DAMAGE OF SEFID RUD BUTTRESS DAM PROJECT IN IRAN CAUSED BY THE MAGNITUDE 7.4 MANJIL EARTHQUAKE OF JUNE 21, 1990

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Abstract

There are only few case histories of concrete dams that have suffered damage during strong earthquakes. The June 21, 1990 Manjil earthquake resulted in the loss of over 35,000 lives and the total destruction of the town of Manjil. Some 100,000 structures, including dams and irrigation canals, were destroyed or severely damaged. The epicenter was in the town of Manjil. The focal depth was 19 km and the magnitude Mw = 7.4. The nearest strong motion record available is from the town of Abbar, about 40 km from the dam site, where the horizontal components of the peak ground acceleration (PGA) were 0.65 g and 0.62 g and the vertical one was 0.52 g. The PGA at the dam site was estimated as 0.7 g. Sefid Rud Dam is a buttress dam with a maximum height of 106 m and a crest length of 417 m. There are twenty-three 14 m wide buttresses, with a web thickness of 5 m, and two gravity type abutment blocks. Construction of the dam took place from 1958 to 1962. Damages to the dam structure consisted mainly of cracks along horizontal lift joints and of spalling of concrete along the vertical joints between buttress heads. These damage features affected the central buttresses at the level of the kink in the slope of the downstream face. On the dam crest, slabs of the carriageway suffered cracking and spalling. The dam was subjected to ground shaking, faulting and rockfalls. The different features of the damage of the dam and appurtenant structures including the gate of the intermediate level spillway are described. Very limited information can be found in the literature on this dam, which up to now is the concrete dam that has experienced the strongest ground shaking of any large concrete dam in the world. The author was a member of the official reconnaissance team inspecting the dam shortly after the earthquake. The repair works carried out after the earthquake, which included epoxy grouting of the cracks and the installation of rock anchors in all blocks are also described.

Keywords: buttress dam, earthquake damage, 1990 Manjil earthquake, strong ground shaking, dam rehabilitation

1. Introduction

There are only few case histories where a concrete dam has suffered severe damage due to earthquake action as reported in [1]. The best-known examples are the Hsinfengkiang buttress dam in China, the Koyna gravity dam in India, and the Sefid Rud buttress dam in Iran. The damage pattern due to ground shaking was similar, i.e. cracks appeared near the kink at the downstream face of the dams. The structures could be repaired and strengthened and they are in operation today. Furthermore, two spillway openings of the Shih-Kang concrete weir in Taiwan were destroyed by large fault movements during the 1999 Chi-Chi earthquake.

The above dams are gravity-type structures. Pacoima dam in California, a 116 m high arch dam, was subjected to very strong ground shaking during the 1971 San Fernando earthquake and the 1994 Northridge earthquake and has experienced joint opening and limited cracking, but as the reservoir level was relatively low during these events nothing can be said about its performance under full reservoir condition.

The 21 June, 1990 Manjil earthquake that occurred in the Alborz Mountains in the Caspian Sea region of Iran was one of the most devastating seismic events. It resulted in the loss of over 35,000 lives and the total destruction of the town of Manjil. Some 100,000 structures, including public and residential buildings, dams, industrial facilities, water tanks, irrigation canals either collapsed or were severely damaged. The macroseismic epicenter coincides with the town of Manjil. The focal depth was 19 km and the moment magnitude Mw = 7.4 (Ms = 7.7). The main shock was associated with nearly 80 km of fresh faulting. There were also several strong aftershocks with magnitudes up to about 6.0. No strong motion data was recorded at the dam site. The nearest record is from the town of Abbar, about 40 km from the dam site, where the the peak ground acceleration (PGA) of the horizontal components were 0.65 g and 0.62 g and the vertical one was 0.52 g. The horizontal PGA-value estimated for the dam site was about 0.7 g [1, 2].

Sefid Rud buttress dam, located in the epicentral region of the Manjil earthquake, is the concrete dam, which up to now has experienced the strongest earthquake ground shaking of any concrete dam in the world (Fig. 1). This case is hardly known among dam and earthquake engineers, because in 1990, when the earthquake occurred, only few foreign engineers and earthquake experts were able to visit the devastated region. Sefid Rud dam and also hydraulic structures of the downstream irrigation scheme were among the main damaged infrastructure projects.

