Dam constructions

Author: Prof. Dr.-Ing. habil. Heinz Konietzky
(TU Bergakademie Freiberg, Geotechnical Institute)

1 Introduction

Needs and use, respectively, for dams (most of them are multipurpose):

- Drinking and domestic water supply
- Flood control and irrigation
- Industrial water supply
- Hydroelectric energy production
- Retention and control of sediments
- Navigation (heavy transport via ships)
- Recreation and tourism

Dams can be classified according to different criteria (material, size, shape etc.). This document uses the following classification:

- **Arch dams**: concrete or masonry structure, that transfers reservoir pressure to the valley slopes by means of its arched shape
- **Buttress dams**: concrete or masonry structure, which withstand the reservoir pressure by means of own weight and additional buttress construction (columns etc.)
- **Gravity dams**: concrete or masonry structure, that withstands the reservoir pressure by means of its own weight
- **Embankment dams (rock fill or earth fill dams)**: structures (mainly small to medium size) based on rock or soil material, that withstands the reservoir pressure by means of its own weight. They represent 75% of all dams worldwide.

Special forms of dams are also dikes, coffer dams or industrial waste dams (tailing dams).

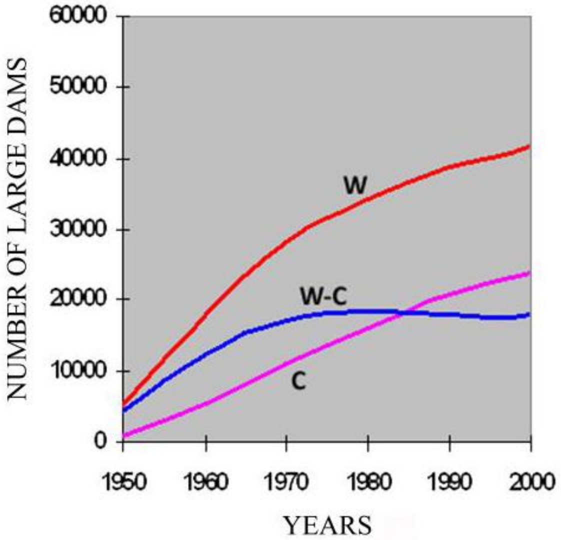


Fig. 1.1: Number of large dams worldwide: C: China, W: World, W-C: World minus China (Luio et al., 2014)

According to ICOLD (International Commission of Large Dams) a large dam is characterised by (see also Fig. 1.1):

- More than 15 metres in height measured from the lowest point of the general foundation to the crest of the dam,
- More than 10 metres in height measured as described above provided they comply with at least one of the following conditions:
  - The crest is not less than 500 metres in length
  - The capacity of the reservoir formed by the dam is not less than 1 million cubic metres
  - The maximum flood discharge dealt with by the dam is not less than 2000 cubic metres per second
  - The dam is of unusual design

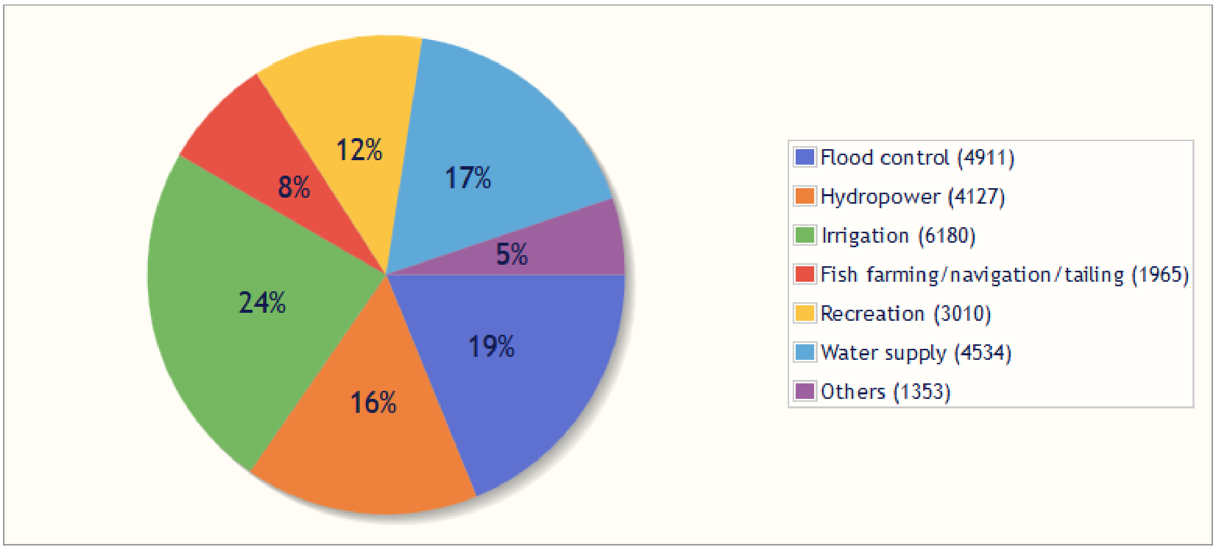


Fig. 1.2: International distribution according to purposes (ICOLD, 2020)

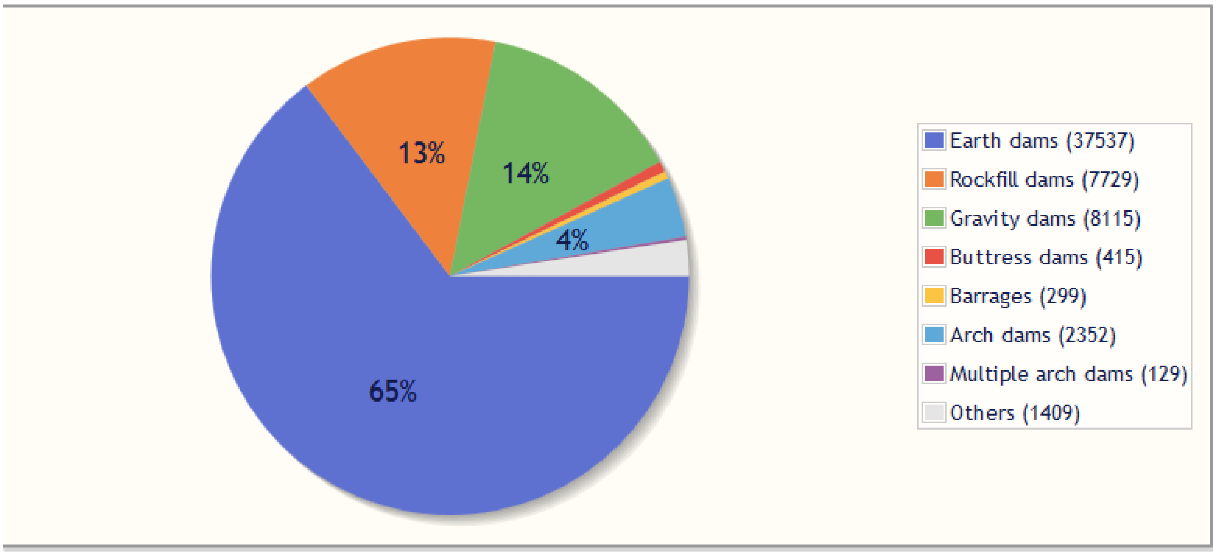


Fig. 1.3: International dam type distribution (ICOLD, 2020)

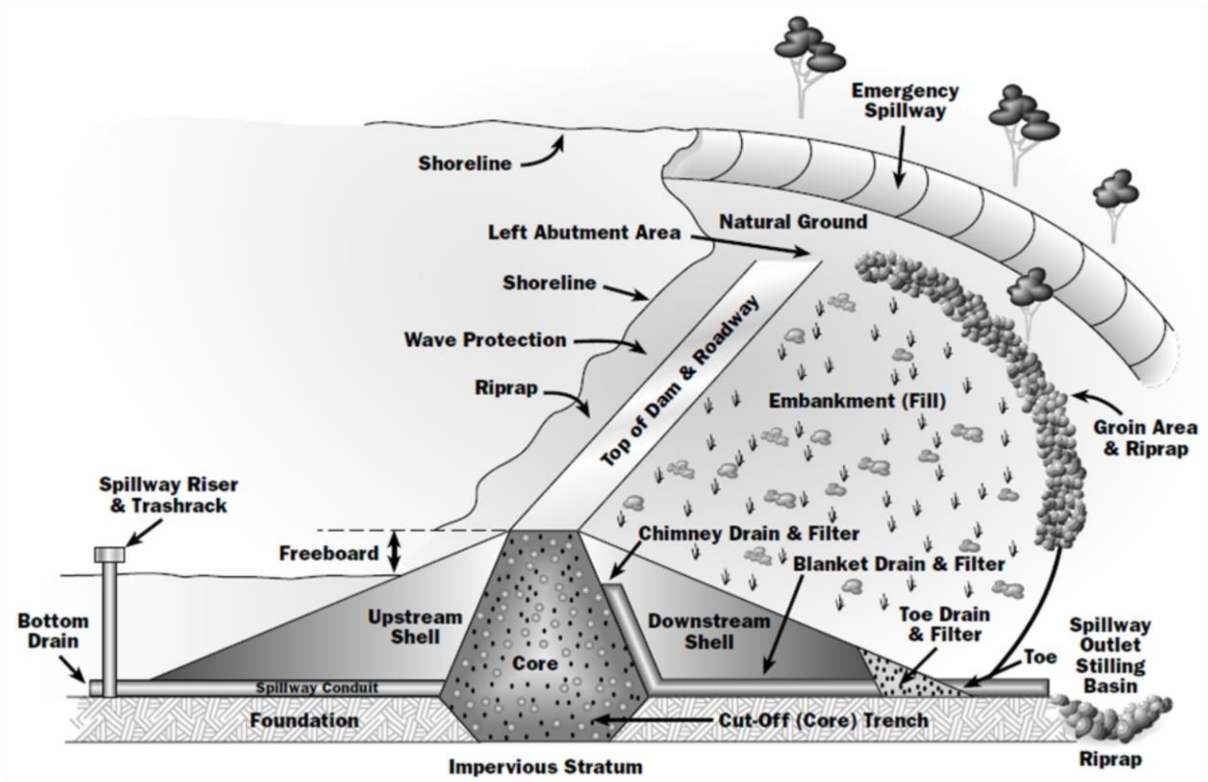


Fig. 1.4: Dams: basic construction and technical terms (TCEQ, 2011)

The main components of a dam are shown in Fig. 1.4. The choice of the dam type depends on the following criteria:

- Topographic situation
- Geological structure
- Climatic situation
- Purpose of dam
- Access to construction material
- Infrastructure (transport) situation
- Georisks (earthquake and landslide potential)
- Financial and economic situation

During the planning and pre-investigation phase the following aspects have to be considered:

- Engineering geological and geophysical field investigation
- Lab testing on rock samples from the site
- Dam site investigation for potential location of powerhouse, spillway, dam axis etc.
- Earthquake hazard evaluation
- Leakage potential of reservoir area
- Environmental studies
- Slope stability and landslide potential
- Potential of erosion and sedimentation

2 Gravity dams

The main characteristic of a gravity dam is that the resisting force is generated mainly by gravitational force towards the ground. Resistance (stability) is generated by frictional resistance and form lock. To generate sufficient force (weight on the ground), that dam needs a certain minimum of thickness. The shape of the cross section is nearly a rectangular triangle (see Fig. 2.1). The force situation is illustrated in Fig. 2.1.

Today most gravity dams, especially the bigger ones, are concrete dams. Nowadays RCC (Roller Compacted Concrete) dams are popular (ICOLD, 2019). RCC is a special blend of concrete, which reduces thermal loads on the dam, allows faster construction and also reduces costs. Optimisation and sensitivity tools can be applied to optimise the construction process and to minimize the loading (Konietzky & Schlegel, 2013). Fig. 2.2 illustrates a typical concrete gravity dam.

