Earthquake-Induced Deformations in Embankment Dams: Darbandikhan Dam as a Case Study

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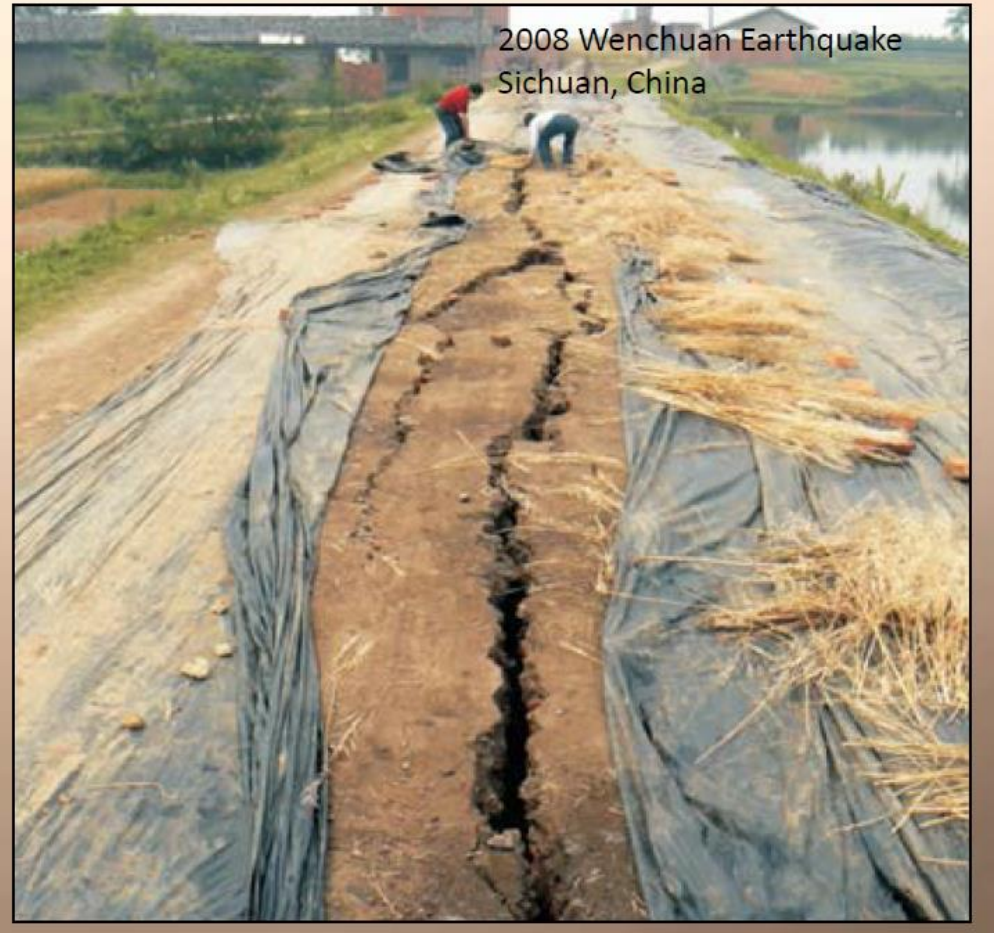
Outline

1. Effect of Earthquakes on Embankment Dams
2. Type of Cracks in Embankment Dams
3. Darbandikhan Dam
4. Weak & Strong Points in Darbandikhan Dam
5. The November 12, 2017 Earthquake Properties
6. Detailed Safety Inspections
7. How the Safety of the Dam Was Assured?
8. Rehabilitation of Darbandikhan Dam
9. Conclusions

