (1967). Although modal figures could apply to a sound rock, the very large scatter and scale effect were signs of intense fracturing (see further details below in the section 'The Swiss cheese model of accidents').

Pierre Habib suspected that the permeability of this rock could be sensitive to compression caused by the thrust of the dam. He tested the radial permeability and found that its variation with stress was very high, far more than for any other rock tested in the same way (Habib 2010). Immediately, this unsuspected property was considered as the main cause for the failure, as it could form a deep underground barrier below the dam, upon which an extended water head could push the dihedron upwards (see below, Fig. 14).

The stress distribution in the dam shell had been analysed through a simplified 'trial load' method, and 6 years later it was checked by the newly available finite element method, which fully confirmed the first analysis.

Research in rock mechanics

André Coyne having died a few months after the failure, the task of researching deeper into dam foundations was taken by Pierre Londe, an engineer of the Bureau Coyne & Bellier who was later to chair the International Commission on Large Dams. Londe began to discuss the position of classical drainage and grout curtains (Fig. 14; Londe & Sabarly 1966) and devised a method to check the stability of mega-blocks just under the dam (Fig. 15; Londe 1973, 1993). Together with Pierre Habib, he launched four PhD courses in connection with Ecole Polytechnique and various universities: Claude Louis worked at Karlsruhe, Germany, under Professor Mueller, on water flow in rock mass fissures (Louis 1968); Bernard

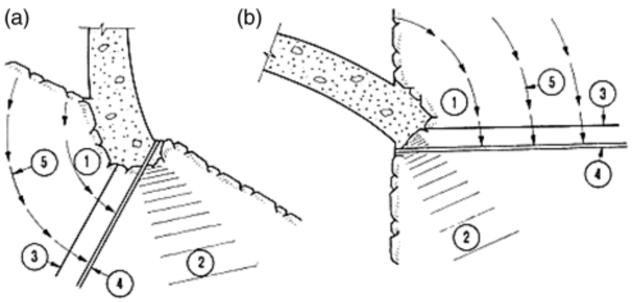

Fig. 14. Vertical (**a**) and horizontal (**b**) cross-sections of arch dam rock foundation showing: 1 & 5, flow lines; 2, compressed zone; 3, grout curtain; 4, drainage curtain (after Londe & Sabarly 1966).

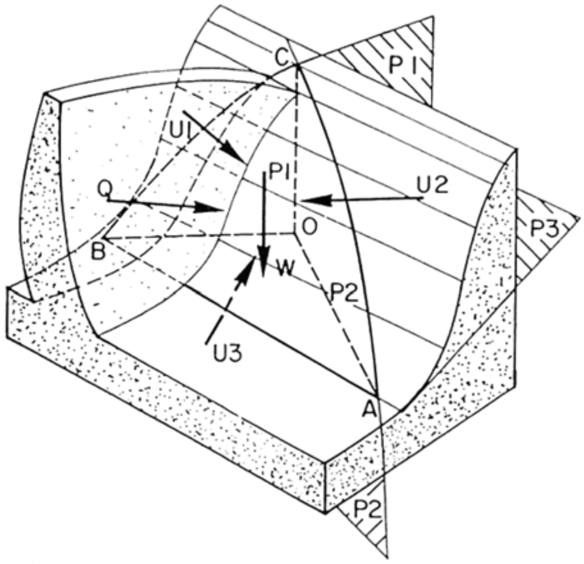

Fig. 15. Scheme of the forces acting on a tetrahedral rock block in the abutment of an arch dam: planes P1, P2 and P3 limit block ABC; W, block weight; Q, dam thrust; U1, U2, U3, uplift pressures (after Londe 1973).

Schneider worked at Grenoble on analysis of seismic signal (the so-called 'petite sismique' method; Schneider 1967); Bernaix (1967) and Maury (1970) worked at Ecole Polytechnique, on laboratory and model tests, the latter through photoelasticity (Fig. 16). Within less than 10 years Rock Mechanics had made tremendous progress.

Understanding the failure mechanism

Three enquiry commissions have worked on the trial, the first one commissioned by the government, and the other two by the tribunal, altogether involving 18 experts. The third commission was named because the first two could not agree on the issue of the failure's predictability. New investigations in spring 1962 helped to make progress: Bellier (1967) and Mary (1968) proposed the following mechanism (schematized in Figs 17 and 18), which is compatible with all investigations.

(1) Owing to the thrust of the dam, the permeability of the foundation rock was reduced by a factor of 10 or even much more, so forming a true underground dam.

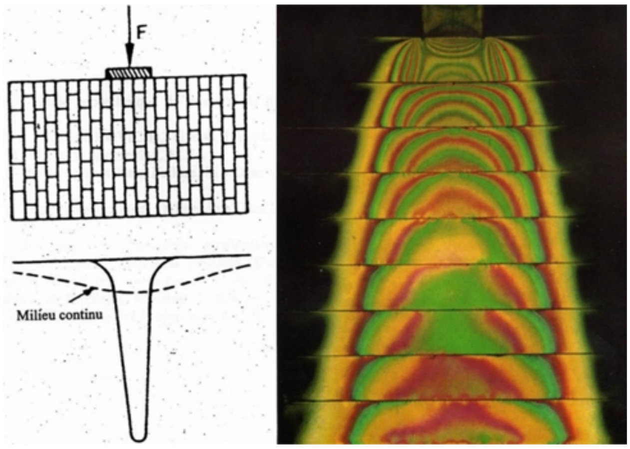

Fig. 16. Stress distribution under a punch; left, brickwork models by Bernaix; right, photoelasticity by Maury (no friction between horizontal planes).

