Dam Safety

Reducing the risk

AFRY

The need for dam safety

Dams are some of the largest man-made structures on earth, and they impound huge volumes of water in their reservoirs. This presents the risk, in the absence of dam safety, of the sudden and uncontrolled release of water which can lead to severe damage, and loss of life in the inundation area downstream.

DAM AND RESERVOIR RELATED RISKS

Dams and reservoirs have been operated for decades, and frequently for centuries, mainly for the purpose of irrigation, hydropower, water supply, flood retention, navigation, recreation or for the storage of tailings materials.

The risks arising from large dams and reservoirs are related to the sudden and uncontrolled release of critical amounts of water which can lead to the following in the area downstream:

- Loss of life and injury.
- Damage to infrastructure and property.
- Damages to the ecosystems.
- The loss of storage water, but also loss of electricity generation and irrigation supplies.

HISTORY OF DAM FAILURES

Dams are among the oldest man-made structures and dam safety is as old as the ancient dams themselves. Currently over 60,000 large dams are in use worldwide and some of them are older than 3,000 years.

Various catastrophic accidents have occurred at dams and hydropower plants in the past and some of them caused significant fatalities and damage.

The Marib Dam in Yemen, which has now been replaced, dates back to 1750 BC and suffered numerous breaches during its lifetime, including a final breach which was left unrepaired in 570 AD.

Weirs must be capable of safely passing floods without being damaged.

Clogging of the spillway led to overtopping of the dam during a flood event.

However, it is recognised that there has only been limited number of dam failures in history with the main causes relating to:

- Structural design: The failure of a buttress of the Gleno Dam (Italy) in 1923 led to flooding of downstream villages and the loss of 356 lives.
- Piping: Piping and erosion processes led to the collapse of the entire Teton Dam (USA) in 1976.
- Floods: Discharges exceeding the spillway capacity, leading to dam overtopping caused the collapse of Banqiao earthfill dam (China) in 1975, the worst dam burst in history, causing an estimated 170,000 – 250,000 fatalities.
- Geological instabilities: A huge landslide in the reservoir of Vajont Dam (Italy) in 1963 led to a huge flood wave and overtopping of the arch dam that took the lives of more than 2,000 people.
- Mal-operation/Human Error: Uncontrolled pumping of water into the upper reservoir of the Taum Sauk Pumped Storage Scheme (USA) in 2005 led to overtopping and failure of the embankment dam.
- Poor maintenance: Several people died when Lawn Lake earth dam collapsed in 1982 due to lack of maintenance leading to deterioration and internal erosion.
- Seismic impact: Earthquakes can cause serious damages on dams as observed e.g. in the Zipingpu concrete face rockfill dam after the Wenchuan earthquake in China in 2008 and at the Sefid Rud buttress dam after the Manjil earthquake in Iran in 1990.

Dams in alpine regions have to withstand various natural disasters.

Dam safety concept

Dam safety concepts must be comprehensive and deal with structural safety to state-of-the-art practices, inspection and monitoring, operational safety, maintenance and emergency planning. AFRY's extensive experience in dam engineering can optimise Clients' investments whilst ensuring the targeted levels of dam safety.

OVERVIEW

Every dam safety concept must eliminate risks or safely manage them in an acceptable way. The primary goals are reflected in various national and international dam safety guidelines and regulations. Modern dam safety concepts cover the following key aspects:

- Structural safety
- Dam safety monitoring
- Operational safety and maintenance
- Emergency planning.

Deriner Dam, Turkey

Nam Ngum 2 Dam, Laos PDR

STRUCTURAL SAFETY

The minimisation of risk requires an appropriate dam design for all possible load conditions.

To ensure the structural safety of the dam over its lifetime, the design and design criteria must be reviewed periodically to check if current requirements are met.

The structural safety includes:

- Stability, including static and dynamic stability of the dam body, foundation and abutments as well as of the spillway under operational, unusual and extreme conditions.
- Seismic safety taking into account the different types of hazards caused by strong earthquakes.
- Hydraulic safety, including spillway capacity, freeboard requirements and energy dissipation.
- Geological safety, like rockfall in the dam area (potential damages to spillway structure and gates, bottom outlet, powerhouse, switchyard, etc.), landslides into the reservoir causing impulse waves blockage of access roads, slope instabilities, seepage or piping phenomena at abutments and/or dam foundation.

