On The Failure of Malpasset Dam

Richard E. Goodman
Consultant and Prof. Emeritus of Geol. Eng,
Univ. Cal., Berkeley
Le barrage de Malpasset

Problème industriel: alimenter Fréjus en eau potable,
2 solutions à 2000 ans d'écart.
Solutions basées sur les techniques disponibles à l'époque.
Port militaire de Forum Julii, → Reyran étant à sec 8 mois pas an → les romains choisirent de capter une source permanente
Ville de Fréjus → Conseil Général du Var, 2000 ans plus tard, → stocker l'eau intermittente d'un torrent méditerranéen,
Cette dernière solution s'avéra catastrophique en raison d'une chaîne de dysfonctionnements impressionnante.
mylonitic Augen Gneiss and Schist;
Carboniferous sediments
Rhyolitic flows
Prélude à l'océanisation : le rifting continental

a. Les structures tectoniques de rifts

Rift continental

Blocs basculés

Le système de failles parallèles ainsi que les blocs basculés sont bien visibles en RD du Reyran.
Insufficient Geologic Investigation of Dam Site

“Malpasset” in the 18th century inferred “landslide, dangerous ground, friable”.

In 1865 – the first of several studies began, for a 25 m high gravity dam. It confirmed “water-tightness” of the reservoir and reported “optimal” geologic conditions” for a 25 m. high dam.

Subsequently investigations by geologists from “the Geology Dept at the Univ in Marseille” (Prof. Corrot) reported a fault in 1946 and worried about leakage; ordered “foundation ground” to be made “leak proof”. Recommended “excavations and tunnels” to supplement mapping from outcrops and fixing final location only after such studies were made. Two additional alternate axes were recommended for investigation.
In 1949 engineering studies resumed, but at a new site 200 m downstream, apparently without any new geological investigations.

This sounds bad, but the entire valley has so many geologic difficulties that almost any site would have been very difficult for a thin arch dam, but that was the choice of the designer Andre Coyne.

These difficulties were apparently not spelled out, however, in pre-construction geology reports. A meager number and depth of drill holes were made – additional funds for drilling were refused by the government administrators. It was technically an irrigation dam, with a reduced...
The designer – Andre’ Coyne (1891–1960)

“The arch dam: A type of structure that has never collapsed is a rare and probably unique thing in engineering. But despite appearances, despite its slender shape and elegant lines, and high stresses, it is a fact that the arch dam is the safest of structures. This is only added confirmation of what has been known for thousands of years about the stability of arches.”

“….the abutments are the most important part. Stated briefly, nothing serious can happen to an arch dam, provided the abutments stand up.” At the time of the failure, Andre’ Coyne was to be the next President of ICOLD. He had a grand charisma and few would disagree with his opinions. He was a leader.

From Andre’ Coyne’s Class Notes at Ecole des Ponts et Chausées, Quoted by G. Post and D. Bonazzi of Coyne and Bellier “Latest Thinking on the Malpasset Accident” in Dam Failures (Cited here).
THE ROCKS AT THE SITE:

Banded gneiss and schist of sedimentary origin – mainly schistose augen gneiss, and phyllite. Schist is prominent on the left bank and in the lower part of the right bank.

The foliation dips generally 30 to 50 degrees downstream and into the right bank. (The river at the dam site flows S 11 E.)

Sericite and chlorite are plentiful. (Sericite can be created when mica and feldspar are heated, and by hydrothermal action.

These rocks were exposed at surface since the Pliocene or earlier.
THE DAM:
Double curvature arch (curved both in plan and section). 60.55 meters high. Dam reached higher than the steep wall of the left abutment so a 22 m. (72 ft) long rectangular concrete THRUST BLOCK was provided to carry the arch to the top elevation (102.55 m) (199.8 ft.). The thrust block was protected from the horizontal reservoir force by a 22 m (72 feet) long, rectangular wing-wall. The crest length of the concrete arch was 223 meters (736 feet).

Dam thickness varied from 1.50 meters (4.95 ft) at the top to 6.78 meters (22.4 ft.) at the center base.

Spillway: Ungated – located on the crest at the center of the arch with depth of 1.5 meters, with scour protection by means of a protective slab below. There

Total storage: 41,345 Acre Feet

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Malpasset: un barrage voûte ultra mince

Conditions d'équilibre
La force principale est la poussée de l'eau sur la coque.
Cette force F doit être reprise par les réactions des appuis F1 et F2.
La transmission des efforts doit toujours passer à l'intérieur de la coque.
- si aval → éventrement
- si amont → fermeture comme un livre

Si le barrage est très mince, l'effet des sous pressions est moins important.
A Malpasset il n'y avait pas de voie d'étanchéité ni de drainage
Ces dispositions sont indispensables.