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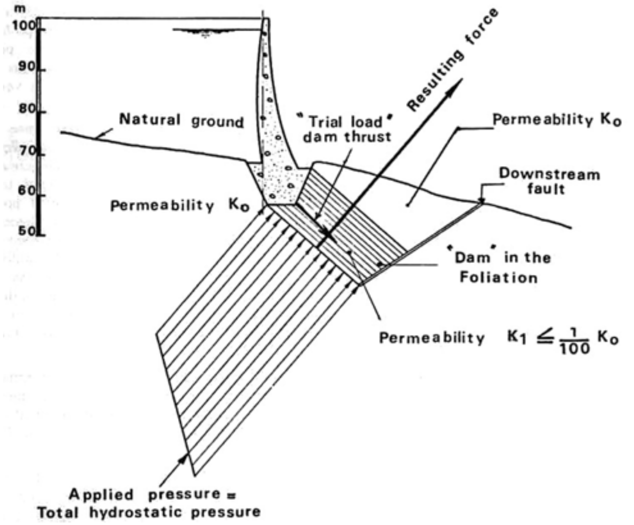

Fig. 17. Cross-section of the dam and foundation at mid-height of left side: the full hydrostatic pressure on the 'underground dam' created by the arch dam thrust can push the dihedron upwards along the fault (adapted from Mary 1968).

(2) This thrust may move the dihedron along the fault, both upwards and towards the left; the cantilevers on the left bank could no longer take support from the dihedron and the whole shell tried to obtain support from the thrust block.

(3) Because the thrust block had not enough weight, it gave up after a 2 m displacement, which ended any arch effect.

(4) The whole dam shell burst, some parts in horizontal bending and others in vertical bending.

Of course the great deformability of the rock mass, especially on the left bank, helped open a fissure along the heel of the shell (still visible on the right bank); it was easily propagated at depth on the left bank because of foliation of the gneiss, so the water thrust on the dam structure and its foundation rock increased (as the square of the head). Views may differ in weighing the relative influence of the deformability or the sensitivity to stress of the rock mass; however, both operated in the same direction and were unknown at the time.

Some years later, in 1982, Leonards (1987) invited at Purdue University, Lafayette, Indiana, a colloquium on four recent dam accidents (Malpasset in 1959; Vajont, Italy in 1963; Baldwin Hills, California, in 1973; and Teton, Idaho, in 1976; the last two being fill dams). Among international experts, P. Habib, P. Londe, G. Post and D. Bonazzi for France, Laginha Serafim for Portugal and W. Wittke for Germany all agreed with the mechanism first proposed by Mary and Bellier (e.g. Post & Bonazzi 1987). Among more recent papers, Damjanac & Fairhurst (2000) checked the role of water pressure inside the rock mass using novel programs.

However, although the scientific rigour of the experts allowed identification of the technical and natural traps and failures we have described so far, there is a phenomenon whose importance has been neglected or at least underestimated: this phenomenon is the capacity of human organizations to create intrinsic conditions for failures and accidents within themselves.

The organizational accident theory

> We cannot change the human condition but we can change the conditions under which humans work (Reason 2000, p. 394).

An exclusively technical analysis of any accident neglects a set of aspects likely to explain it. Unrecognized in the 1950s and 1960s, Human and Organizational Factors (HOF) have since been subject of numerous works in the field of safety studies. This section offers a brief history of the HOF studies and presents one of the most popular accident causation models.

A brief history of safety studies

Since the industrial revolution, safety has mainly been a technical issue: efforts of design engineers and maintenance ensuring the technical reliability of the systems. The variability of individuals was identified early as a risk factor (Heinrich 1936), but back then efforts to improve matters focused on how to rationalize and constrain behaviours ('one best way'). It was not until the aftermath of World War II that the 'human factor' became a specific field of scientific investigations. The war effort indeed made technical or organizational change difficult, by guiding optimization efforts towards the operator's performance and training. After the war, engineers and ergonomists become interested in the person and their interaction with the machine (this is the birth of the concept of the Human–Machine Interface). In 1958 the Human Factor and Ergonomic Society was created in the USA. At the time, variability and human errors were studied to prevent accidents that affected productivity. The first methods of quantifying and predicting human errors were born (Swain 1963).

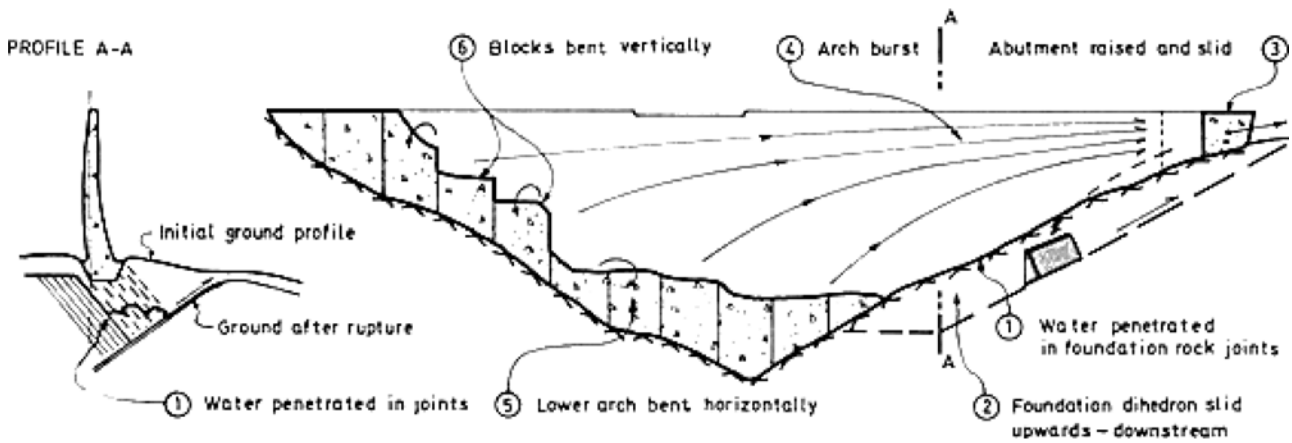

Fig. 18. Phases of failure in downstream view and profile A–A. (1) Water penetrates the traction fissure along the dam heel; (2) the foundation dihedron is pushed along the fault, upwards and rightwards; (3) the whole arch thrust concentrates on the thrust block, which cannot withstand it and gives way; (4) deprived of the arch effect, the shell bursts; (5) and (6) the right bank cantilevers fail in bending.