DAM SAFETY MONITORING

Monitoring of dams is required at periodic intervals during the entire lifetime of the dam to assess the condition, performance and safety of the dam, its foundation, surrounding, abutments and the reservoir area.

A prerequisite for dam safety monitoring is the definition of the project-specific failure modes. By proper instrumentation the development of these failure modes shall be detected as early as possible.

Monitoring is carried out by visual inspections, geodetic surveys and readings from installed instrumentation:

- Visual inspections are carried out by the operating staff, experienced engineers and dam safety experts. Mainly deformation, damage, seepage and early indicators for such phenomena are the focus.
- Geodetic surveys measure surface and internal displacements of the dam and appurtenant structures and also the reservoir slopes where appropriate.
- Instrumentation is installed on, inside, and below dams to measure movements, water pressures, temperature, water levels, drainage and seepage flows, and possible erosion processes.

The evaluation of monitoring data by experienced engineers and experts leads to a global understanding of the behaviour of the safety relevant structures.

In the event that the instrumentation does not confirm the safety of the structures, recommendations will be given regarding increased monitoring or remedial measures, etc.

OPERATIONAL SAFETY AND MAINTENANCE

Spillways and bottom outlets are safety relevant structures for dams. Thus, the operational safety of these structures must ensure the reliable functionality of the hydromechanical equipment, electrical equipment and the power supply.

Comparatively small but regular maintenance measures when carried out improve dam safety avoid big investments at a later date. Such maintenance measures are generally related to the condition of the dam (e.g. rip-rap, vegetation on the dam faces, drainage system, cracks in concrete), reservoir (e.g. potential landslide masses) and the freeboard margin (e.g. drift wood, ice, landslides).

EMERGENCY PLANNING

The main purpose and scope of an Emergency Action Plan (EAP) is to save lives, protect people from injuries, reduce damage to property or structures and to minimize the environmental impact in the event of flooding caused by the release of large quantities of water from the reservoir during floods, dam failure and other types of events that present hazardous conditions.

An EAP provides a guide for identifying, monitoring, responding to and mitigating emergency situations. It outlines “who does what, where, when and how” in an emergency situation or other unusual occurrence affecting a dam.

The main components of an EAP are the definition of responsibilities, communication rules, rules for emergency evaluation, detection and classification, measures to achieve preparedness, preparation of inundation maps for different scenarios, identification of escape ways, and descriptions of the EAP implementation procedures.

Our services

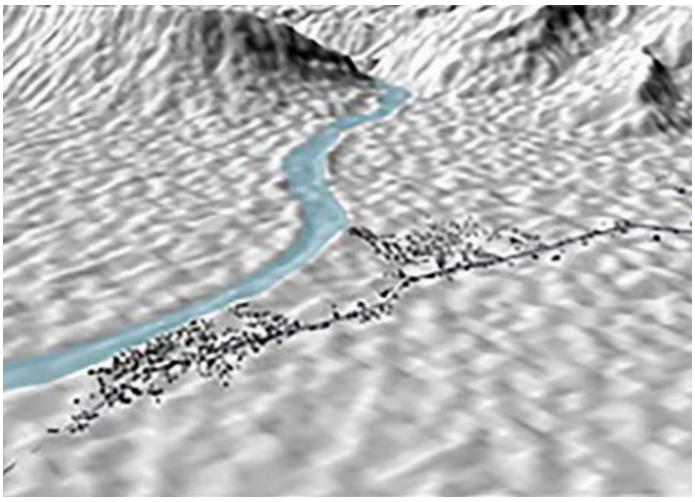
AFRY has been active in the hydropower business for more than 100 years and is well qualified to provide all necessary dam safety services during all project phases.