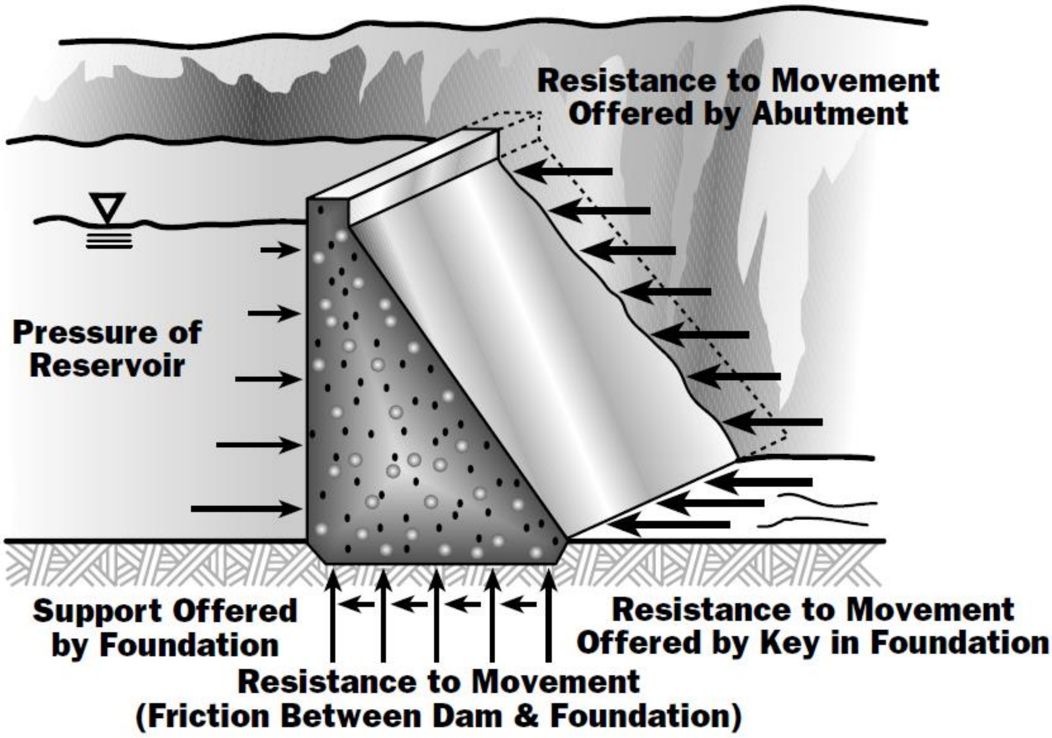


Fig. 2.1: Simplified sketch to illustrate force situation for a gravity dam (TCEQ, 2011)

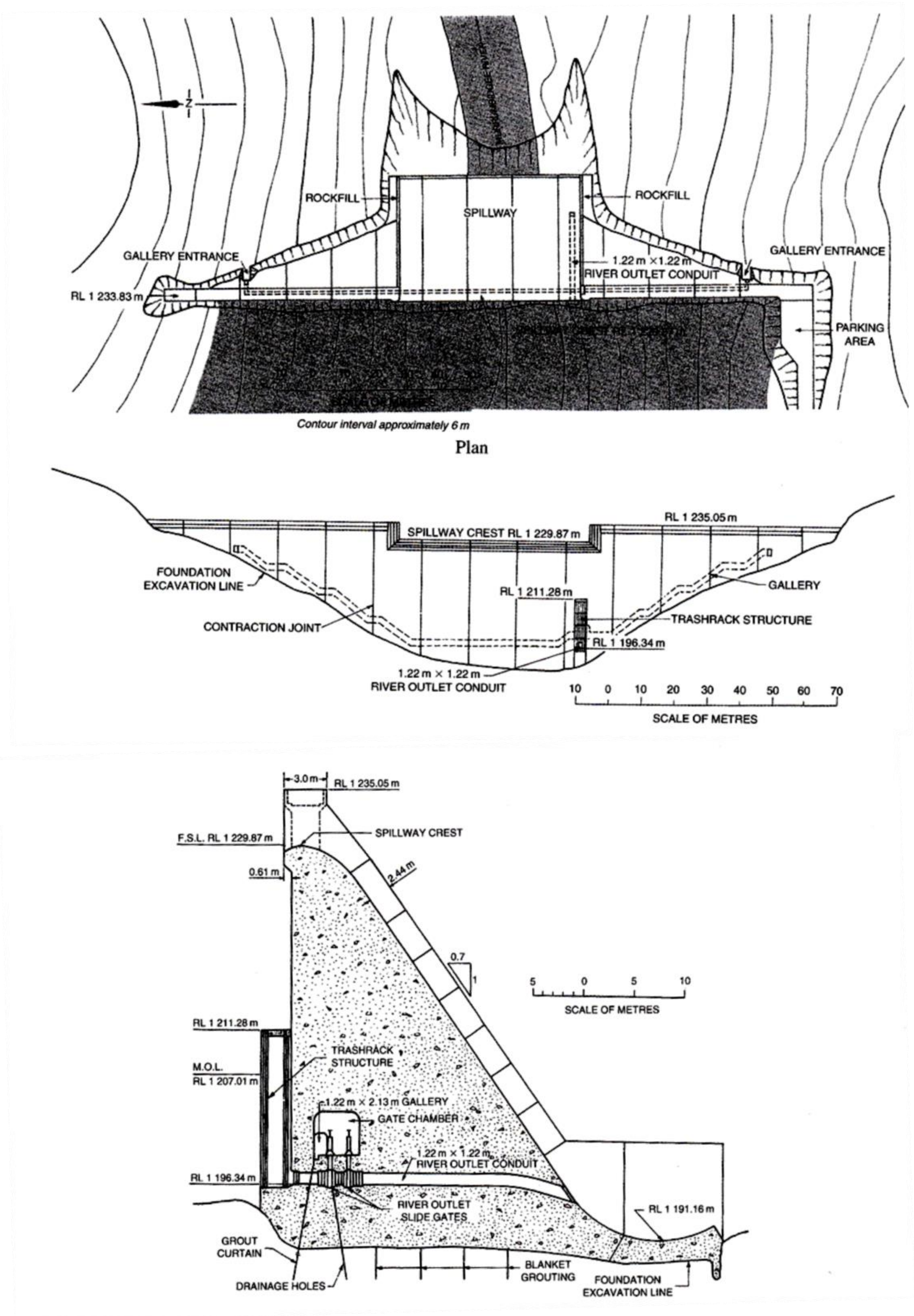


Fig. 2.2: Typical concrete gravity dam plan (Fell et al., 2015)

3 Arch dams

Arch dams (see Fig. 3.1) can be divided into the two following groups (Fig. 3.2):

- Arch dams with constant radius (radius of dominant construction feature is constant)
- Arch dams with variable radius (radius of arch rings vary with height)

Sometimes arch dams are also subdivided according to the arch angle and its position. Intrados and extrados of the arched dam are in general different. The resulting dam body has varying thicknesses along both, the arches (horizontal section) and the cantilevers (vertical section). The main aim of the design is to minimize or avoid tensile stresses in the dam.

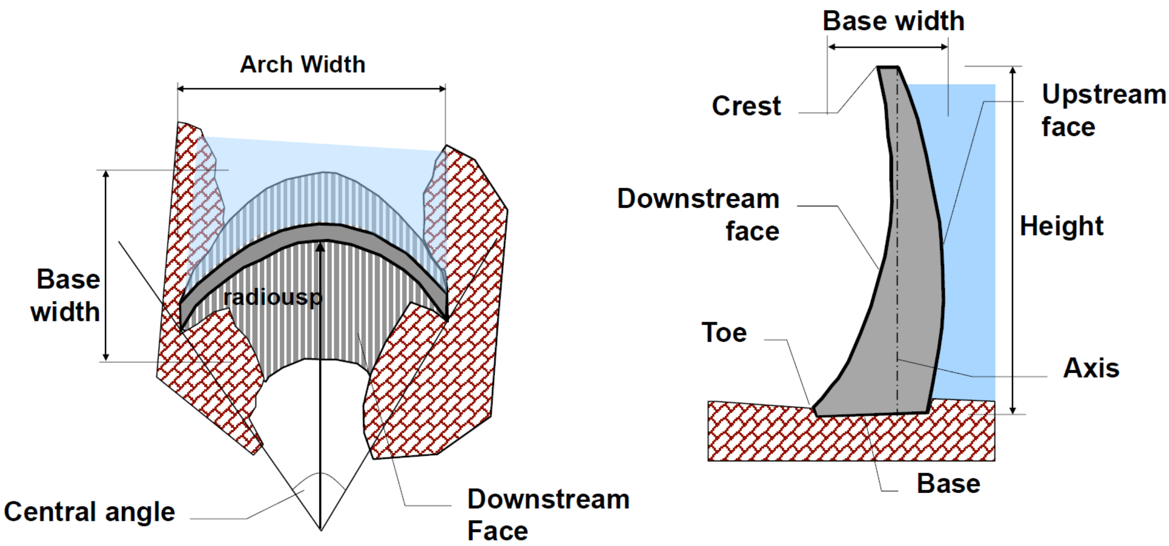


Fig. 3.1: Basis terms for arch dams (Yurtal, 2020)

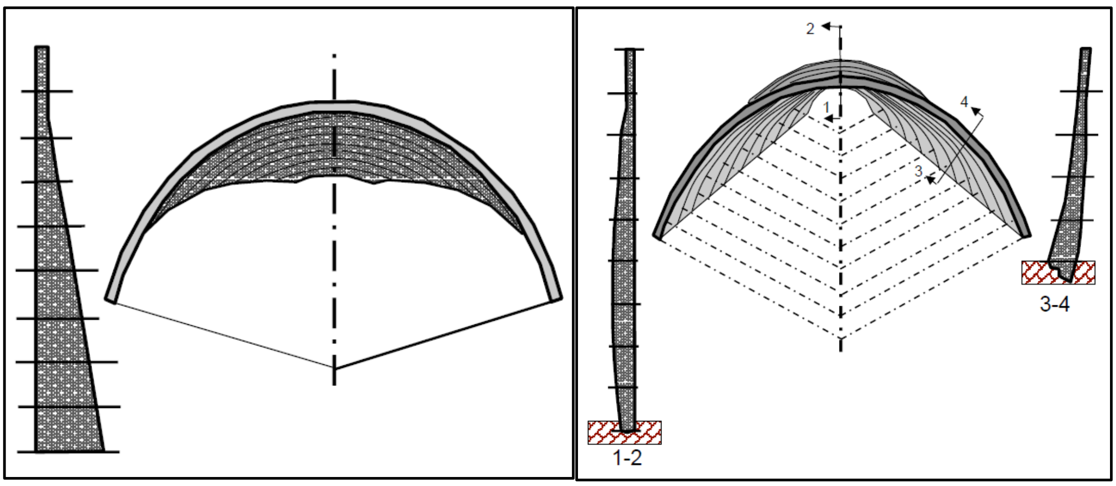


Fig. 3.2: Sketch illustrating different types of arch dams (Yurtal, 2020)

Fig. 3.3 illustrates the main acting forces incl. the resistance due to the foundation and the sidewalls. Fig. 3.4 illustrates a typical layout of an arch dam. Compared to gravity dams less construction material is used and the safety level is quite high. On the other side special requirements are necessary:

a) The sidewalls (valley flanks) and foundation should be stiff and stable with high bearing capacity
b) The ratio between valley height to width should be large (narrow and deep gorge).

Fig. 3.5 gives an insight into a concrete arch dam. Several horizontal, vertical or inclined control drifts (galleries) are installed, which are used for visual and sensor based inspections but also maintenance and water control (leakage etc.).