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A series of accidents from the late 1970s to the late 1980s (including the 1979 Three Mile Island and 1986 Chernobyl nuclear accidents) initiated a paradigm shift: the human factor focusing exclusively on the operator's actions and errors turned into a broader organizational approach. The concept of organizational accident, proposed by the British psychologist Reason (1990, 1997), was gradually (but widely) being adopted during the 1990s.

The organizational accident theory no longer considers operator error as the root cause of the accident but as the consequence of a set of systemic factors (ranging from the organization itself to the local work environment and of course cognitive process; see below). It thus opens up the field of investigation from psychology towards other human sciences such as sociology and anthropology; new concepts appeared (e.g. resilience engineering, safety culture, highly reliable organizations). Further details on the evolution of thinking and the study of accidents have been given by Guarnieri *et al.* (2008). In the next section, we present in more detail Reason's organizational accident theory and its most popular accident model: the Swiss cheese model.

The Swiss cheese model of accidents

> Major disasters in defended systems are rarely if ever caused by any one factor, either mechanical or human (Reason 1990; p 768).

James Reason is a psychologist who specialized in the 1970s in the study of everyday errors (e.g. absent-mindness, slips of the tongue, attentional failure). His work led him to propose a taxonomy that distinguishes active and latent errors (Reason 1990) (the term 'latent error' would later be replaced by the broader one 'latent conditions'). To demonstrate the respective roles of the two types of errors in the aetiology of accidents, Reason used the 'resident pathogens metaphor'. According to this metaphor, industrial accidents are comparable with cancers or heart attacks, being the result not of a single cause but of a combination of several factors (each necessary but not sufficient to overcome the defences of the immune system or the industrial one). It follows that: (1) the accident sequence is rooted in organizational processes (e.g. planning, design, communication, maintenance); (2) latent failures, thus created, produce deleterious effects in different organizational structures (departments, services, teams) and ultimately affect the local working environments where they create 'local conditions' (e.g. fatigue, technical problems, lack of communication, contradictory objectives); (3) these 'local conditions' not only increase the probability of errors, but also affect the integrity and efficiency of the system's defences.

Trying to capture this understanding of the complex accident phenomenon in a drawing, Reason published a fairly simple model in 2000 that quickly became the most widely used, commented on and cited accident model in the safety studies community (Larouzée & Guarnieri 2015). This model was based on a new analogy, Swiss cheese (see Fig. 19), and has thus been nicknamed 'the Swiss cheese model'. Each slice of cheese represents a defence of the system (being technical, human or organizational). The holes represent weaknesses of these defences (one must imagine the holes being 'dynamic': moving, opening or closing depending on managerial arbitrations, audits or maintenance plans). These holes can be created by latent conditions or operator's active errors. This model shows that an accident occurs only when the holes are lined up by an (often) improbable combination of several factors.

In the next section, we will try to show that the Malpasset accident was a genuine organizational accident. We have already detailed its technical causes; we will now turn to its human and organizational causes.

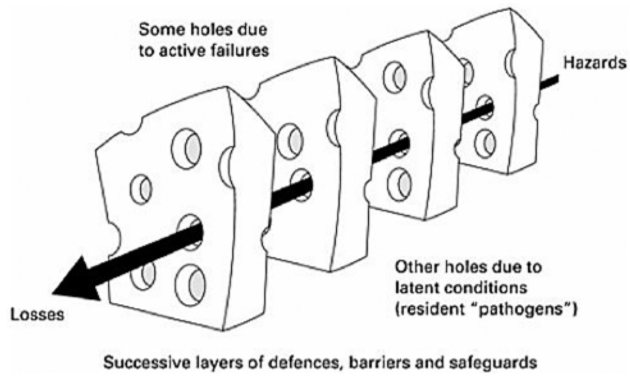

Fig. 19. The Swiss cheese model of accidents, where each slice of cheese represents an altered defence of a sociotechnical system (Reason 2000).

A non-technical story of Malpasset dam failure

This section focuses on a set of non-technical facts (organizational factors) that have been in play in the collapse of Malpasset (each necessary but not sufficient). Reason (1997), amongst others, has warned of the risk of going ever further in the quest for latent conditions, so we start by explaining the time bounds we have set for our approach. The rupture of the dam was not a consequence of any individual human action (active error) and the final judgement stated that 'no fault has been committed, at any stage'; so far it seems reductive and misleading to attribute the catastrophe to fate or solely to the limits of technical knowledge at the time. The organizational factors of the accident were not recognized, or at least not named as such, during the commissions of inquiry, but it is now possible to highlight many of them. Our approach does not intend to discuss the judgement that has been made; it aims rather to discuss the role of these organizational factors so as to contribute to the prevention of such accidents in the future.

How far to dig?

Reason gave two precious guidelines for the conduct of post-accident investigations: (1) he warned that 'the pendulum may have swung too far in [the] attempts to track down possible errors and accident contributions that are widely separated in both time and place from the events themselves' (Reason 1997, p. 234); (2) he thus reminded us of the necessity to focus on what one can manage and/or change.