Mauvoisin Arch Dam, Switzerland

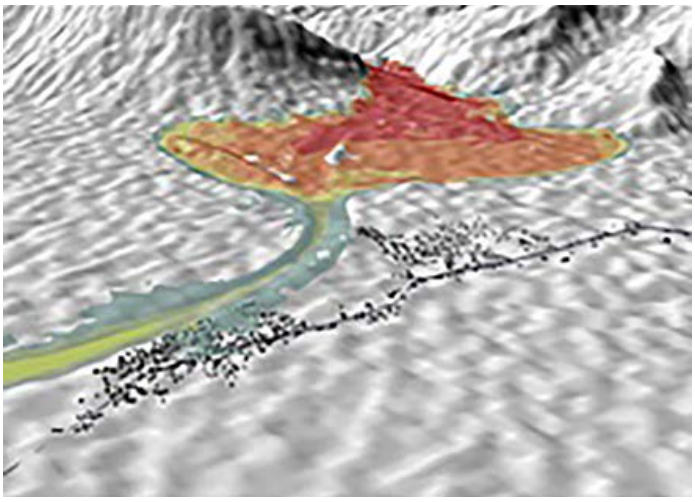
SERVICES DURING THE ENTIRE PROJECT LIFECYCLE

AFRY's proven track record with regard to dam safety services includes the successful delivery of the following:

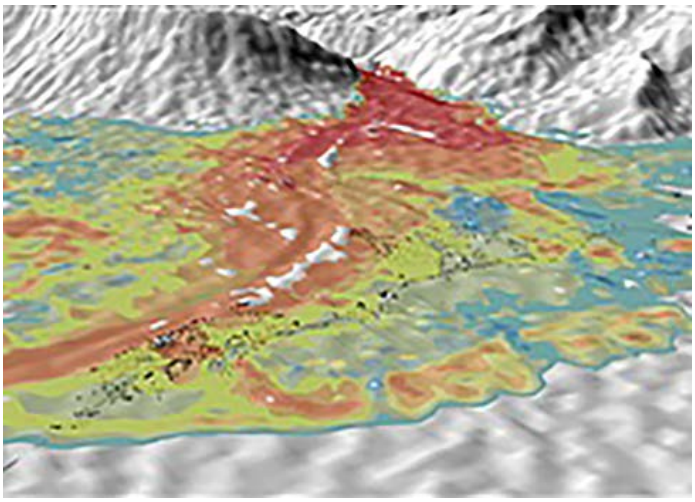
- Hydrological studies covering Probable Maximum Precipitation (PMP) and Probable Maximum Flood (PMF).
- Seismic studies (Probabilistic and Deterministic Seismic Hazard Analyses, definition of worse case earthquake scenarios) and the determination and assessment of the required design parameters.
- Geological studies covering relevant stability and seepage aspects and the evaluation of potentially active faults.
- State-of-the-art dam and plant designs considering all relevant safety aspects including structural safety, hydraulic safety and seismic safety.
- Dam safety concepts for the entire lifecycle of a project including the various design phases, the construction phase and operation and decommissioning phase, all in accordance with national and international standards and regulations.
- Structural analysis and stability assessments of dams, spillways and appurtenant structures.
- Special studies related to structural safety, e.g. detailed analysis of concrete arch dams facing long-term concrete swelling phenomena including finite element analysis, concrete sampling, elaboration of an refurbishment concept, etc.
- Special studies related to hydraulics (spillway capacity, computational fluid dynamics analysis, etc.) and operation procedures.
- Safety evaluation and assessment of dams and plants after extraordinary events, such as strong earthquakes or flood events.