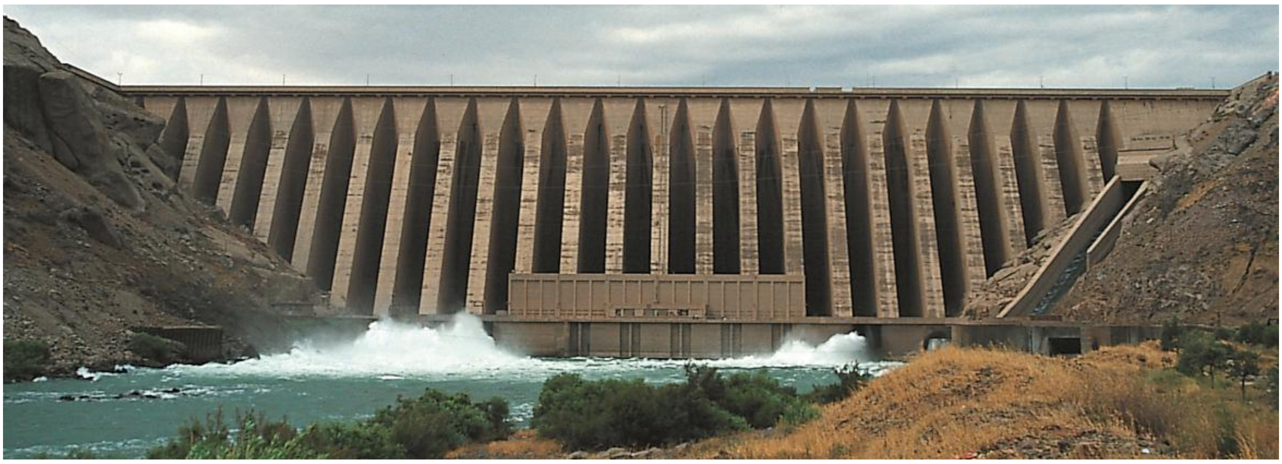

Fig. 1 – Sefid Rud buttress dam in Iran with irrigation outlets in operation for lowering the reservoir immediately after the 1990 Manjil earthquake; the powerhouse is at downstream foot of the dam.

The author was among a team of four Swiss dam engineers and a seismologist, who inspected Sefid Rud dam a few days after the earthquake and was the main earthquake and dam engineer among this team. The team also included one Iranian engineer from Mahab Ghodss Consulting Engineers in Tehran. The dam safety inspection was initiated by the then Iranian President Akbar Hashemi Rafsanjani. The safety of this dam was essential for Iran as it is part of large irrigation scheme, where most of the Iranian rice is grown. A

Swiss team was appointed because at that time the Swiss Joint Venture Stucky-Electrowatt in cooperation with Mahab Ghodss was involved in the safety evaluation of all major dams in Iran.

Other Iranian engineers have also visited and inspected the dam afterwards. Most of the photo documents available on this important case study are those from the Swiss team, and are kept in Iran, as at that time we were requested to hand over all photos to our Iranian partner Mahab Ghodss. There was also a camera team of Mahab Ghodss, who made videos and after completion of all repair works a video on the Sefid Rud dam and the Manjil earthquake was assembled, but is hardly known outside of Iran. The main publications describing the effect of the Manjil earthquake on Sefid Rud dam are [1, 2]

Thirty years have passed since the Manjil earthquake has happened. It was the worst earthquake in the last decade of the 20th century and it had a major impact on site-specific seismic hazard studies and the dynamic analysis of large dam projects in Iran.

2. Sefid Rud Buttress Dam

Sefid Rud buttress dam, located about 200 km NW of Tehran and about 2 km from the town of Manjil, has a maximum height of 106 m and a crest length of 417 m. There are 23 buttresses, 14 m wide, with a web thickness of 5 m, and two gravity type abutment blocks. The gravity block on the left bank accommodates an intermediate level spillway of 2000 m^3/s capacity. The dam is part of a multi-purpose storage project with irrigation and power production as main purposes. The powerhouse at the downstream toe of the dam has five 17.5 MW units. The dam stores a reservoir with a volume of 1.8 km^3. The right-hand side of the dam is founded on competent andesite rock while the left part rests on andesite breccia and pyroclastic rock. Construction of the dam took place from 1958 to 1962. The layout of the project is shown in Fig. 2.