In response to the first guideline, we defined *a priori* the time boundaries of our approach. The starting point is the 1954 decision of the Conseil Général du Var to collect and study projects to address the needs of water supply in the Fréjus area. The ending point is 2 December 1959 at the moment when the front of the submersion wave had reached the Mediterranean Sea, 20 min after the dam failure; indeed, during those 20 min it was still theoretically possible to activate protective barriers ('protection' or 'mitigation' barriers are activated after the event and must be distinguished from 'prevention' barriers intended to prevent its occurrence) to reduce the impact of dangerous phenomena (e.g. alerts or evacuation). We stress that no such protective barrier was activated at Malpasset and that no such barriers (alert plan, or plan of evacuation) existed at the time.

In response to the second guideline, we propose to distinguish the organizational factors that we present as causes of the accident as (1) the fortuitous causes and (2) the induced causes. This distinction directly questions the 'opportunity' to act rather than the 'merits' of an action, a non-action or a decision (Table 2).

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Table 2. *Taxonomy of failures distinguishing 'induced' and 'fortuitous' causes*

	Definition	Generic example
Fortuitous	Events located outside the field of action of the actors involved and independent of their decisions. A fortuitous failure is independent of the actors involved	Heavy rain, political decisions
Induced	Events located inside the field of action. Notion of free will, possibility to do differently. An induced failure is caused by a choice, an act	Oversizing a valve (or not), allocation of budgets

Expert commissions

Several experts, engineers and academics, including geologists, have worked, from the first days after the disaster and for many years later, to establish explanatory scenarios. A first group of six high-level engineers from ministries (and one representative of contractors) was appointed by the ministries to search for any causes of the failure; they verified that no earthquake occurred and discarded any effect of explosives use on the rock cuts along the motorway, a short distance from the site (Fig. 20). They called one geologist, Jean Goguel, who spent about 5 days on site and provided a report to the first commission (Goguel 2010).

A few days later, the court of Draguignan appointed six academics to establish responsibilities; they pointed out many faults and concluded that the Génie Rural bore the whole responsibility (André Coyne the designer had passed away before any trial, recognizing his entire and sole responsibility). The cause of the dam failure was for them directly related to the water pressure under the left bank of the dam. Uplift was known about, as it was responsible for previous dam failures at Bouzey, France (Lévy 1895). Finally, they noted the absence of studies, geotechnical tests and controls of the first filling. This established the liability of the builders and the dam operator.

A counter-expertise was requested by their lawyers. A new panel of six experts, two from Académie des Sciences level, and with a younger soil mechanics professor, the only one to fully understand uplift, then confirmed the role of circulation of water under the dam but contradicted the other conclusions, arguing that this phenomenon was unknown at the time of the construction of the dam and escaped direct investigation (it was only discovered with the benefit of methods and techniques developed during the lengthy trial proceedings). The second panel of experts also stressed that the standards did not require geotechnical investigations at that time.

After two successive judgements, the court finally declared no malpractice, exempting the builders of the dam whose work was considered 'technically flawless' (CASS 1967). However, there is no such thing as fate to explain the Malpasset tragedy; this judgement simply reflects the fact that incompetence is not a crime. One can imagine that today, such a trial would involve an investigation of the organizational mechanics (mainly in search of responsibilities). Let it be understood that this article is not intended to discuss the 1967 Court of Cassation's conclusions. It does not address the legal study of responsibilities; it proposes a scientific study of the organizational mechanisms, in the light of newer theories from the field of safety studies and humanities. We assume that, although there was no analysis of organizational factors in the Malpasset trial, their discussion is nonetheless essential to the global understanding of this disaster to avoid its recurrence.

Malpasset: an organizational failure

In the following, we do not intend to deliver another detailed chronological account of the facts (for this, the reader may refer to Foucou 1978). This section aims to isolate, characterize and comment on human actions or decisions that contributed to the disaster. Each element described below represents either a hole in a slice of Swiss cheese, or at worst the total absence of a slice (i.e. a defence; see Fig. 19). It should be noted that all the failures presented below are 'human failures' (which are not, for example, the fault or the compressive sensitivity of rock's permeability) but this does not mean that they all are individual failures. Some may be but others may come from the organization or even the social or economic context. The main sources used in this part are Foucou (1978), Valenti & Bertini (2003), Moine (2009), Duffaut (2009, 2010, 2011), Boudou (2015) and also direct knowledge of the accident gained by the first author.

Geological studies: geologist are humans after all

The geologist who was consulted for the pre-project studies was Professor Corroy from the University of Marseille (France), an expert in Mediterranean geology but with no experience in dams. He was probably chosen because of his geographical proximity to