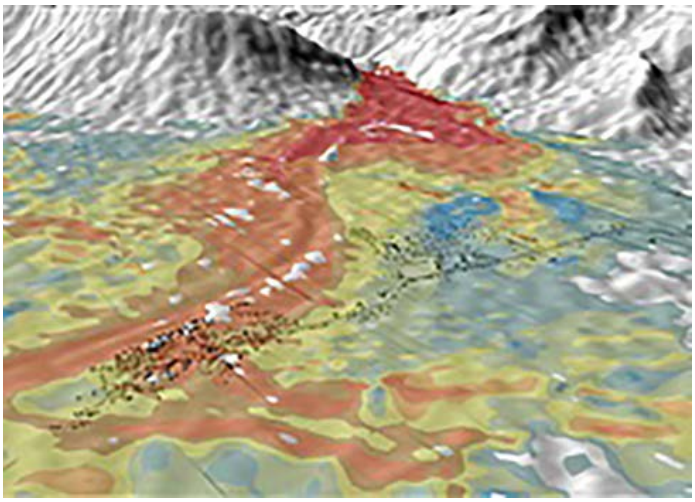
Normal condition



Dam break simulation: Flood wave after 5 minutes



Dam break simulation: Flood wave after 10 minutes



Dam break simulation: Flood wave after 15 minutes

- Assessment of the instrumentation system including recommendations for refurbishment of the equipment and improvement of the monitoring system.
- Review and interpretation of measurement data.
- Inspection of existing dams in intervals of one or five years including surveys, reporting and recommendations for remedial measures.
- Review and evaluation or preparation of Operation & Maintenance procedures.
- Training of staff to improve their awareness of dam safety requirements.
- Construction supervision of various construction works including remedial measures.
- Review, assessment and development of Emergency Action Plans.
- Dam break analyse with flood wave development using state-of-the-art hydraulic modelling software packages and tools.

All services are provided by AFRY's engineers and dam safety experts who have gained experience on numerous projects all over the world. National legislation and international standards, guidelines and dam safety concepts are followed.

Furthermore AFRY is in a position to tackle any project-specific tasks by its interdisciplinary teams of experts.

Selected references

Ambuklao, Binga and Magat Dams, Philippines

Comprehensive dam safety assessments:

- Ambuklao Dam is a 129 m high earth core rockfill dam (ECRD) with gated spillway at the Agno River, which was subjected to strong ground shaking during the 1990 Philippine earthquake.
- Binga Dam is a 107 m high ECRD with gated spillway at the Agno River, which experienced strong ground shaking during the same earthquake in 1990.
- Magat Dam is a 114 m high ECRD at the Magat River, which consists of three saddle dams, a concrete gravity intake structure and a large gated spillway.

The dam safety assessments included:

- Visual inspections to assess the present condition of the Schemes
- Probabilistic seismic hazard assessment
- Estimates and flood analysis studies (PMP/PMF)
- Static and dynamic stability and deformation analyses of the dams and appurtenant structures
- Review operation and maintenance (O&M) manuals and practices
- Recommendations for the finalisation of emergency action plans (EAP).

Atatürk Dam and HEPP, Turkey

Monitoring of dam behaviour

The Atatürk Dam located at the Euphrates River in Turkey is a 170 m high zoned rockfill dam with a central core and is slightly curved in the plane. The crest length is 1,670 m, the maximum base width is approx. 900 m. With a dam volume of 84 Mm³ the Atatürk Dam is one of the largest fill dams of the world. The fill works for the dam lasted from 1987 and 1990.

During and after construction of the dam, large settlements of the dam crest have been observed. A comprehensive and detailed geodetic monitoring program is being carried out by AFRY since 1992.

AFRY was the designer of the dam and carried out a detailed assessment of the long-term behaviour of the dam based on an elasto-plastic analysis and predicted the future displacements. The measured displacements are regularly checked against the predicted displacements and show good agreement.

Further, AFRY dam experts have carried out the annual and five year dam safety assessment since its completion in 1990.

Dam safety, Oman

AFRY's services included safety evaluations of seven existing recharge dams built between 1985 and 1992 in the Sultanate of Oman.

The objectives of the studies were to evaluate the condition of each dam, assess their compliance with public safety requirements, perform detailed analysis of dams to be rehabilitated, prepare detailed designs, provide cost-benefit analysis of proposed remedial measures and to prepare tender documents. The Safety Evaluation of Existing Dams (SEED) procedure was used to determine the condition of each dam with respect to its structural and operating integrity.

Dam safety and operational efficiency improvement of 32 dams, Sri Lanka

Sri Lanka has about 400 medium-sized and large dams, of which 80 are classified as large dams. Some dams date back thousand years. The large dams show signs of deterioration and have various deficiencies and shortcomings related to their operation and monitoring facilities which could pose a threat to public safety and structural sustainability.

The aim of this project was to the rehabilitate 32 large dams showing signs of considerable risks and/or deterioration. The scope of services was as follows:

- Inspection of the dams and formulation of a rehabilitation plan
- Preparation of tender documents for the rehabilitation of the 32 dam structures (civil and hydro-mechanical upgrades)
- Evaluation and interpretation of instrumentation data
- Provision of basic dam safety facilities for 80 dams
- Preparation of Operation & Maintenance manuals for the hydro-mechanical equipment
- Provision of a computer-based maintenance management system
- Preparation of emergency action plans.