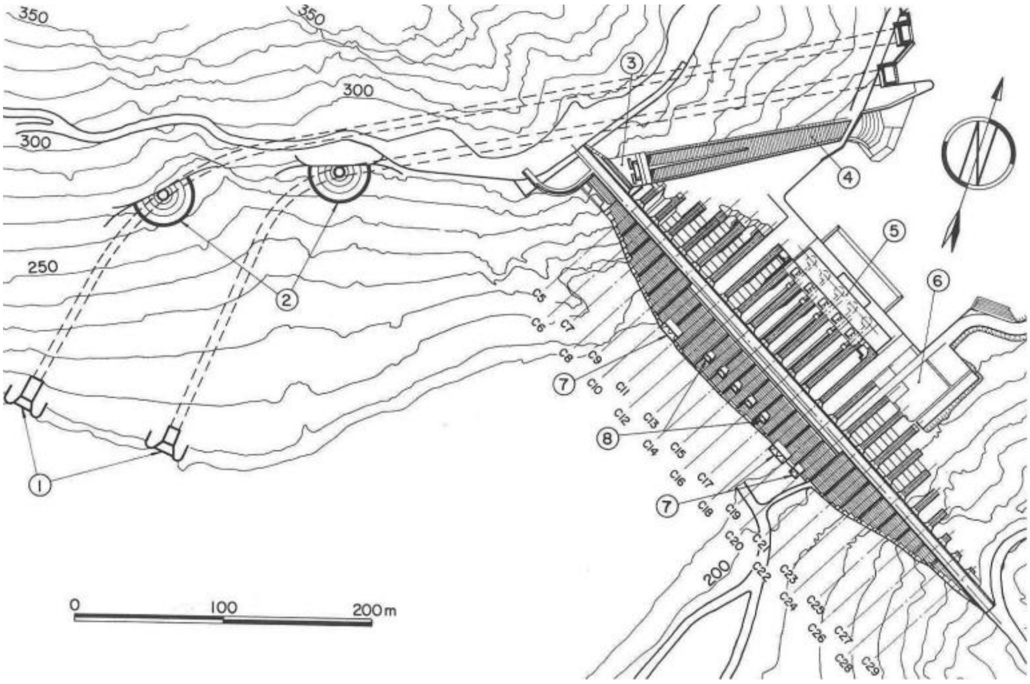

Fig. 2 - Layout of Sefid Rud dam: (1) Intakes for diversion tunnels, (2) Morning glory spillways connected to diversion tunnels, (3) Orifice spillways, (4) Chute of intermediate spillway, (5) Powerhouse, (6) Switchyard platform, (7) Bottom and irrigation outlets left and right bank , (8) Intakes for penstocks [2]

The seismic design was done by the pseudo-static analysis method using seismic coefficients of 0.1 and 0.25. No tension was allowed at the upstream face under static and seismic loads for a seismic coefficient of 0.1. For a value of 0.25 the allowable concrete stresses were specified as 7 MPa for compression and 0.7 MPa for tension. The dynamic analyses carried out after the Manjil earthquake gave much higher stresses than the original pseudo-static analysis [3]. This was expected as the pseudo-static analysis method used in the past has severe deficiencies, and shall no longer be used today for large dam projects, especially for those located in seismic areas [4].

3. Earthquake Damage of Sefid Rud Buttress Dam

Damages to the dam structure consisted mainly of cracks along horizontal lift joints, which were spaced at 2 m (Figs. 3 and 4). Cracks appeared also in central buttresses that were located at the level of the kink in the slope of the downstream face. There was at least one major horizontal crack along working joints in all of the buttresses (Fig. 4). In one buttress, the cracks formed a wedge in the buttress web, which displaced by about 20 mm. On the dam crest, slabs of the carriageway suffered cracking and spalling (Fig. 5).

Fig. 3: Crack at kink location in buttress (left) and horizontal crack along lift joint (right)

Fig. 4 – Horizontal crack at upstream dam face through several buttresses along lift joint (left) and horizontal crack and spalling of concrete above intake gates (right)

Fig. 5 – Cracks on dam crest due to high compressive stresses: Longitudinal crack (left) and compression-shear crack at block joints (centre and right) (Note: Relative movements occurred between some of the block joints)

Typical damages of concrete parapet walls are shown in Fig. 6. The rockfall hazard above the intakes of the morning glory spillway can be seen from Fig. 7, and Fig. 8 shows the inelastic deformations of the arm of a radial gate of the intermediate level spillway, which was caused by high hydrodynamic pressures.