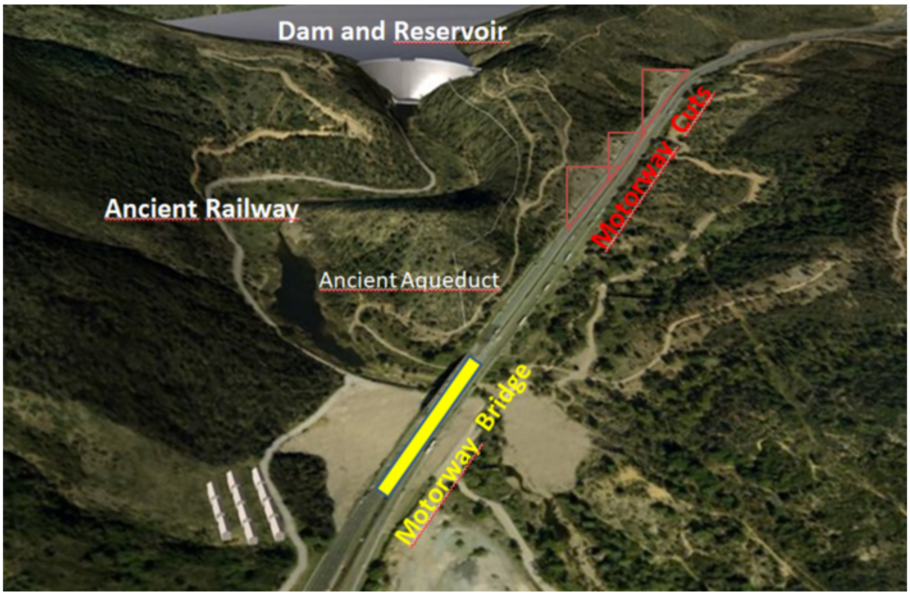

Fig. 20. J. P. Christie, superimposed on a Google Earth view of the Reyran gorge, the dam and the motorway, with its bridge on the river and the triangle cuts the explosions of which were suspected to have affected the shear strength of the dam foundations (courtesy Cinécapital), a hypothesis earlier denied. The barracks of the dam worksite were reused for the motorway. Map data: Google, DigitalGlobe.

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Table 3. *Synthesis of the human failures related to geology*

Failure	Origin	Category	Type
Choice of Professor Corroy, a geologist not specialized in dams (chosen for his proximity)	Organizational	Decision Skill management	Induced
Decision by André Coyne to move the dam site and to build an arch dam instead of a gravity dam (with only mail consultation of the geologist)	Individual	Decision Overconfidence Communication	Induced
Agreement of the new dam's site by Georges Corroy (without further field investigations)	Individual	Communication Risk appreciation	Induced
Absence of strengthening work after the rock excavation and during the construction	Organizational	Risk appreciation	Induced

the dam site. It follows that (1) his study was based on a reasoning in terms of the tightness of the reservoir and risks of instability of the structure, (2) for the abutments he simply reasoned in terms of compression, and (3) the surface faults were appreciated only in terms of watertightness, and thus thought to be without impact. Somehow, the geologist reasoned on only a part of the problem (as he was lacking a necessary experience with dams).

In 1949, the original dam project was modified by Coyne & Bellier (see above). Consulted only by mail, Professor Corroy gave, in 1950, his written agreement to move the project's site 200 m downstream, considering that anchoring would '*a priori*' not present any other difficulty (quoted by Foucou 1978). The decision to move the structure and change its type was technically and financially motivated: it allowed an arch dam to be built instead of a gravity dam (this being more aesthetic and less expensive) and increased the volume of the reservoir. However, taken without further geological studies, it led the designers to blindly locate the dam just over one of the 'natural traps' (the dihedron).

Finally, even if it was noted that the left bank abutment rocks were much degraded, nothing was done to consolidate them. During the rock excavation, it was found that the gneisses were much degraded but again no corrective action was undertaken. Overall, the geological monitoring was never allowed to 'sound the alarm' (Table 3).

In summary, it can be observed that if the geological analysis was incomplete and although the knowledge of the time was limited, it was subject to 'technical' insufficiencies. But moving the dam without any real coordination dialogue between the project engineer and geologist, nor any field investigation, and starting construction without strengthening work were decisions made without a safety net. Such decisions also imply the acceptance to operate blindly. Here, we note poor communication between the project engineer and the geologist and globally a poor appreciation of the risks (owing to a lack of specific experience of the geologist and possibly to an excessive confidence in arch dams of the project engineer).

Budget: an external factor with internal effects

The lack of attention to geological studies appears even more clearly when it is noted that of the 27 million francs originally planned for geological surveys only 8 million were spent. Economic pressure is, therefore, what can (directly) explain the facts listed in the previous subsection, and budgetary considerations will certainly have weighed on the project.

The total cost of the dam and its main water-supply networks for drinking and irrigation water was a significant financial effort for the Var Department. In the context of post-war reconstruction (the Marshall plan was launched in 1947), the project was part of an ambitious financial plan from the Commissariat Général au Plan, so the Department should have received subsidies from the Ministry of Agriculture (for the dam and the irrigation network), the Ministry of Defence (for the water supply of the Fréjus Saint-Raphaël military base) and the Ministry of the Interior and Reconstruction (for the drinking water network). However, during the 1950s, a period of monetary inflation caused the franc to lose about 10% of its value per year. This devaluation of the currency undoubtedly pushed the project stakeholders, especially the ACJB office, to complete the work as soon as possible. This economic pressure helps to explain the choice of a more economical arch dam and the non-occurrence of certain studies or work.

Financial resources also fell after the construction of the dam because the financing from the Ministries of Defence and Interior was not obtained. As a result, the irrigation network was never operational (the main branch of the water supply system was received too late during 1959; Table 4).

Although mostly fortuitous, it is important to note that ecosystem and context factors (in this case the national context of economic recovery and then money inflation) exerted a non-negligible influence on the project (through the choices and arbitration of its actors).

A project made of humans

We have already mentioned that this or that might have 'influenced the project'; of course, a project does not think or act by itself. But, although this may seem trivial, it is important to keep in mind that a project, an administration or any other human organization is in the end only made up of humans. As Douglas (1986) demonstrated, there is a mutual influence between the thought of institutions and the thoughts of individuals that compose the given institution.

Table 4. *Synthesis of the effects of budgetary environment on the actors*

Failure	Origin	Category	Type
Use of 8 out of 27 million francs earmarked for geological studies	Organizational	Risk appreciation	Induced
Period of economic recovery (ambitious plan from the French Commissariat Général au Plan); but significant currency inflation threatening project credits	Ecosystemic	n.a.	Fortuitous
Drop in financial resources after the dam's construction (withdrawal of funding from the ministries of the Interior and Defence)	Ecosystemic	n.a.	Fortuitous

n.a., not applicable.