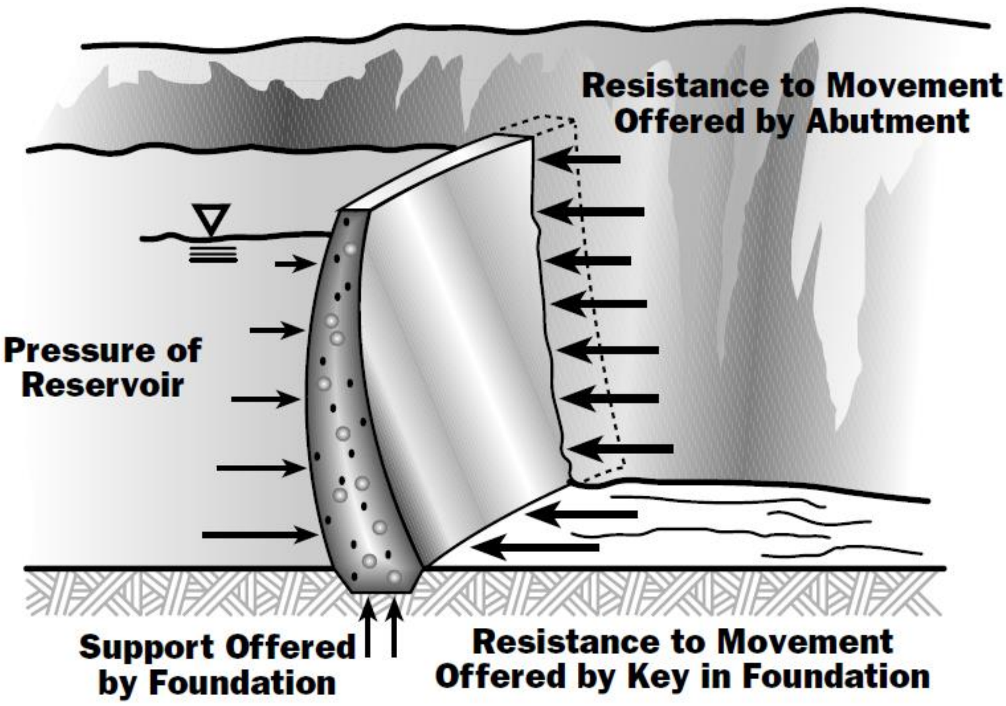


Fig. 3.3: Simplified sketch to illustrate the force situation for an arch dam (TCEQ, 2011)

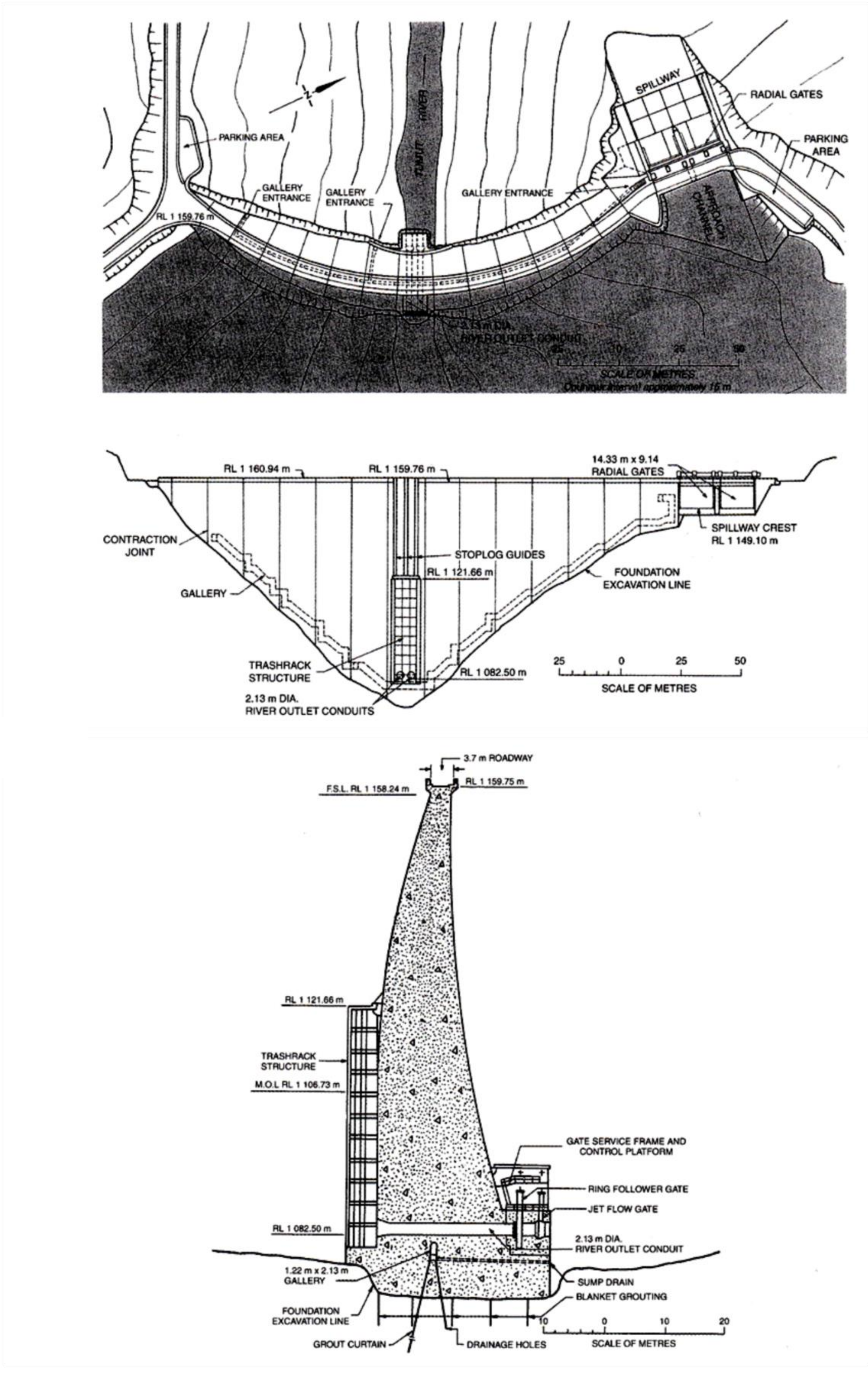


Fig. 3.4: Typical arch dam plan (Fell et al., 2015)

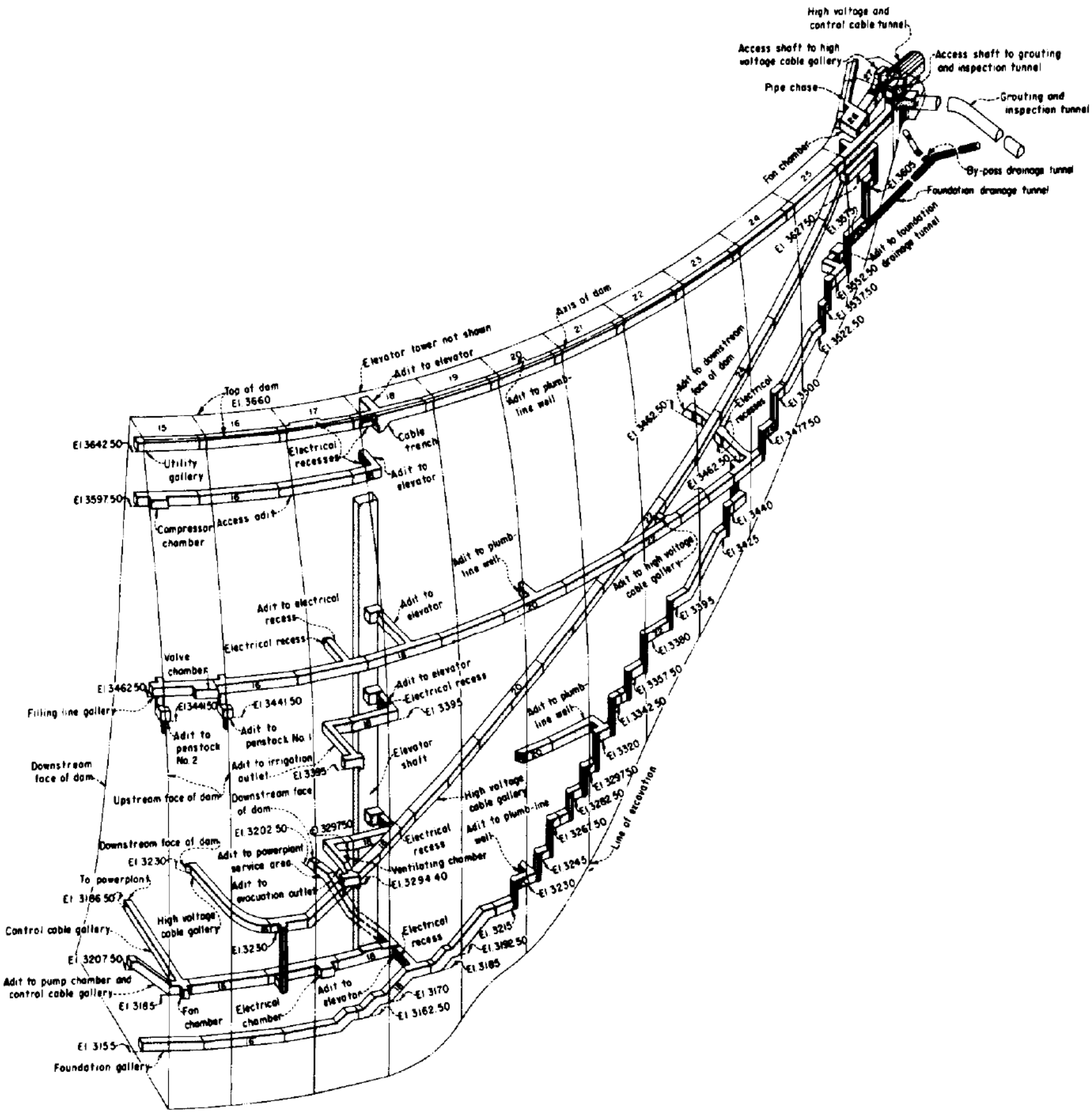


Fig. 3.5: Right abutment of Yellowtail arch dam (ACE, 1994)

4 Embankment dams

Most of the water dams are embankment dams. Their construction can be quite different. The following types of embankment dams can be distinguished (see Fig. 4.2):

- Homogeneous earth fill dam
- Earth fill dam with toe drain
- Zoned earth fill dam
- Earth fill dam with horizontal drain
- Earth fill dam with horizontal and vertical drain
- Earth and rock fill dam with central core
- Earth and rock fill dam with sloping upstream core
- Concrete face rock fill dam

Typical materials used for construction of embankment dams are given in the table 4.1. Special attention has to be paid to filters inside the dam and the foundation. Their main functions are:

- Control of seepage flow to avoid critical water pressure built-up
- Control (minimisation) of erosion and suffusion to avoid leakage and dam instabilities

Besides Filters also other construction means are used to control the seepage, like:

- Trenches filled with low permeable material
- Concrete diaphragm walls
- Grout curtains
- Sheet pile walls or intersecting bored piles

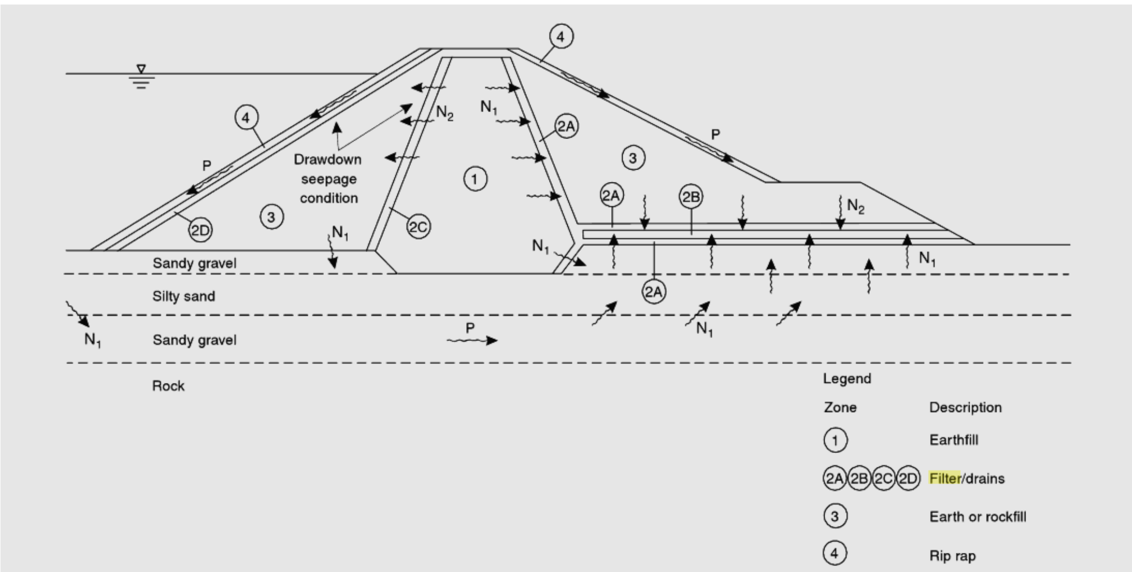


Fig. 4.1: Filters and flow conditions (P: flow parallel to interface, N_1: Flow with high gradient normal to interface, N_2:Flow with low gradient normal to interface) (Fell et al., 2015)