Fig. 6 – Tilting of concrete parapet wall on downstream crest (top left) and secured tilted wall after the earthquake to protect it from falling on the powerhouse (top right), damage at upstream face parapet walls above intake gates (bottom left and right)

Fig. 7 – Rockfalls at intakes of morning glory spillways on left dam abutment: main rocks could be withheld by horizontal platform above intake (right)

Fig. 8 – Damage of radial gate of intermediate level spillway causing leakage (left and centre) and deformed portion of spillway arm due to high hydrodynamic pressures (centre and right)

In Fig. 9 different types of damage to the downstream irrigation scheme is displayed. Multiple gates installed in long weirs are critical elements as all of them are of the same type. If one fails, the others are very likely to fail in the same way. The main seismic safety problem of gates of existing older projects is that they have been designed for seismic loads acting in river direction but not in cross-river direction.

Fig. 9 – Damage of lining of downstream irrigation canal (left) and several counterweights for gate lifting of diversion structure of irrigation scheme were falling down (right)

In Fig. 10 a reactivated old fissure in the foundation gallery is shown, which was leaking after the earthquake as fine material was washed out due to seismic fissure displacements. Cracks and fissures in concrete dams indicate that uplift pressures exist, which have a negative effect on the post-earthquake stability of concrete blocks. In the same figure a segment of the main fault of the Manjil earthquake can be seen, which passes through the footprint of the dam. The related movements were very small.

Fig. 10 – Leaking fissure in foundation gallery (left) and trace of fault of Manjil earthquake (right)

Fig. 11 – Rockfall at the dam site: Large displaced rocks above the spillway intake on left bank (top left)

In mountainous regions the seismic hazard is a multi-hazard, which besides ground shaking (Figs. 11 and 12), the hazard considered by all dam engineers, we must also taking into account faulting in the dam foundation and the reservoir, landslides, rockslides and rockfalls as well as ground movements (Fig. 13). During the Manjil earthquake, thousands of rockfalls could be observed; many of them were located very close to the dam site (Figs. 7 and 11).

Fig. 12 – Damage in the control room of the hydropower plant caused by ground shaking (Note: The sandbags at the left were placed as protection from missiles as the dam and power plant were attacked by fighter planes during the Iran-Iraq war of 1980-1988)

Fig. 13 – Collapsed buildings at dam site caused by strong ground shaking

Fig. 14 – Damage of switchyard equipment due to ground shaking and ground movements

Electro-mechanical equipment installed in the powerhouse and switchyard are vulnerable to ground shaking, because some have high centres of gravity and are not properly anchored to the foundation or structural walls and, therefore, are vulnerable to overturning (Figs. 14 and 15). But more important is the fact that electrical and mechanical engineers are often not familiar with the overall seismic safety concept used for large dam projects and some of the design guidelines may have to be revised. Furthermore, transmission towers can easily be destroyed by rockfalls. This has also happened with the first transmission tower in Sefid Rud, which caused the shut-down of the power plant.