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One of the factors of failure (which can only be described as such *a posteriori*) was the tremendous authority of André Coyne. Coyne was a recognized personality in the dam community; he was also known for his quick wit, his great intelligence but also for his dry character and his authority (it was said of him that he frightened some of his younger collaborators). These traits had undoubtedly been a strength that allowed him to achieve his goal (for all of which he received the prestigious grand prize of architecture in 1953), but they somehow played against him in the Malpasset case. During the 1964 trial, geologist George Corroy explained the confidence he had in André Coyne, who had already built many dams. He thus explained that he was 'subjugated' by Coyne to whom he attributed 'the soul of geologist, who admirably knows the rock'. Corroy also said that he had referred to the project manager (Coyne) for decisions regarding in-depth ground investigations and had preferred to gradually withdraw from the project. Another example of the great confidence inspired by Coyne can be found in the response made by Fréjus' mayor Henri Giraud to catastrophist statements published in a local newspaper (*Nice-Matin*): 'What you cannot ignore is that the author of the project is Mr. Coyne, Inspector General and General Chairman of the Société d'étude des barrages de France. To date, Mr. Coyne has built more than eighty dams on wadis, on rivers, and torrents. Mr. Coyne has just been appointed by the Government of Southern Africa to study a dam on the Zambezi River, dam that will retain one billion 600 000 m^3, or thirty-five times more than Malpasset dam'. (The response was published in the newspaper *La France* on 5 February 1957).

Excess of confidence mixed with poor communication amongst stakeholders and lack of skills or experience led 'the project' to another critical decision regarding the sizing of the bottom valve. We have already mentioned the torrential regime of the Reyran and that the filling of Malpasset was marked by a dry period of 5 years followed by long and heavy rains in late 1959. It has been estimated (Moine 2009) that the maximum filling rate (reached during the last 24 h) was *c.* 150 $m^3\ s^{-1}$. In the absence of a diversion tunnel, the only way to control the first filling would have been to have a bottom valve capable of evacuating such a flow. However, the valve of Malpasset was sized for a flow three times lower (50 $m^3\ s^{-1}$). It was considered that the bottom valve was dimensioned according to the state of the art. However, taking into account the absence of a diversion gallery and the torrential regime could have alerted the owner to a control issue regarding the first filling. We note here a double phenomenon: (1) overconfidence in the standards and state of the art preventing any questioning of the evidence that showed deviation from these; (2) partial consideration of the first filling problem: the fear was not being able to fill the reservoir behind the dam quickly and not that its filling may go out of control.

Finally, owing to the lack of a first full filling, only a temporary handover of the dam took place on 9 February 1955 and 1 August 1956. This induced fuzzy responsibilities between the builder and the owner, the effects of which weighted on the surveillance plan (see the next subsection and Table 5).

Although of various origins, the human failures in connection with the project are all induced. We can note the deleterious effects of overconfidence, both in the expertise and decisions of André Coyne and in the technical state of the art. Blind confidence can become a danger. Indeed, it alters the vigilance, the critical spirit, as much as the possibility of contradictory exchanges, of questioning one's opinions, etc. As the saying goes, 'trust but verify', and control failed on many levels in the Malpasset case. Lastly, we note that the relation to time, perceived as a constraint (delays in the expropriation of the old mine, economic context pressing the final handover of the work), influenced decisions and practices.

Technical controls but human planning of the controls

We have mentioned the work of Douglas on how institutions think. To understand the facts described below one must bear in mind the effects produced by what must be called technocracy, which was important during the 1950s and 1960s. The Corps des Ponts et Chaussées was (and still is) a very prestigious state body, much more prestigious than the Génie Rural. This state of affairs contributed to giving more weight to the opinions of engineers from one state body than the other; in particular in the matter of technical decisions concerning the surveillance of the dam. We also mentioned that the irrigation system had never been operational because of delay in delivery of certain parts. This had the effect of depriving the dam of its utility; it thus became an almost useless concrete wall, and this possibly made its monitoring less urgent.

In 1952, the Var Department mandated the Génie Rural to be responsible for the surveillance of the dam but without issuing any specifications. (In fact, it was the ACJB office that ensured it until the end of the construction work in 1954, before passing the baton to the Génie Rural.) Mr Dargeou, a Génie Rural engineer, asked the Prefect several times to specify and organize the general survey and monitoring (including its development of the structure's deformations and their interpretation). On 7 January 1955, the Departmental Commission authorized the signature of an agreement (which was only to be signed more than a year later on 15 February 1956) entrusting the Société de Photo-topographie to undertake the topographical surveys of the dam, but still no expert was mandated for interpretation of the measurements. Most importantly, no action was taken between the completion of the work and the start of dam reservoir filling (see Fig. 5). This lack of reference measurement inevitably altered the interpretation of future campaigns (there is no record during the filling of the first 40 m). A check in 1958, communicated to the Coyne office, did not show any irregularity. In summer 1959, the last measurements were made, and their results reached the Coyne office only shortly before the dam break; they were also transmitted (4 months later, in November 1959) to the Génie Rural, which forwarded them to the prefect and the Conseil Général du Var for simple archiving. The question arises: 'Who monitors what? The client sends the measures to the prefect and no one is able to interpret them' (Duffaut 2010). However, these measurements revealed the presence of non-negligible deformations. (Without being alarming (maximum deformation of 17 mm on the deep part of the left wing) they indicate rotation of the structure.)

In terms of survey, the presence of a guard on site must be mentioned. This guard, Mr André Ferro, was responsible for making visual observations of the terrain and structure during filling. He is the one who first noticed seepages in the dam's

Table 5. *Synthesis of failures in the project*

Failure	Origin	Category	Type
Not calling into question Coyne's opinions	Individual	Communication	Induced
Sizing of the bottom valve in accordance with the rules of the art (could have been oversized)	Technical State of the art	Risk appreciation	Induced
Dam delivery before completing the first filling (5 year dry period combined with delay in the expropriation of the upstream mine)	Organizational	Risk appreciation Skill management	Induced

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structure in November 1959, along with the appearance of springs on the right bank. He also noted the appearance of cracks in the stilling basin, always on the right side (Duffaut 2010).