Angat dam safety, Philippines

The Angat multi-purpose scheme is located in Luzon Island, approximately 60 km north east of Metro Manila. It was built in the 1960s. The reservoir is impounded by Main Dam, Main Dyke and Secondary Dyke. The rockfill dams have an inclined impervious core. The maximum height of the Main Dam is 131 m. Its failure, in the worst case, would lead to flooding of large populated areas and considerable damages downstream.

Angat scheme is located in a highly seismic area. During construction of the dam and dykes, faults in the footprint of the dam and dykes were encountered, which are considered active and connected to the West Valley Fault. A comprehensive safety assessment of the dam and dykes was carried out.

The scope of the dam safety assessment comprised the following tasks:

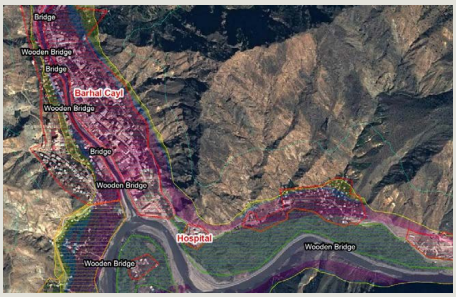
- Failure mode analysis
- PMP/PMF study, and flood safety evaluation
- Probabilistic and deterministic seismic hazard assessment
- Verification of the existence of active faults
- Static and dynamic stability and deformation analysis.

Kainji Dam, Nigeria

Kainji HPP is a 750 MW hydropower scheme in Nigeria, impounding a huge reservoir on the Niger River.

The water retaining structures include a main embankment dam with a central concrete section and a separate saddle dam. The central concrete section includes the intake, powerhouse and spillway. The dam has a length of about 8.3 km and a maximum height of 80 m.

A comprehensive dam safety survey was carried out which included studies of structural safety, flood safety and operational safety. The studies also focused on an evaluation of the current condition of the 50 year old structures including consideration of Alkali Aggregate Reactivity in the spillway, potential erosion in the plunge pool and an evaluation of the stability of the structures based on visual inspection, data from monitoring instruments and geodetic surveys.



Emergency action plans, Turkey

Emergency Action Plans (EAPs) for the construction and impounding phases of five hydropower plants in Turkey, according to international standards. The hydropower plants comprise long tunnels, weir structures and dams of different types up to a height of 140 m. The main tasks for the EAPs were the structural, hydrological and geological failure mode assessment, 2D hydrodynamic simulations of dam break and failure induced floods, alert level determination of potential emergency situations and the preparation of notification charts, inundation maps and evacuation plans.

Plavinas Dams, Latvia

Dam safety inspection of Plavinas, Kegums and Riga run-of-river hydro power plants on the Daugava River. An important aspect was the safety of the powerhouse spillway structure of the Plavinas HEPP, founded on glacial till filling a deep ancient valley.

Scope of services:

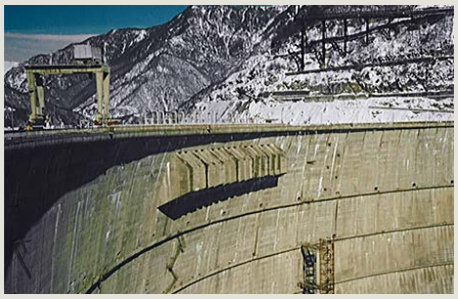
- Dam safety monitoring annual dam safety inspections and preparation of annual reports
- Feasibility design for emergency spillway
- Dam break analysis and preparation of EAPs
- Static and dynamic slope stability analyses
- Dam Safety Risk Assessment
- Design and supervision of repair works of relief wells.

Dos Mares Embankment Dam, Panama

The Dos Mares dam is located at Chiriquí province of Panama close to the city David. Six weeks after impounding the embankment dam breached and emergency measures had to be designed to repair and rehabilitate the remaining dam.

Scope of services:

- Design of emergency measures
- Failure-cause analysis
- Design of rehabilitation measures
- Site supervision
- Monitoring and dam safety assessment.