Le calcul des barrages voûte est très complexe.
Failure Events

• **Failure scenario** – dam inaugurated in 1954, after judicial delay concerning land appropriation for the dam project – at the start of a long drought; five years to fill; last 4 meters by large storm – very rapid filling – Approached max level at a very high rate at the end – last 4 meters in 3 days of rain.

• Early November 1959, a “trickle of clear water observed high in the right abut.

• Mid November, 1959 cracks noticed in the concrete apron at the dam toe; no information as to exactly when the cracking occurred. Designer not contacted.

• Dec 2. 1959 afternoon – engineers met to discuss how to avoid damaging highway bridge in construction just downstream. No abnormalities were noticed or discussed;

• The bottom outlet gate opening was delayed until 6pm.

• At 8:45 pm, the care-taker on the crest did not notice anything unusual.

• Dam Failed at 9:13 pm without warning – releasing a wave of water, then an air-blast apparently as developed cracks allowed the structure
Fig. 21. Geological sketch of the principal discontinuities at the site.
THE ROCKS AT THE SITE:

Mainly banded gneiss and schist of sedimentary origin. It is mainly an augen gneiss, phyllite rich and poor in feldspar, with a schistose structure. Schist, prominent on the left bank and in the lower part of the right bank.

Schistosity dips generally 30 to 50 degrees downstream and into the right bank. (The river at the dam site flows S 11 E.)

Sericite and chlorite are plentiful. Sericite is created when mica and feldspar are heated, and from hydrothermal action.

These rocks were exposed at the surface at least since the Pliocene.
Looking upstream into the right abutment

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The downstream fault exposed by the failure is an individual feature “belonging to the most recent type of east–west faults” with an irregular thickness of clayey-breccia gouge fill up to 80 cm (31 inches). Its strike can be traced across to the right bank.
The Upstream fault (foliation shear) exposed by the dam failure is “a stepped pattern of shear planes forming a stepped surface, coated with fine mylonite.”
STRUCTURE – JOINTS, FOLIATION SHEARS, FAULTS

The entire rock mass is generally highly fractured at the microscopic and macroscopic scales.

Very fine fractures are extremely numerous, with openings as small as a few microns near the layers of micaceous minerals. There is also a significant intersecting network, often filled with sericite and an interbedded argillaceous material. Their average spacing is of the order of a few millimeters.

Irregularly shaped joints are very closely spaced (2–3 cm apart). They tend to be lined with sericite. There are also planar joints, more widely spaced (20 to 50 cm apart)

Faults (shear?) are very numerous and occur in all the directions of the joint sets. They are generally filled with up to 4–5 inches of mylonite or breccias and sericite.
VISIT Report of USBR Chief Geologist, Bill Gardner, 2-1/2 hrs at site + office visit

“No geological reports, maps, or records were obtainable.” Electricité de France geologist The rock is a medium grained mica schist cut by very coarse pegmatite dikes up to 3 ft thick….”. Gardner’s impression of the site from walking on the access road was of deformed and faulted rock everywhere at the site. Shearing, faulting, crumpling, next to and between seams. There are Innumerable faults, many of major size with displacements of 1000 to 2000 meters. A few km NE of the site there is a 200 meter wide zone of mylonite parallel to faults.

The downstream Shear ( Seam B) (fault footwall) had minor undulations and the appearance of movement along it that could produce gouge. Reportedly 1-1/2 inches of gouge but the Guide indicated there were 2 meters of broken rock and gouge.
Additional information from Bill Gardner’s report

Exploration Work:
Shallow cuts would have exposed the character of the formation but were not reported. Some trenches and test pits were made. Gardner saw no actual records of geologic investigations.

One map showed two drill-holes high in the rock abutment, six in the thrust block area, and many in the stream section. Generally 20–25 m deep (not deep enough to have reached the downstream Shear (B) except in the thrust block area.

Little water loss in Lugeon tests.