Tab. 4.1: Functions of different zones in embankment dam structures (Fell et al., 2015)

Zone	Description	Function
1	Earthfill ("core")	Controls seepage through the dam
2A	Fine filter (or filter drain)	(a) Controls erosion of Zone 1 by seepage water, (b) Controls erosion of the dam foundation (where used as horizontal drain), (c) Controls buildup of pore pressure in downstream face when used as vertical drain
2B	Coarse filter (or filter drain)	(a) Controls erosion of Zone 2A into rockfill, (b) Discharge seepage water collected in vertical or horizontal drain
2C	(i) Upstream filter	Controls erosion of Zone 1 into rockfill upstream of dam core
	(ii) Filter under rip rap	Controls erosion of Zone 1 through rip rap
2D	Fine cushion layer	Provides uniform support for concrete face; limit leakage in the event of the concrete face cracking or joints opening
2E	Coarse cushion layer	Provides uniform layer support for concrete face. Prevents erosion of Zone 2D into rockfill in the event of leakage in the face
1–3	Earth-rockfill	Provides stability and has some ability to control erosion
3A	Rockfill	Provides stability, commonly free draining to allow discharge of seepage through and under the dam. Prevents erosion of Zone 2B into coarse rockfill
3B	Coarse rockfill	Provides stability, commonly free draining to allow discharge of seepage through and under the dam
4	Rip rap	Controls erosion of the upstream face by wave action, and may be used to control erosion of the downstream toe from backwater flows from spillways

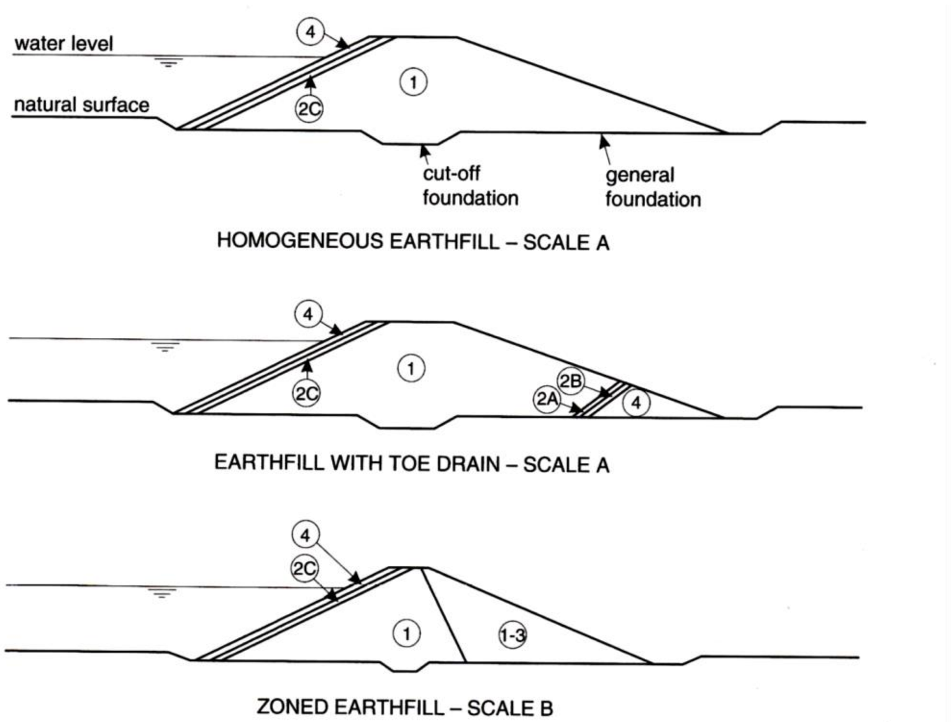


Fig. 4.2 (I): Typical embankment dam structures (Fell et al., 2015)

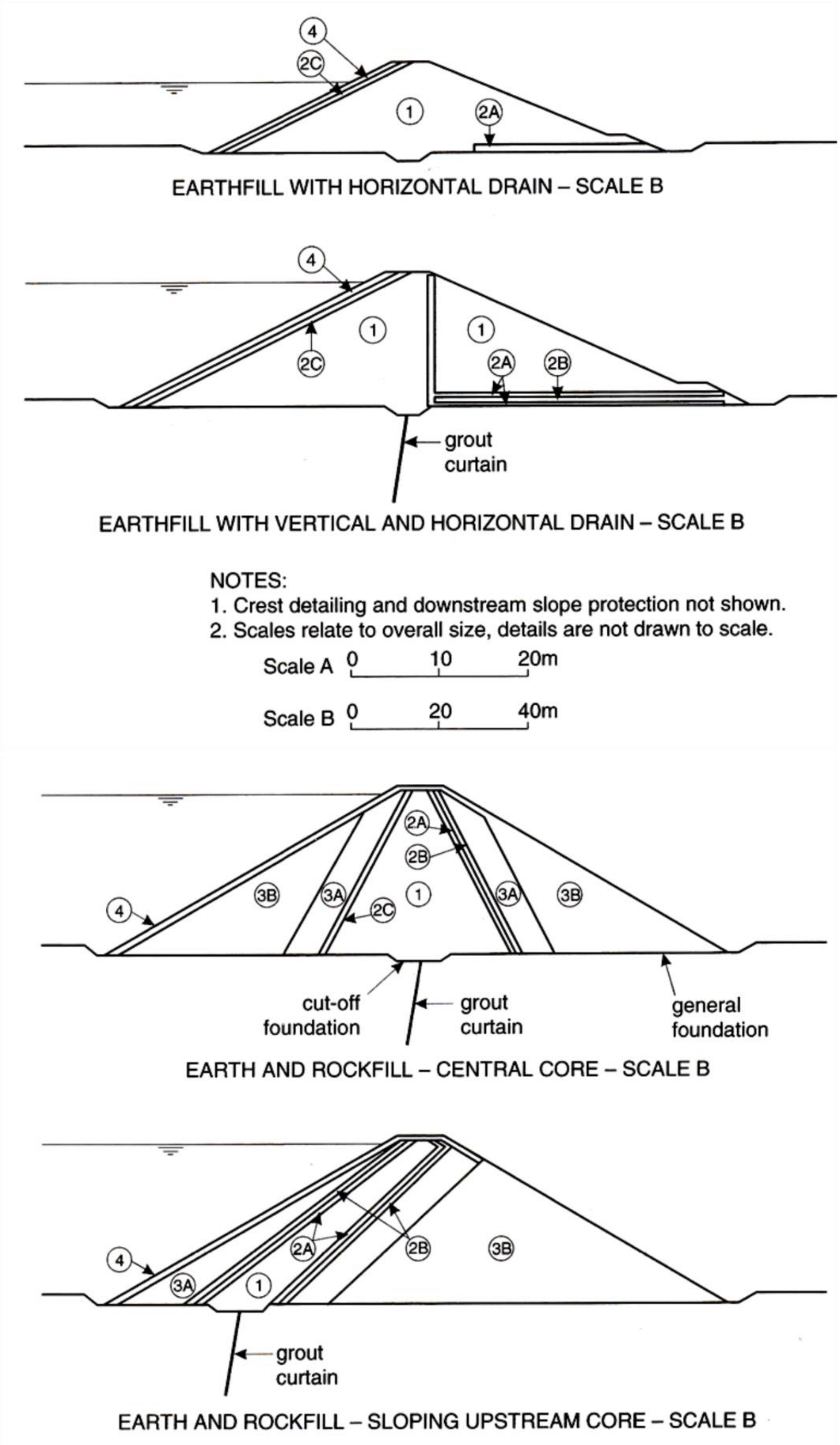


Fig. 4.2 (II): Typical embankment dam structures (Fell et al., 2015)

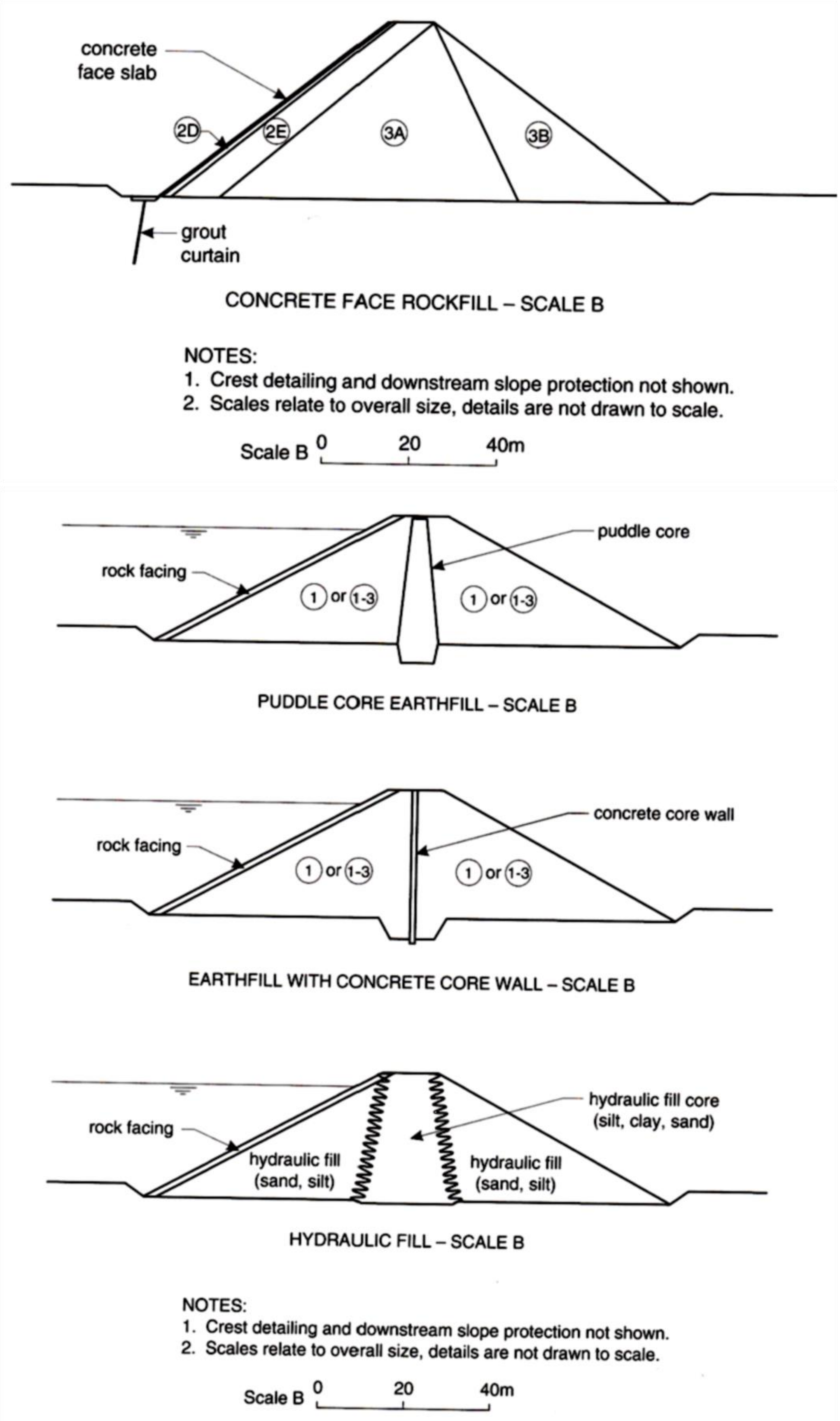
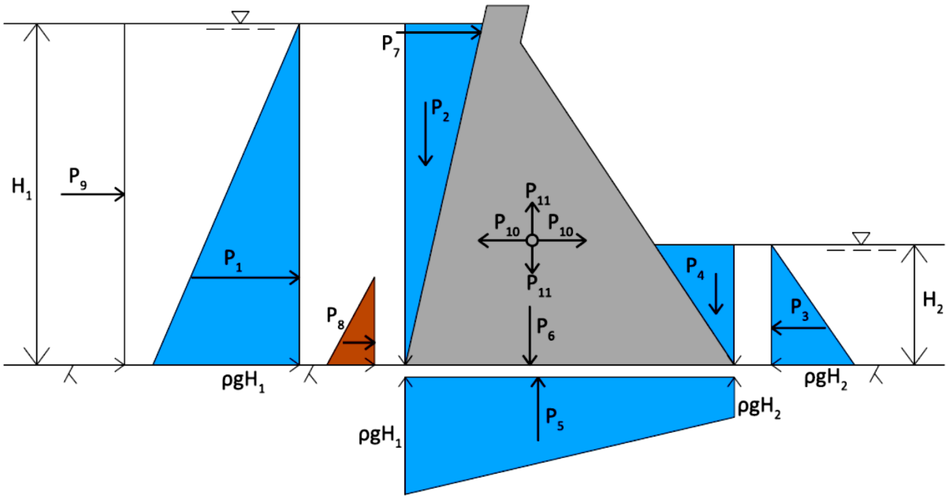