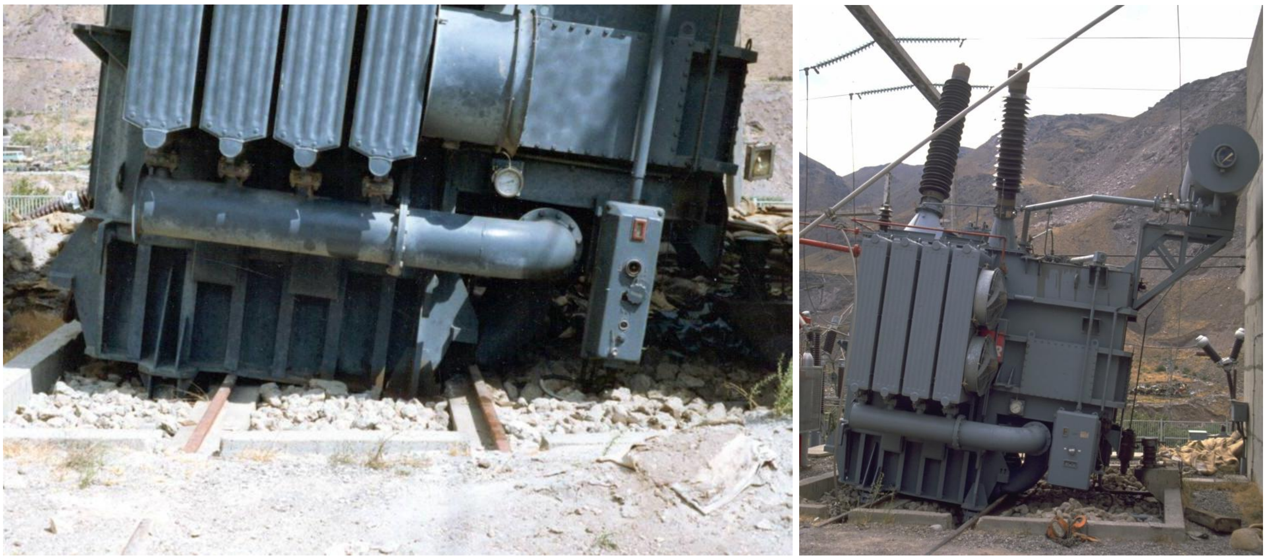

Fig. 15 – Derailed transformers that were not properly anchored

4. Rehabilitation of Sefid Rud Dam

Immediate repair of the damage was of high priority and started in November 1990 and was completed in 1991 [5].

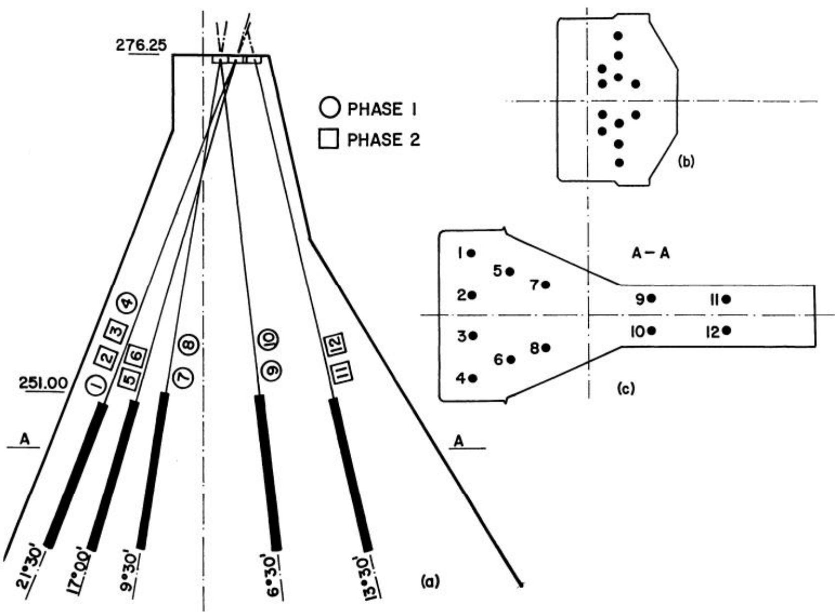

Fig. 16 - Arrangement of post-tensioned anchors in damaged buttresses: (a) cross-section of buttress, (b) top elevation, (c) Section A-A [1]

Fig. 17 - Repair work at Sefid Rud dam: Excavation for placement of anchor heads (top left), placement of anchor by homing device mounted on a crawler chassis (top right) and installed rock anchors before stressing (working load of each tendon: 8.4 MN) and final placement of anchor heads (bottom)

The seismic rehabilitation work was based on the following concepts [2, 5]:

(i) Re-establishing watertightness of the cracked buttresses by epoxy resin grouting. Initial estimates based on water testing arrived at about 80 cracks that had to be treated by grouting.

(ii) Re-establishing the shear strength of the cracked horizontal lift joints by post-tensioned rock anchors passing through the fractured joints (Figs. 16 and 17).

The objectives of the post-tensioned rock anchors were to increase the sliding resistance of the cracked surfaces, and to improve the sliding and overturning stability of the top portion of the dam The design of the strengthening works called for a post-tensioning force of 100 MN per buttress for buttresses 8 to 23 and of 50 MPa for buttresses 5 to 7, and 24 to 27. With this normal force applied to the sheared lift joints, it was expected to restore the shear strength in the block joints that had moved during the earthquake [1, 2]. High capacity strand anchors of 8.4 MN working load were selected. Twelve anchors or six respectively were required per buttress to match the design force (Figs. 16 and 17).