The observations of André Ferro gave rise to the first concerns. On 30 November, a request for preventive drawdown was made by the Génie Rural but it was refused by the Ponts et Chaussées so as not to damage the construction site of a highway bridge, the formwork of the piers being still in place (Duffaut 2009). The operating level of the reservoir (98.5 m Nivellement Général de la France (NGF)) was eventually exceeded on the morning of 2 December (reaching a level of 100.00 m NGF) but the bottom valve was kept closed. In the afternoon, an on-site crisis meeting of the engineers of both the Ponts et Chaussées and the Génie Rural finally led to the decision to open the bottom valve (it was actually opened at 6 pm, 3 h before the rupture; Valenti & Bertini 2003).

The existence of hierarchical relationships between institutions is outside the field of action of most actors in a system. However, it is interesting to keep in mind the difference between an organization chart (the organization as it is ideally thought of) and a sociogram (the organization as it actually exists). Within the actor's field of action this time, let us note the negative effects of the administrative slowness demonstrated by the Conseil Général du Var (concerning the implementation of an adapted monitoring plan) and a relative recklessness of the services of the prefecture regarding the existence of a potentially dangerous dam on their territory and the skills of the people in charge of its integrity.

Most failures in monitoring and control are not fortuitous. They were induced by poor risk assessment or perception (e.g. regarding the alerts of the guard, the decision to save the piers of the motorway bridge) and bad appreciation of 'weak signals' (e.g. lack of early concerns with the deformations observed by the geodetics). (One could also consider a (very) weak signal the toponymy of the selected site: the pronunciation of 'Malpasset' in French is the same as 'mal passé' meaning '(it) went wrong'; in fact, Malpasset means 'bad track' because of the danger of brigands). Of course, all the elements analysed above also came into play in a systemic manner: Coyne's authority and accorded trust, the overconfidence in the arch dam (none of which had ever failed before), the imperative to complete the reservoir filling to achieve the final delivery (partly for economic reasons dictated by the economic background of the French society); all these factors contributed to shaping the risk perception. This risk perception itself affected the relationship to time in the decisions (e.g. delay of valve opening, crisis meeting with Coyne convened too late), and so on up to the failure.

Some considerations about the absence of protective measures

It has been possible to draw a very precise chronology of the events following the rupture thanks to testimonies and recordings of tension drops on the electric network indicating the fall of pylons or the destruction of transformers by the flood wave (this chronology can be consulted online at http://frejus59.fr/Malpasset_chronologie (last accessed March 2019)). It was thus possible to establish that it took 26 min for the wave to reach the town of Fréjus and another 10 min before reaching the sea, flooding the aero-naval base and killing the last victim, a meteorologist who remained at the observation post on the night of 2 December.

Although very short, this delay could nevertheless have made it possible to shelter a part of the population and thus limit the number of victims. However, and this was emphasized during the trial, there were no such emergency plans at the time. Moreover, after 6:30 pm there was no direct telephone connection between the emergency management officer (an army squad leader) and the Var prefecture. More surprisingly, and witnessing the low awareness of risks and the interest of a potential warning chain, the guard André Ferro did not have a phone in his house and had to use the one at the work-site. However, even assuming he had a phone, as his house was one of the first destroyed by the wave, he could not have used it. The weakness of the alert management was not retained as a determining factor during the trial.

The Malpasset dam failure was accompanied by several aggravating factors (all absolutely fortuitous but also unconnected and unlucky) that contributed to an increase in the number of victims of the disaster. The failure occurred at night, when most people were at home and younger children were asleep; it was a total and instantaneous failure; and the localities that were most affected were mainly located very close downstream of the dam. These aggravating factors were also present in the 1963 Vajont dam disaster in Italy (failure at night, instantaneous phenomenon and

Table 6. *Synthesis of failures in the different controls*

Failure	Origin	Category	Type
Technocracy (Ponts et Chaussées v. Génie Rural)	Organizational	Policy	Fortuitous
Absence of external control (community as owner (MOA) and public body as engineer (MOE))	Organizational	Policy	Fortuitous
Poor communication between owner (MOA) and engineer (MOE)	Organizational	Communication Skill management	Induced
4 year delay in the monitoring and maintenance plan requested by the Génie Rural from the first reservoir filling	Organizational	Risk appreciation Relationship with time	Induced
No interpretation of the measurements by anyone responsible (and no reference measurements)	Organizational	Skill management Risk appreciation	Induced
Guard not qualified (thus not trusted)	Organizational	Skill management	Induced
July 1959: last measurement campaign, showing important distortions of the structure (4 month delay in reporting of the results to ACJB consulting firm)	Human	Risk appreciation Relationship with time	Induced
Late November 1959: significant seepage downstream of the dam and cracks in the protective mat. Crisis meeting convened (too late) on site with ACJB on 7 December	Human	Risk appreciation Relationship with time	Induced
3 days before the dam break: the Génie Rural requested authorization to open the bottom valve; refusal owing to the construction of a motorway bridge downstream	Organizational	Risk appreciation	Induced
	Ecosystemic	Relationship with time	

MOA, maîtrise d'ouvrage (project owner); MOE, maîtrise d'oeuvre (project management).

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Table 7. *Absent protective measures in Malpasset dam failure*

Failure	Origin	Category	Type
Absence of emergency plans (alert, evacuation)	Organizational	Policy	Fortuitous
The dam guard had no phone in his house	Organizational	Communication Risk appreciation	Induced

immediate proximity downstream of the most affected localities). The Vajont dam disaster caused more than 2000 casualties. On the other hand, and as an illustration rather than a comparison, the Grand Teton dam failure in the USA took place in the daytime and in a progressive manner (albeit rather rapid) that allowed an emergency plan to be activated (still 14 people died).