Fig. 4.2 (III): Typical embankment dam structures (Fell et al., 2015)

5 Dam dimensioning

A dam design has to satisfy stability and serviceability. The minimum expected life-time of dams is 50 years; in most cases it is longer. The dimensioning of dams has to consider all affecting static and dynamic forces (see Fig. 5.1), like:

- Weight of the dam
- Hydrostatic water pressure
- Basic pore/joint water pressure incl. ice pressure
- Potential earthquake forces



1. Hydrostatic pressure (P1-P2) – depends on the water level in the dam
2. Tailwater pressure (P3-P4) – depends on the tailwater level
3. Uplift pressure (P5) – hydrostatic pressure acting vertically, assumed to vary linearly from hydrostatic pressure at the heel to the tailwater pressure at the toe
4. Dead weight (P6) – the weight of the concrete
5. Ice pressure (P7) – load acting on the face of the dam due to an ice cover
6. Silt pressure (P8) – settled sediments exerting active pressure towards the dam
7. Seismic loads (P9-P11) – horizontal and vertical accelerations caused by earth quakes

Fig. 5.1: Loads acting on a dam (Broberg & Thorwind, 2015)

On the other side- under consideration of a certain factor-of-safety - forces of resistance have to be balanced, like:

- Strength (bearing capacity) of construction ground (bottom and valley flanks of the dam)
- Strength of construction material (concrete, masonry, rock fill etc.) incl. reinforcement measures
- Strength of contact between construction ground and construction material

Typical and most critical are the following proofs in respect to the safety analysis:

- Slope failure
- Sliding of dam body
- Bearing capacity
- Stability against overturning
- Local instabilities of dam
- Allowable base pressure
- Failure of sealing
- Failure of drainage system
- Damage due to cracking
- Proof of acceptable deformations and displacements
- Proof in respect to erosion and suffusion
- Proof in respect to earthquake excitation

The dam design has to follow national and international regulations and recommendations. For instance, in Germany the following regulations are obligatory:

- DIN 19700 (19700-10 and 19700-11)
- DIN 1054 and EC7
- ATV-DVWK-M 502

According to the German regulation DIN 19700 three loading situations (regular, seldom, exceptional) and three design constellations (very likely, less likely, unlikely) have to be considered. They result in the specific design categories BS I, BS II and BS III with corresponding safety factors (see Tab. 5.1).

Tab. 5.1: Design situations according to DIN 19700

Load situation	Design (dimensioning) situation		
	Very likely	Less likely	Unlikely
regular	BS I	BS II	BS III
seldom	BS II	BS III	----
exceptional	BS III	----	----

For each design situation a corresponding overall factor-of-safety (FOS) is defined:

- BS I: FOS = 1.3
- BS II: FOS = 1.2
- BS III: FOS = 1.1

The different load components, which have to be considered, are:

- Permanent (regular) loads:
  - Own weight of dam
  - Traffic loads and other additional loads
  - Water pressure and seepage forces
- Loads, which seldom occur:
  - Water pressure and seepage forces at high operation level
  - Water pressure and seepage forces at low operation level
  - Extraordinary load situations
  - Earthquake loading with return period of 100 years (small and medium reservoirs) or 500 years (big reservoirs)
- Unlikely load situation:
  - Water pressure and seepage forces at highest possible water level
  - Earthquake loading with return period of 1000 years (small and medium reservoirs) or 2500 years (big reservoirs)

Nowadays, dimensioning, optimization and corresponding proofs are mainly done by numerical simulation methods. In respect to reservoirs the simulation tasks can be subdivided into three classes:

- Model for stability and serviceability analysis of the dam itself incl. foundation
- Model for stability of reservoir slopes
- Model to simulate water flow including flooding and run-out

Models for stability and serviceability of the dam are mainly based on HM- or HTM-coupled FEM, FDM or DEM simulation techniques (see for instance Fig. 5.2 and 5.3). Models to simulate water flow incl. flooding are mainly based on CFD techniques based on VEM or FEM (Fig. 5.4). Up-to-date simulation approaches are integrated in BIM-systems using Digital Elevation Models and advanced numerical simulation tools. Fig. 5.4 shows, exemplary, the 3-dimensional flow field for a certain constellation using the Finite Volume Element Method. Nevertheless, due to the hydro-mechanical complexity physical models (see Fig. 5.5) are also still in use (e.g. Sassaman et al., 2009; Rosca, 2008; Güney et al., 2014).

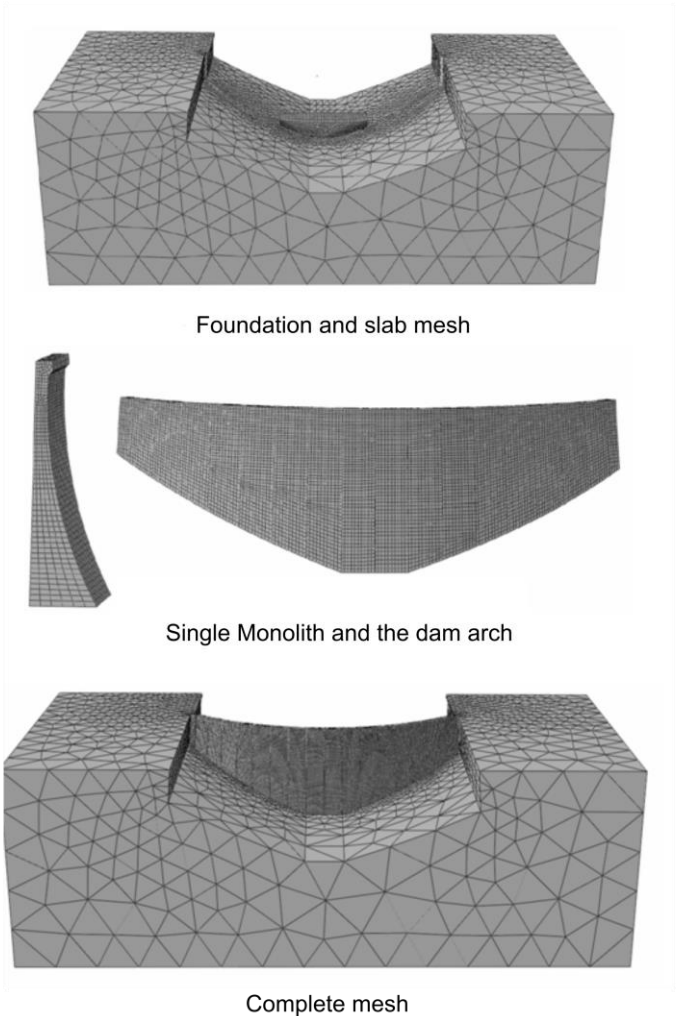


Fig. 5.2: Exemplary 3D numerical dam model (modified after Andersson & Seppäla, 2015)

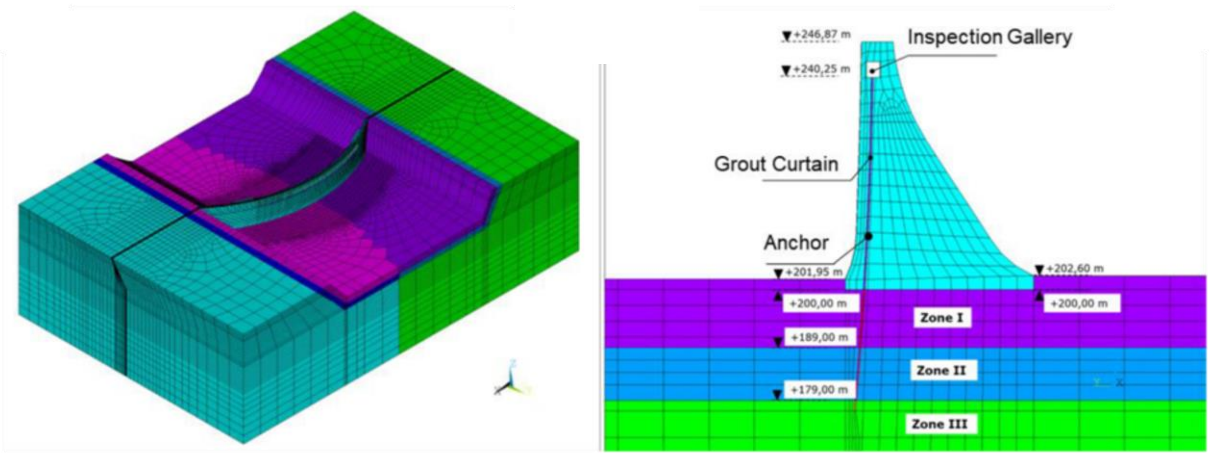


Fig. 5.3: Exemplary 3D numerical dam model (Schlegel et al., 2017)

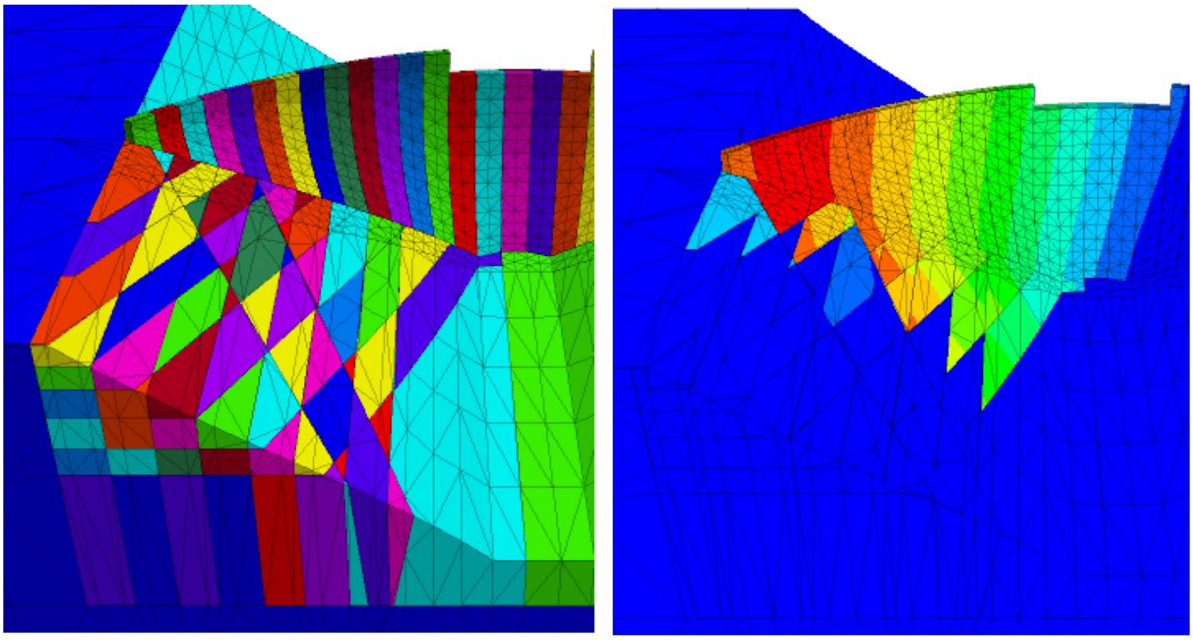


Fig. 5.3: Exemplary: 3D numerical dam model with explicit consideration of rock joint pattern using Discrete Element Method (Lemos, 2012)