There was apparently no geologic work during construction. And no geologic reports or maps of as-excavated...
Analyse du verrou rocheux RG aval de l'ouvrage

Ce verrou rocheux à l'aval du barrage illustre parfaitement la cause de la rupture du barrage.
Pourquoi ? Et comment faire une lecture géologique du terrain.
Dans cette phase il faut observer et voir les éléments du paysage: les formes, les couleurs, la nature des roches, le torrent à sec etc.
Dans cette 2ème phase on va faire une analyse et donner du sens à ce qu'on a vu
Roche massive + pas de végétation, => c'est du gneiss.

massif découpé en blocs par des failles qui se recoupent, dans un contexte de rift donc en extension,

à découpage du massif en blocs indépendants à l'image d'une palette de peinture;
torrent à sec; => comment installer un barrage de 50 Mm3 sur un torrent à sec? => étude hydrologique.
Massif sans cohésion → implantation d'un barrage?
Le bloc est éjecté : c’est la ruine de l’ouvrage.
Découpage du massif en un bloc expulsable entre les 2 failles
Plan de la faille n° 3 amont du dièdre
La roche est très fracturée avec des blocs de grandes tailles. On observe une faille et un décollement important: c'est un terrain idéal pour l'établissement de sous pressions et donc d'un vérin.
Plan de la faille n° 4 aval du dièdre.
Fracturation intense en petites plaques parallèles au plan de faille.
Roche très dégradée et se brise très facilement.
Roche est mécaniquement incapable de résister au glissement du bloc dans le sens de la faille.
Présence de séricite qui facilite les glissements.
Il est invraisemblable que ce système de failles n'ai pas été vu par le géologue, au moins pendant le déroctage.

On retiendra que dans le processus d'analyse géologique proposé en début du document, il y a l'aspect impératif de la synthèse entre le géologue et le technicien connaissant les barrages.

Si à Malpasset une concertation régulière et constructive s'étaient établie entre le géologue et le maître d'œuvre, on peu raisonnablement penser que le problème des failles de surface aurait été vu et des solutions mises en œuvre.
Londe’s Analysis for one case of the rock wedge stability

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Fig. 15. Schematic of the “explosive” phase.
Fig. 14. Relations between the geological structure and the arch.
Normal stress distribution under a plate load on jointed rock; from P. Londe in Dam Failures (see references); based on doctoral thesis of J. Bernaix.
Fig. 11. Water pressure on the “underground dam”.
Fig. 8. Scale effect.
Gneiss from Malpasset left abutment (sample M III 2 A)

\[
\begin{align*}
  d &= 10 \text{ mm} & R_c &= \begin{cases} m = 52.7 \text{ MPa} \\ s &= 19.0 \text{ MPa} \end{cases} \\
  d &= 36 \text{ mm} & R_c &= \begin{cases} m = 25.0 \text{ MPa} \\ s &= 10.0 \text{ MPa} \end{cases} \\
  d &= 60 \text{ mm} & R_c &= \begin{cases} m = 18.0 \text{ MPa} \\ s &= 6.0 \text{ MPa} \end{cases}
\end{align*}
\]

See text for explanation of symbols.
Fig. 3. Radial seepage. Sample: Malpasset M III 2.
Fig. 9. Radial permeameter tests.
Fig. 6. Deformation moduli for dam foundations (jack test). After Electricité de Fra
Fig. 6. Investigations beneath the dam.
Fig. 7. Tentative relationship between upstream crack vs. dam height and rock modulus.
Fig. 5. Malpasset Dam — plan views of deformation before failure.

1. Scale
   (A) September 1955 level: 79.75
   (B) July 1956 level: 83.85
   (C) July 1958 level: 87.30
   (D) July 1959 level: 94.10
Sources of information


Remembrances of my visit to the site in 1963 and correspondence with Pierre Londe over many years;

Les Barrages de Malpasset et de Saint Cassien, Personal presentation of Maurice Moine, former Chief of dams and hydro power for Electricity de France

Burst of a Dam, 2 Dec, 1959, Malpasset (Var) France, (French Ministry of Sustainable Development, updated April, 2009).

Article on Malpasset Dam in Wikipedia


Notes, correspondence, photos and maps of J. Barry Cook,
The French chose to fill a surface reservoir. Two thousand years earlier, the Romans elected to find a permanent spring and successfully conducted water to Frejus.

The investigators concluded that the basin would hold water but did no relevant investigation of the site. Yet they chose a dam design that absolutely required solid rock.

The designed dam lacked sufficient means to fully control reservoir elevation. There was no foundation /abutment grouting or deep drainage (*)

The public administration was incompetent and overly-powerful. Funds were repeatedly restricted for exploration galleries and a sufficiency of drill holes.

“They” were slow to open the drains to lower the lake level when mysterious leakage and a 15mm displacement appeared; the reservoir had then reached a level 7 meters (23 feet) below the operating elev. for that date. Was the dam failing its proof test?

The engineers, hydrologists, geologists, and contractors failed to communicate effectively with one/another.

Because of concern about the safety of the highway bridge job downstream, there was lethargy in opening the main drain valve until it was too late. Tragically, no attempt was initiated to communicate a warning