Discussion

> La complexité provient de la quasi impossibilité de maitriser les phénomènes vivants […] instables par définition (Fiévet 1992). ('The complexity comes from the almost impossibility of mastering living phenomena […] unstable by definition')

Reviewing a disaster that has entered the history of a scientific community in the light of contemporary theories allows a long and meticulous search for explanations to be fulfilled. This contemporary reading is also intended to keep these lessons alive, either by bringing them to the knowledge of new people or by subjecting them to debate from a new angle. It is in such a spirit that the authors of this article were invited to give a keynote lecture on the Malpasset dam failure to the 2018 Engineering Group of the Geological Society (EGGS) annual conference 2018 themed 'Keeping Lessons Alive' held at Christ's College, Cambridge.

Reviewing the Malpasset dam failure in the light of the study of the humanities also invites an ethical and moral reflection on the articulation what of we know, what we can do and what we must do. Thus, the distinction we have proposed between induced and fortuitous failures could be supplemented by a reflection on the difference between the lack of visibility (characteristic of a phenomenon) and the lack of vision (characteristic of the observer or analyst of a phenomenon).

It is impossible (in essence) to foresee all the forms that an accident could take (lack of visibility), yet the moral judgement (which will be that of the expert, the politician or the judge) could qualify as improvident the organization that initiated the accident by its activities (lack of vision); considering it has not sufficiently sought and used the advice of dedicated teams, managers and control services to prevent its occurrence. Amongst the initiators of the Fukushima nuclear disaster is a sea dike that was not designed and built (planned > vision) high enough to stop the tsunami wave (e.g. Guarnieri & Travadel 2018). Was the wave unpredictable (lack of visibility) or has the Japanese society been improvident (lack of vision)? Answering such questions is a prerequisite for a society to (1) establish liability that allows a form of compensation (legal aspect) and (2) call the technical or practical state of the art into question when needed.

The 'state of the art' question seems central because it is this that often discriminates the culprit of improvidence (the one who did not foresee > lack of vision in relation to what was known) from the victim of an unforeseeable event (also called a Black Swan). However, this reference to the state of the art cannot be more than a legal attempt to rationalize a philosophical (even metaphysical) problem: the accident is, by definition, the break with a state we are used to. It is an integral part of normality, except that its frequency or intensity makes it remarkable. For example, the awakening of a volcano represents an accident only on the temporal and spatial scale of a given human community.

The question of the lack of visibility and/or vision places us in the face of our responsibilities, in the realm of the possible and perhaps, above all, of the impossible. Should we stop building some types of works? Or stop building in some given areas? Shall we return to questions of destiny? Turn to a metaphysical determinism to validate the fact that mankind is fallible? That it only has a limited control over the vast system of nature?

As true as an engineer is technically and morally responsible for the quality of his or her studies and achievements, so also is a society responsible for its technical and scientific choices.

Conclusions: lessons to be kept alive

Malpasset is the only known total failure of an arch dam. This disaster has deeply marked the French spirits, as well as the spirits of a whole community of practice (that of the builders and operators of dams, of course, but more broadly that of builders and operators of engineering structures). During post-accident analyses, many technical and organizational aspects appeared to have failed or been lacking and were to be (re)invented, modified and/or imposed by state regulations. With the passage of time, there is a risk that one may forget the origins and thus the sense of some norms or good practices. Therefore, as a conclusion of this paper, we would like to sum up the most important lessons of the Malpasset dam failure, which must be kept alive. Such lessons are tentatively listed below in three scientific fields (which always interconnect): geology (natural sciences), engineering (technical sciences) and sociology (human sciences).

The first lessons are related to geological investigations. The geological history of the massif (far older than granitic rocks in other reliefs) was neglected, as was information from the shape of contours and the general foliation of the rock (preventing the discovery of the main fault). Knowledge of geology, the 'anatomy' of the ground (say materials and structures), is always the first prerequisite of any dam project, as also is 'physiology' (what is moving inside). Only experienced geologists have a chance of discovering all defects and traps (hazards) of a site.

Second are lessons regarding engineering. We have pointed out the lack of foundation drainage, the lack of knowledge of extreme rains and flash floods (likely to fill up the dam remnants), and poor survey and monitoring. Only dam engineers fully understand the power of water, including groundwater, behind a dam, under a dam, inside a dam, and all around it, just as inside any natural relief or any heap of sand or other material; standard hydrogeology usually applies to water resources; here water plays through its power, and has thus been compared to the libido in human life (Duffaut 1978). Any engineer or architect in earthworks and construction (upon or under the soil surface) needs geology, exactly as any surgeon needs to know the anatomy and physiology of their patients.

Finally, in the Malpasset case, there is much to say regarding human sciences. The case is made for many wrong decisions induced by excessive confidence, lack of trust or competencies, poor communication and so on. If each single human or organizational failure is necessary but not sufficient to explain the catastrophe, one can note that amongst the 21 'human failures' (Tables 3–7), 75% are

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'induced' failure ($n = 16$). This suggests that nothing was linked to fatalism, inevitable. Without trying to designate any culprit, it is nevertheless possible to retain responsibility for the 'human condition'. Malpasset is therefore a catastrophe, certainly linked to geology and engineering but also to (1) political issues variously advanced to the point where they turned into political pressure, (2) the fear of saying or doing, (3) the skills management (a hierarchical responsibility), (4) the relationship to time (appreciation of weak signals, point of no-return) and (5) the relation to uncertainty (overconfidence in the technique, risk appreciation). Having these aspects in mind for future engineering projects is one of the most important lessons to keep alive.

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