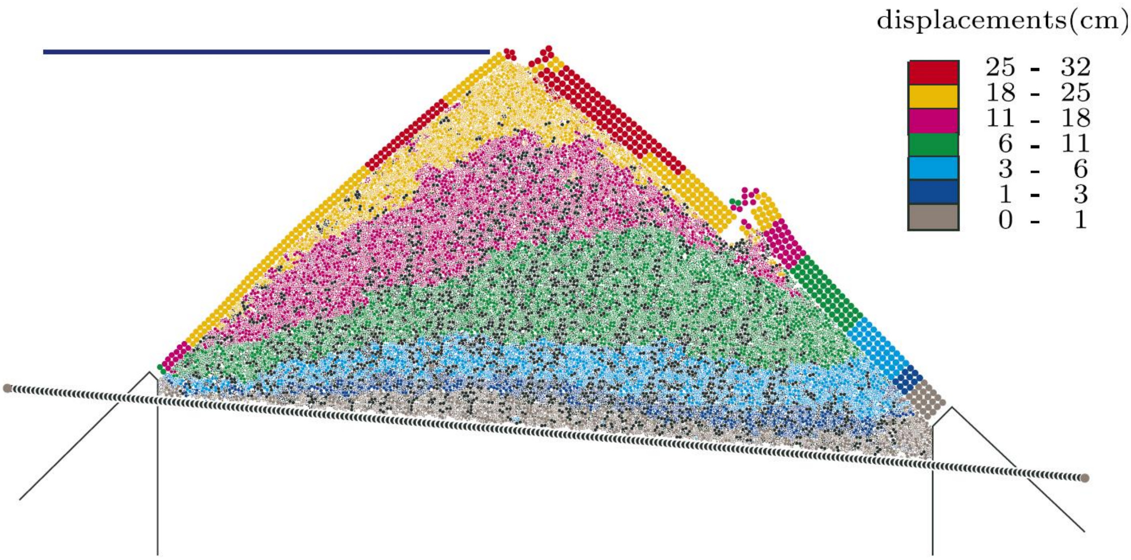


Fig. 5.4: Exemplary: 2D numerical model to simulate failure of rockfill dam using particle based Discrete Element Method (Deluzarche & Cambou,2006)

Fig. 5.5: Physical model to simulate dam breakage and flooding (Güney et al., 2014)

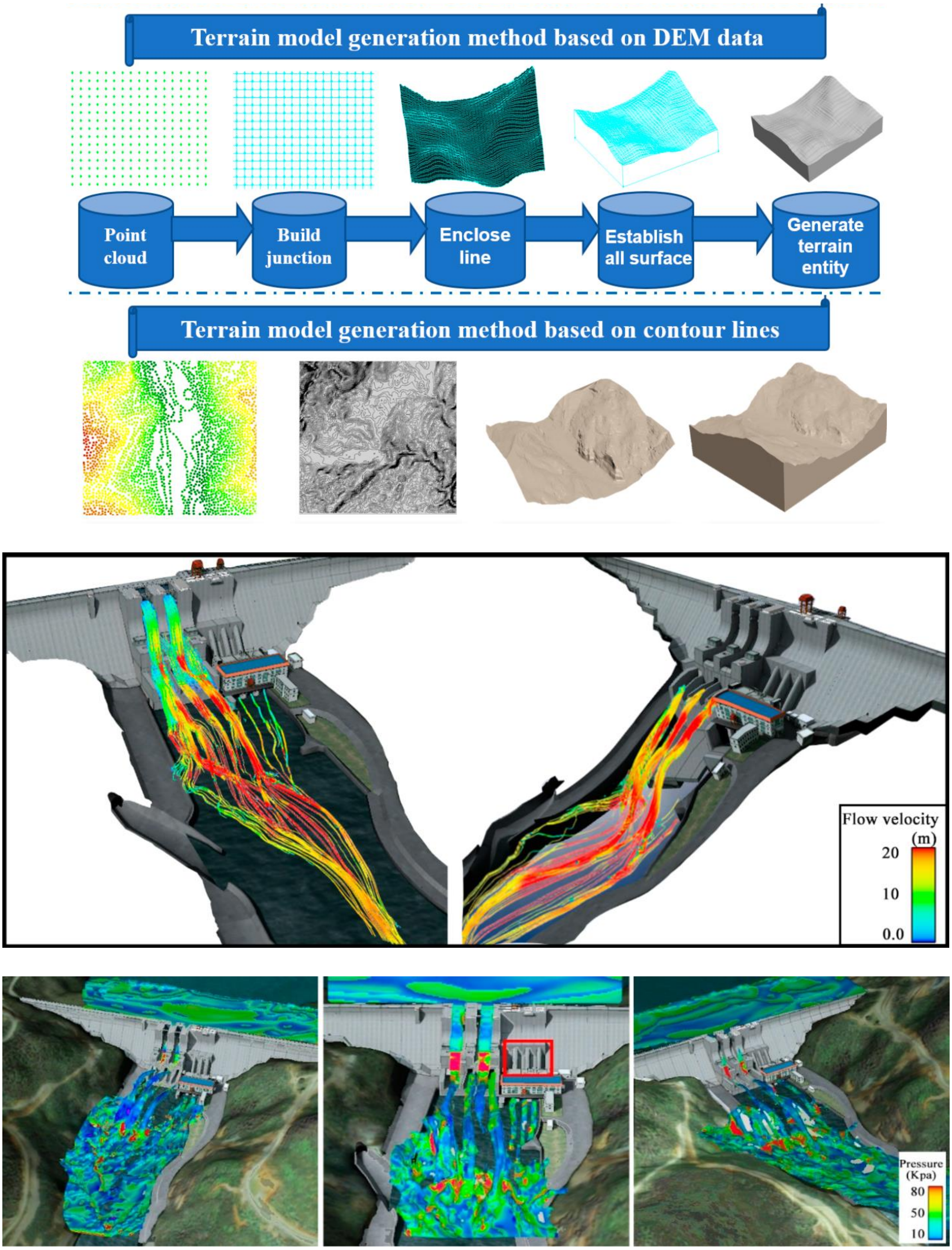


Fig. 5.6: Exemplary: Set-up of Digital Elevation Model (top); Local flow pattern in terms in flow velocity (middle) and water pressure (bottom) (Rong et al., 2019)

6 Dam water levels

Depending on considered country, responsibility and corresponding regulations different reservoir water levels are defined. Fig. 6.1 illustrates the definitions used in Germany. For management and safety of water dams these definitions are very important. In general two different levels have to be considered:

- High water levels (several maximum operation levels)
- Low water levels (several minimum operation levels)

Besides these fixed operation levels, special levels can be defined on demand. Stability and serviceability with different levels of FOS have to be proven for the different water levels.

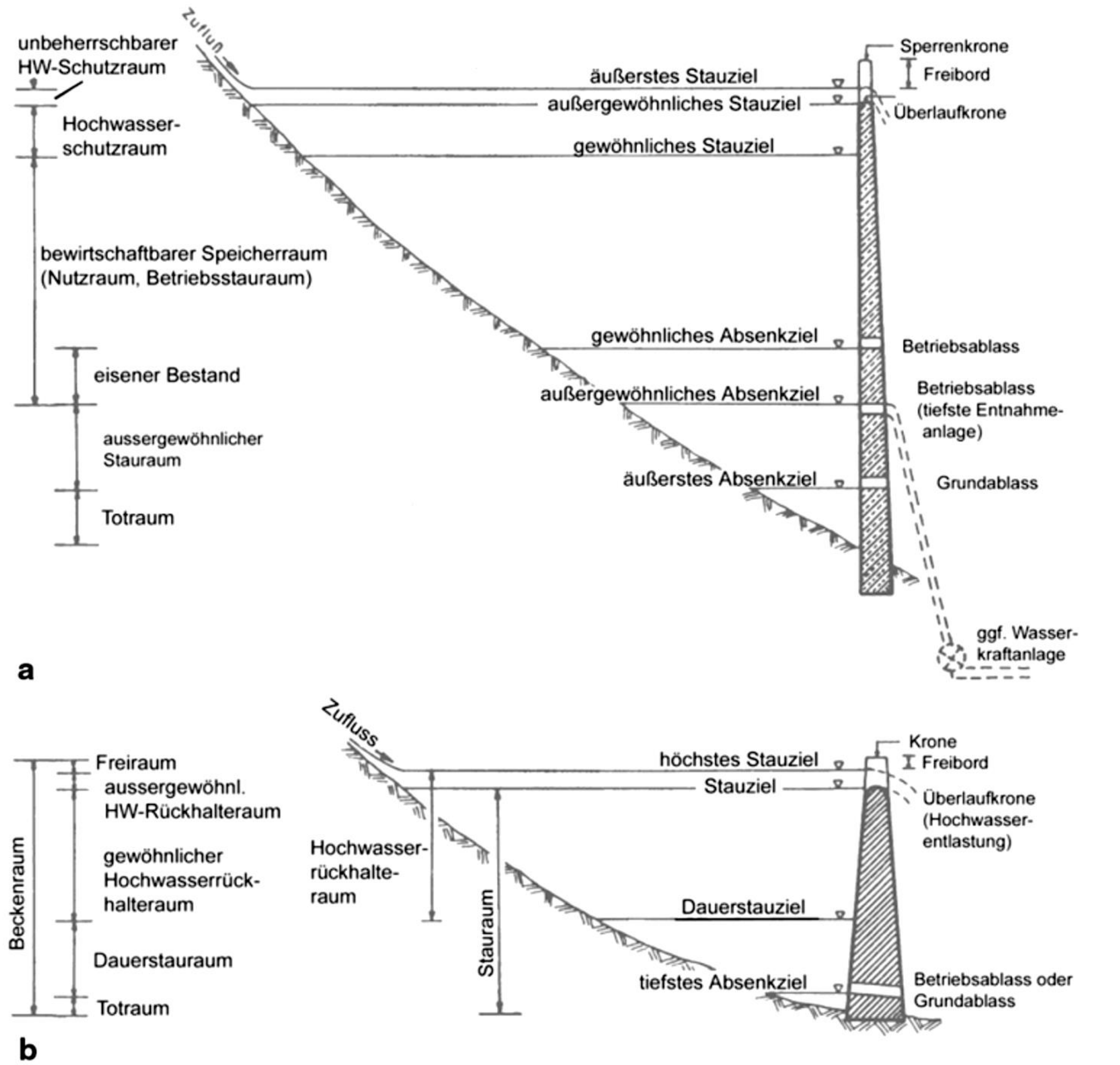


Fig. 6.1: Devision of reservoir space and operation levels according to German regulations (Maniak, 2016)

7 Dam monitoring

The following physical quantities should be monitored:

- Climatic parameters (temperature, precipitation)
- Reservoir water level
- Pore water pressure, contact pressure, seepage water, leakage
- Displacements, deformations and inclinations inside the dam, the slopes and the foundation
- Local seismicity

The monitoring can be performed by the following types of data collection:

- Visual inspections
- Manual readings
- Stand-alone data logger
- Real-time monitoring networks

The following equipment or technology is typically used to monitor dams (see also our e-book 29 about field measurements):