Enguri Arch Dam, Georgia

The principal structure of Enguri HPP is one of the world's highest arch dams (272 m high). Due to political reasons the maintenance of the dam was neglected for years and the instruments of the dam monitoring system were looted.

Scope of services:

- Structure investigation and safety assessment
- Assessment of instrumentation condition
- Design of complementary monitoring instrumentation
- Improvement of drainage system
- Installation of electronic survey equipment
- Construction supervision services.

Mattmark Dam, Switzerland

The Mattmark Dam is located at a tributary of the Rhone River in Switzerland. The dam is an earth rock-fill dam with an inclined core. The dam is 117 m high, has a crest length of 780 m, a dam volume of 10.6 Mm^3 and was completed in 1967. The Mattmark Dam was the first large dam built on top of (up to 80 m) deep pervious soil layers, namely morainic layers and glacial lake sediments. The grout curtain consists of clay-cement grout and bentonite-silica-phosphate gel.

During the construction of the dam, a serac fall destroyed a labour camp killing 88 labourers. This was the largest dam construction accident in the Alps and contributed to the high safety standards that apply today to the construction of dams in mountainous regions.

AFRY was the designer of this dam and has been involved in the annual dam safety inspections and the detailed inspections every five years since its completion in 1967, including a review of the main dam design criteria. A reassessment of the structural safety was required due to changes in the dam safety concept, in particular:

- Following large floods in the 1990s, a reassessment of the flood safety has been carried out. By modifications of the spillway, a flood retention volume could be created, which provides significantly to the flood safety of the downstream valley.
- The dynamic slope stability analysis carried out showed that the dam is still safe according to state-of-the-art design criteria. The dam can safely withstand peak ground accelerations of 0.42 g at the dam site (originally designed for 0.1 g).

TNB Dam safety assessment project, Turkey

Dam safety assessments were carried out on various hydroelectric schemes located in Peninsular Malaysia. The assignment covered all dams forming the Cameron Highlands – the Batang Padang, the Sungai Perak and the Terengganu hydroelectric schemes.

The main dams are:

- Sultan Abu Bakar Dam
- Jor Dam
- Mahang Dam
- Pergau Dam
- Temengor Dam
- Kenering Dam
- Bersia Dam
- Chenderoh Dam
- Terengganu (Kenyir) Dam.

The scope included the review and re-evaluation all historical data and site assessments of the safety of the dams by performing physical technical inspection of the dams and their associated structures.

Punt dal Gall, Switzerland/ Italy

Punt dal Gall Dam is a 130 m high double curvature arch dam located at the Swiss-Italian border completed in 1969. The dam is founded on highly folded and partially crushed dolomite and limestone formations. Gypsum and marl layers with artesian waters are below the right abutments.

AFRY designed the dam and is involved in the annual dam safety inspections since its completion in 1969, including the assessment of the dam monitoring data and the detailed inspections every five years including a review of the main dam design criteria. A reassessment of the structural safety was required due to changes in the dam safety concept, in particular:

- The flood safety was reviewed and changes and modifications were made. Climate change effects were taken into account in this review.
- The seismic safety was reviewed using state-of-the-art design criteria and methods of analysis.

Drin River Cascade, Albania

Safety assessment of the dams of the Drin and Mat River cascades in Albania, namely Fierza (500 MW), Koman (250 MW), Vau í Dejës (250 MW), Ulza (26 MW) and Shkopeti (24 MW). The power plants on the Drin River include four rockfill dams and a concrete face rockfill dam. The two dams on the Mat River were concrete dams.

Scope of services:

- Site inspections
- Seismic hazard analyses of the dam sites
- Seismic safety evaluations of the embankment dams at the Drin River and seismic analysis of the spillway intake tower of Fierze Dam
- Dam break flood wave analyses for Drin and Mat River cascades
- Preparation of EAPs
- Definition of remedial measures with cost estimates
- Specification of water alarm systems and identification of sites for sirens.

Sella Dam, Switzerland

AFRY provides engineering, design, digital and advisory services to accelerate the transition towards a sustainable society.

We are 19,000 devoted experts in industry, energy and infrastructure sectors, creating impact for generations to come. AFRY has Nordic roots with a global reach, net sales of 24 BSEK and is listed on Nasdaq Stockholm.

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