In the region of the downstream kink, the post-tensioned anchors cause an additional vertical stress of approximately 0.8 MPa. This amount of prestress is not sufficient to prevent future cracking during similar earthquakes. However, the dynamic stability of the detached upper portion of the dam is improved substantially.

As the tendons are anchored in concrete and not in rock, the extra corrosion protection typical for permanent rock anchors was not considered a necessity and, therefore not specified [2].

In addition, some grouting works were carried out in the dam foundation.

5. Modern Seismic Safety Criteria for Large Storage Dam Projects

Today, the following seismic safety and performance criteria must be checked for large storage dams subjected to the so-called safety evaluation earthquake ground motion (SEE), which is the strongest ground motion at the dam site [6, 7] (Note: The SEE ground motion parameters can either be obtained from a deterministic seismic hazard analysis, assuming worst-case earthquake scenarios, or from a probabilistic seismic hazard analysis for a return period of 10,000 years [6]):

(i) Dam body and foundation: The reservoir must be retained safely, structural damage (cracks, deformations, leakage etc.) are accepted as long as the stability of the dam is ensured and no large quantities of water are released from the reservoir causing flooding in the downstream region of the dam.

(ii) After the SEE the reservoir level must be controlled and it must be possible to release a moderate flood by the spillway or low-level outlet(s), which must remain functioning.

(iii) After the SEE it should be possible to lower the reservoir for repair of earthquake damage, and/or to increase the safety of a dam, if there are doubts about its static or seismic safety after an earthquake or other incidents.

(iv) Safety-critical components and equipment (gated spillways, bottom outlets) must be fully operable after the SEE. Minor distortions and damage (e.g. leakage of seals of gates) are accepted as long as they have no impact on the proper functioning of the components and equipment. This means that all gates, valves, motors, control units, power supply and emergency power generators for the spillway and low-level outlets must withstand the SEE ground motions and they must be functioning after the SEE, i.e. the equipment shall be properly anchored etc. This is a new requirement [6, 7], which concerns hydro-mechanical and electro-mechanical engineers, who may not have been fully aware of their importance in the seismic safety of dams.

6. Conclusions

Sefid Rud dam was damaged by a very strong earthquake, which corresponds to the worst ground motion expected at the dam site. The dam was repaired and strengthened after the 1990 Manjil earthquake and is in full operation. The following conclusions may be drawn based on the observations made at Sefid Rud dam:

1. Earthquake hazard is multi-hazard: rockfall hazard has been underestimated in most places. Access to dams is a problem after strong earthquakes, especially in mountainous regions.

2. Earthquakes affect all components of storage dams at the same time and all of them must be able to withstand different levels of earthquake shaking.
3. Cracks in concrete dams are discrete cracks developing along lift and construction joints and at locations with sudden changes in stiffness and/or mass (kinks and corners are locations with stress concentrations).
4. It must be possible to lower the reservoir after a strong earthquake in order to increase the safety of a damaged dam. Furthermore, to control the reservoir level after a strong earthquake, spillways and low level outlets must be operable.
5. Hydro-mechanical and electro-mechanical equipment of spillway gates and low-level outlets must be capable to withstand the ground motion of the safety evaluation earthquake. Hydrodynamic pressures may damage gates.
6. The power plant of hydropower projects is most likely out of operation after a strong earthquake.
7. Many people were killed in buildings in the region of the dam, which were not designed against earthquakes or only for much weaker earthquake actions than the dam.
8. Post-tensioning of the top portion of a cracked gravity dams or dams with low strength lift joints is suitable for improving the sliding stability of detached concrete blocks.
9. Although, buttress dams are considered vulnerable to strong earthquake shaking, the Sefid Rud dam performed rather well with damages that were amenable to repair without interfering with its operation.

7. Acknowledgements

The post-earthquake inspection team of Sefid Rud dam included T. Arasteh and M. Wieland and the late R. P. Brenner, W. Indermauer, J.-P. Stucky, and J. Wagner. J.-P. Stucky had overseen the monitoring of the dam since its construction.

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