- Alignment survey to observe horizontal movement
- Level survey to observe vertical movements
- Triangulation measurements
- Piezometers to measure water pressures
- Weirs, Parshall flumes and flow meters to measure water flow velocity
- Plumb lines to measure deformations inside the dam (see Fig. 7.1.)
- Tilt meter and inclinometer
- Crack measurements (especially for concrete dams)
- Seismometers

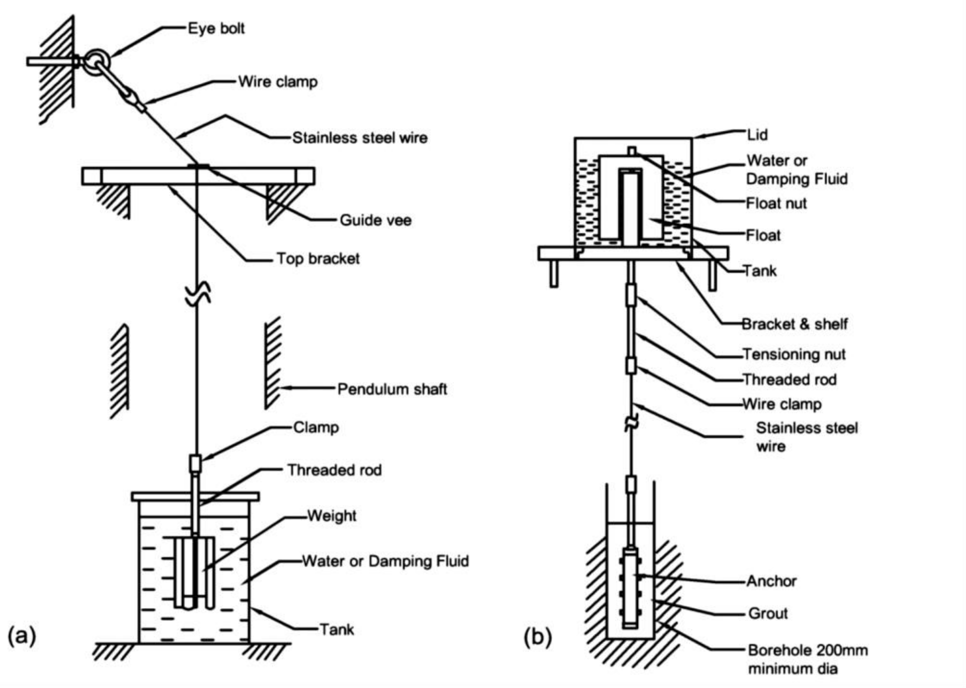


Fig. 7.1: Weighted plumbline (left) and float-supported plumbline (right) (CWC, 2018)

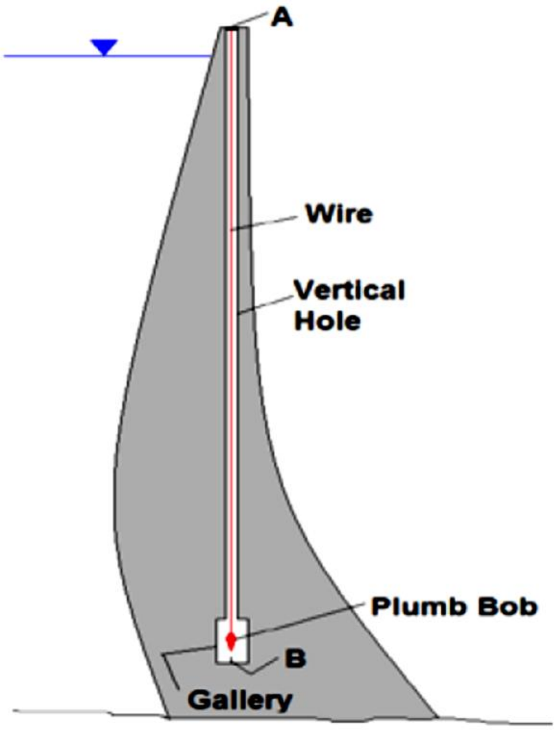


Fig. 7.2: Plumbline installed in an arch dam (FERC, 2018)

Structure Type	Feature	Visual observation	Movements	Uplift and pore pressure	Water levels and flow	Seepage flows	Water quality	Temperature measurement	Crack and joint measurement	Seismic measurement	Stress-strain measurement
Embankment Dams	Upstream slope	●	●	●	●	–	–	–	–	●	–
	Downstream slope	●	●	●	–	●	●	●	●	●	–
	Abutments	●	●	●	–	●	●	●	–	●	–
	Crest	●	●	●	–	–	–	–	●	●	–
	Internal drainage system	–	–	●	–	●	●	●	–	–	–
	Relief Drain	●	–	●	–	●	●	–	–	–	–
	Riprap and other slope protection	●	–	–	–	–	–	–	–	–	–
Concrete and Masonry Dams	Upstream slope	●	●	–	●	–	–	●	●	●	●
	Downstream slope	●	●	●	–	–	–	●	●	●	●
	Abutments	●	●	●	–	●	●	–	–	●	●
	Crest	●	●	●	–	–	–	●	●	●	●
	Internal drainage system	–	–	●	–	●	–	–	●	–	–
	Relief drains	●	–	●	–	●	–	–	–	–	–
	Galleries	●	●	–	–	–	–	–	●	●	●
	Sluiceways/controls	●	–	–	●	–	–	–	–	–	–
Spillways	Approach channel	●	●	–	●	–	–	–	–	–	–
	Inlet/outlet	●	●	●	●	●	–	–	●	●	–

Fig. 7.3 I: Parameters suggested for monitoring (CWC, 2018)

Structure Type	Feature	Visual observation	Movements	Uplift and pore pressure	Water levels and flow	Seepage flows	Water quality	Temperature measurement	Crack and joint measurement	Seismic measurement	Stress-strain measurement
	structure										
	Stilling basin	●	–	–	●	–	–	–	●	–	–
	Discharge conduit/channel	●	–	●	●	–	–	–	–	–	–
	Gate controls	●	–	–	–	–	–	–	–	–	–
	Erosion protection	●	–	–	–	–	–	–	–	–	–
	Side slopes	●	●	●	–	●	–	–	–	–	–
Outlets & Drains	Inlet/outlet structure	●	●	●	●	–	–	–	●	●	–
	Stilling basin	●	–	–	–	–	–	–	–	–	–
	Discharge conduit/channel	●	●	●	●	–	–	–	●	–	–
	Trash rack/debris controls	●	–	–	–	–	–	–	–	–	–
	Emergency systems	●	–	–	–	–	–	–	–	–	–
General Areas	Reservoir surface	●	–	–	–	–	●	–	–	–	–
	Mechanical/electrical systems	●	–	–	●	–		–	–	–	–
	Shoreline	●	–	–	–	–	●	–	–	–	–
	Upstream watershed	●	–	–	–	–	●	–	–	–	–
	Downstream channel	●	–	–	–	●	●	–	–	–	–

Fig. 7.3 II: Parameters suggested for monitoring (CWC, 2018)

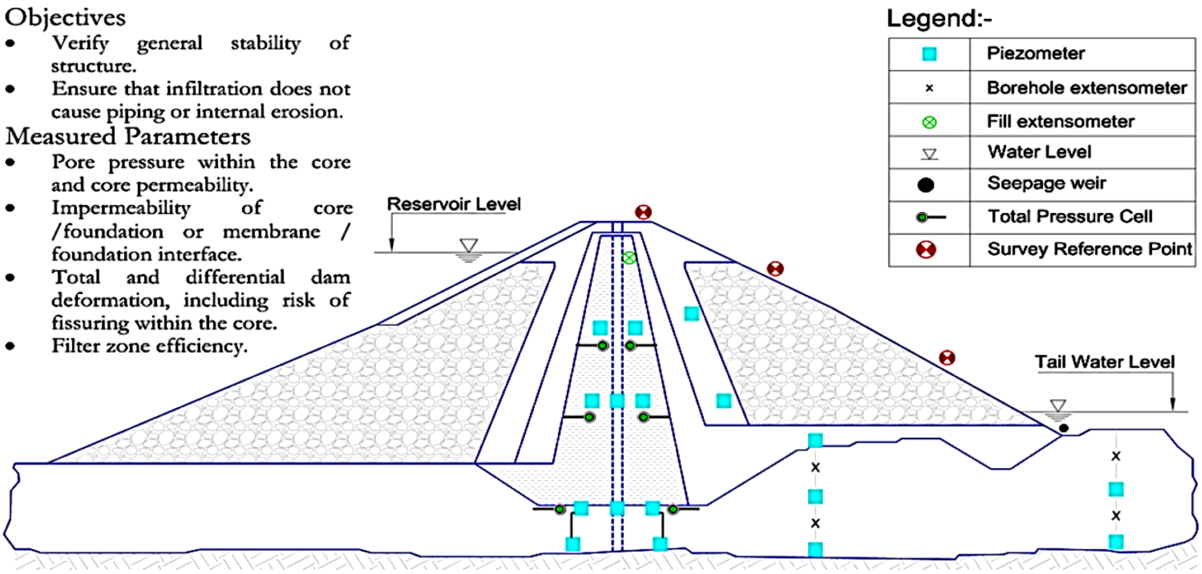


Fig. 7.4: Illustration of a typical monitoring system for an embankment dam (CWC, 2018)

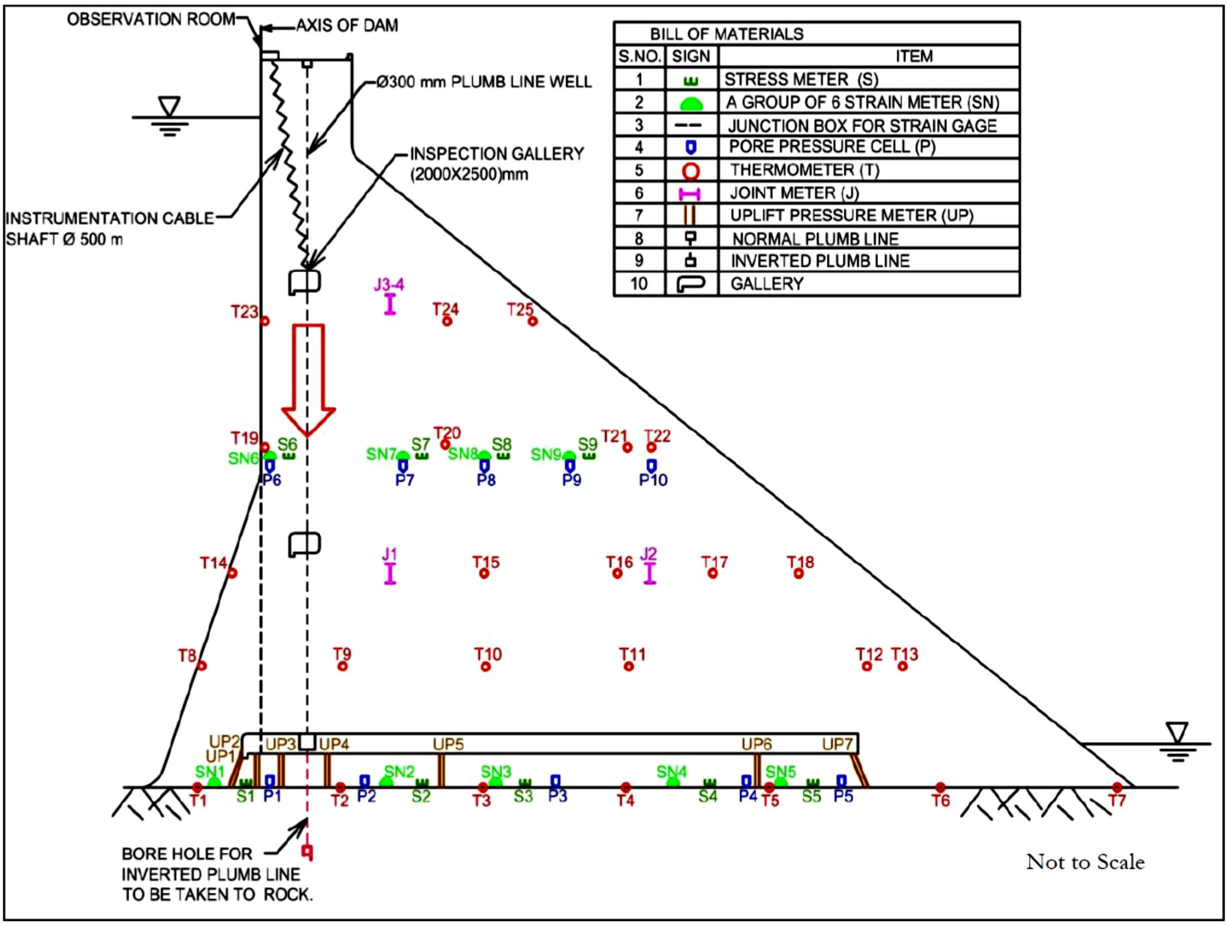


Fig. 7.5: Illustration of typical a monitoring system for a concrete or masonry dam (CWC, 2018)

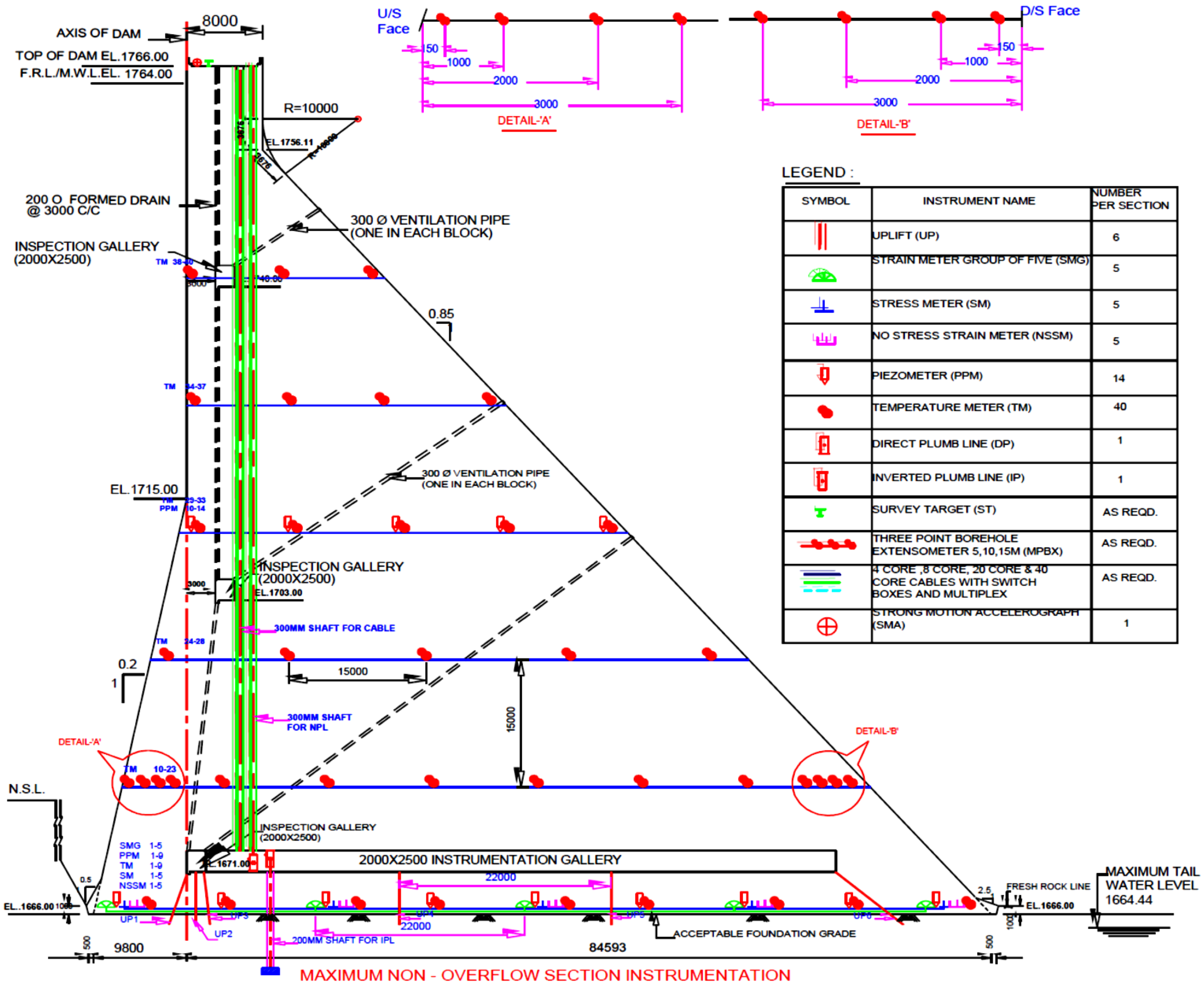


Fig. 7.6: Illustration of a typical monitoring system for a concrete or masonry dam (2) (CWC, 2018)

Fig. 7.3 gives an overview about the physical quantities, which should be monitored. Fig. 7.4 illustrates the location of the different sensors in case of an embankment dam und Fig. 7.5 and 7.6 show sensor positions for a concrete or masonry dam.

Please note again, that each dam is a unique construction in terms of size, shape, material and especially geological conditions. Therefore, not only construction, but also monitoring has to be adapted to the specific situation. Please note also, that instrumentation strongly depends on type, size, function and location etc. of the dam. Exemplary, Tab. 7.1 shows an incomplete extract of the routine monitoring program performed at the water dam Lehnmuehle (app. 50 m high and 400 m long).

Tab. 7.1: Selection (incomplete) of the monitoring program for water dam Lehnmuehle (LTV Sachsen, 2002)

Measured quantity	Measurement method	Number of measurement points	Frequency of measurements	Measurement accuracy
inspection	visual inspection	whole water dam	daily	--
displacements	weight and swimming plumb	8	daily	± 0,2 mm
	different geodetic measurements	In total > 30 levelling measurements and water level gauge measurements	monthly or every 3 months	± 0.03 mm to ± 1 mm
water height inside reservoir	1	1	daily	± 10 mm
seepage	automatic	10 different areas	hourly	± 10 ml/s
	additional manual		daily	
water uplift pressure	piezometer	6 profiles, in total 21 points	weakly	± 1 kPa
temperature air	thermometer	1	daily	± 0,5 °C
temperature water	thermometer	2 at different depths	daily	± 0.5 °C
precipitation	rain gauge	1	daily	± 1 mm

8 Dam failures

Dam failure can occur due to the following reasons:

- Inadequate maintenance and monitoring
- Overtopping caused by floods
- Acts of sabotage
- Failure of construction materials
- Erosion and piping (especially in case of embankment dams)
- Cracking (especially in case of concrete dams)
- Failure or unacceptable movement in the foundation of flanks

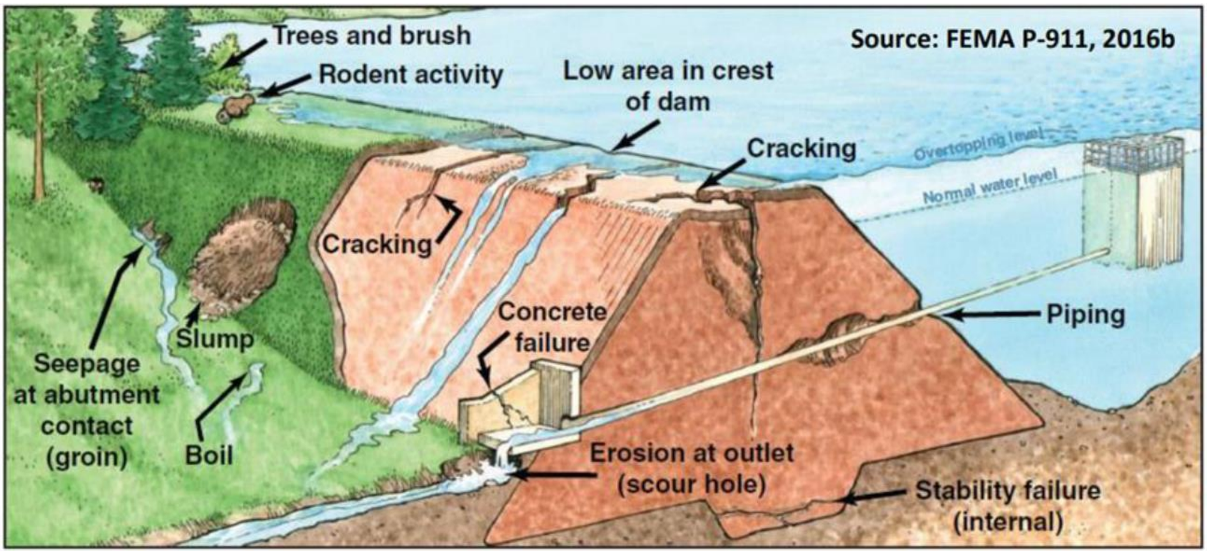


Fig. 8.1: Illustration of typical modes of water dam failures (CRS, 2019)

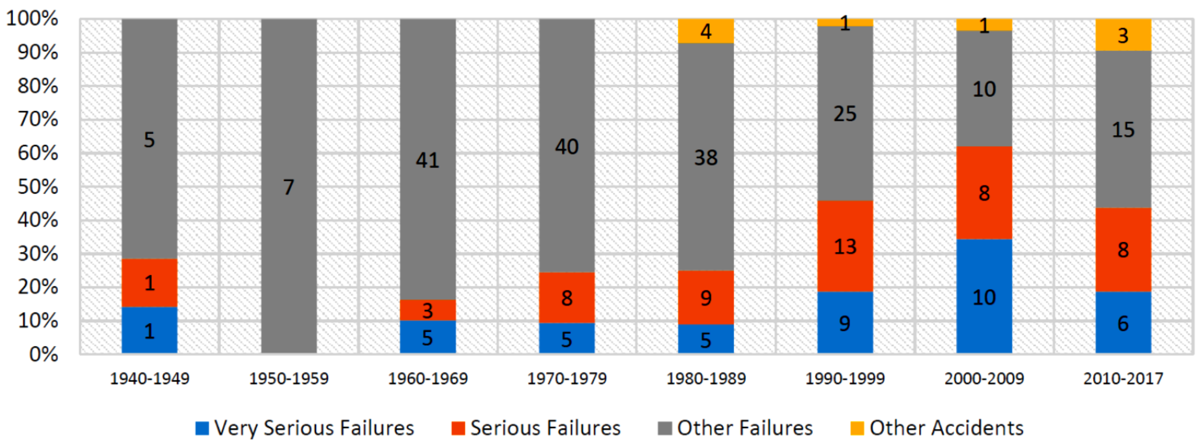


Fig. 8.2: Time-line and severity of global reported tailing dam failures (STINGS, 2018)

Dam failure can have catastrophic consequences in terms of:

- Fatalities
- Huge economic losses
- Negative environmental impact

In case of tailing dam failure the environmental pollution due to toxic ingredients has to be considered in addition (STINGS, 2018; Azam & Li, 2010). The total average cost of tailing dam failure is about 455 Mio Euros (STINGS, 2018).Fig. 8.2 illustrates time-line and severity of tailing dam failures. According to Lunio, F. et al. (2014) approximately 1000 people lost their live due to dam failure only in Italy within the last 100 years.

The main causes for tailing dam failures are (STINGS, 2018):

- Slope instability
- Overtopping
- Seismic events
- Poor management
- Unusual amount of rainfall

Tab. 8.1 summarizes the main causes for water dam failure. The impact of failed water dams in respect to the environment (especially flooding) is described for instance by DNRME (2018).

Tab. 8.1: Distribution of causes of dam failure (Balasubramanian, 2016)

Kind of Event	Percentage
Foundation problems	40%
Inadequate spillway	23%
Poor construction	12%
Uneven settlement	10%
High pore pressure	5%
Acts of war	3%
Embankment slips	2%
Defective materials	2%
Incorrect operations	2%
Earthquakes	1%

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