Effect of Earthquakes on Embankment Dams

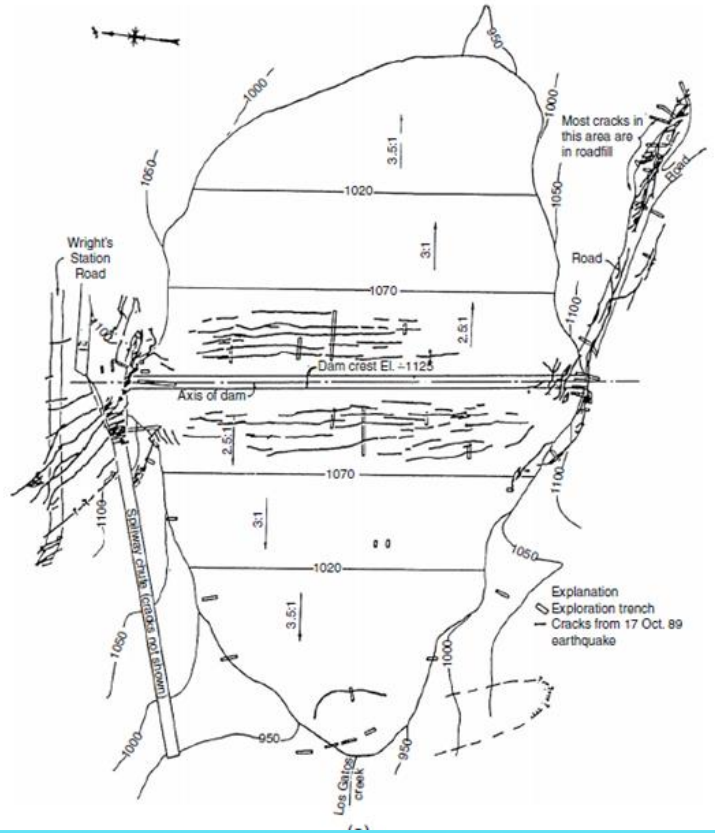
1. Settlement and cracking of the embankment, particularly near the crest of the dam.



Effect of Earthquakes on Embankment Dams

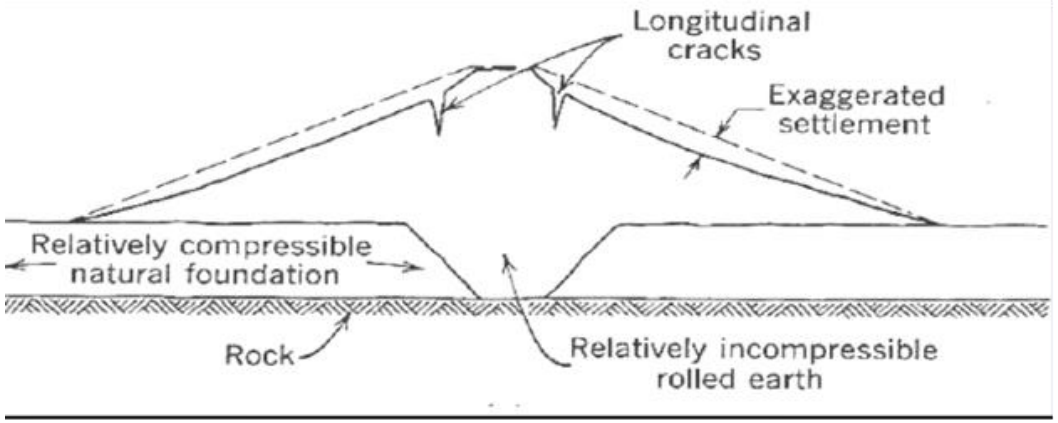
1. Settlement and cracking of the embankment, particularly near the crest of the dam.

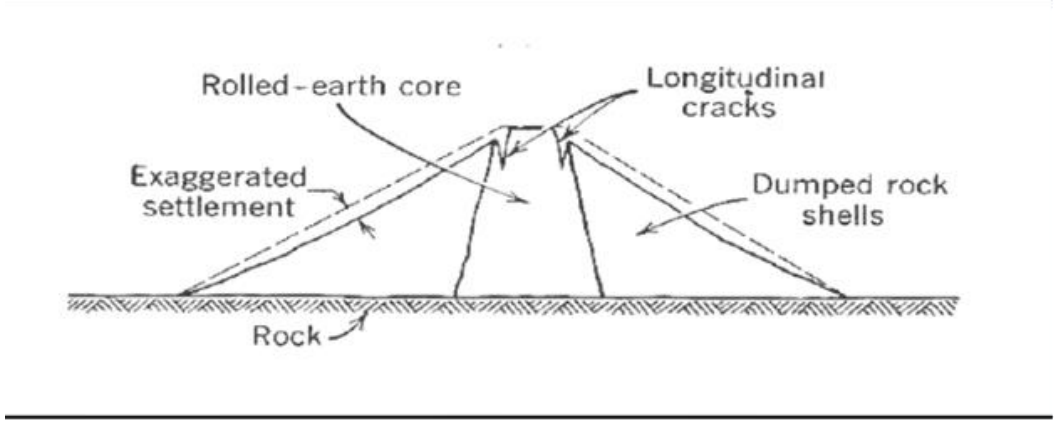
Austrian Dam – 55 m high - October 17, 1989 Loma Prieta Earthquake – M = 7.1.

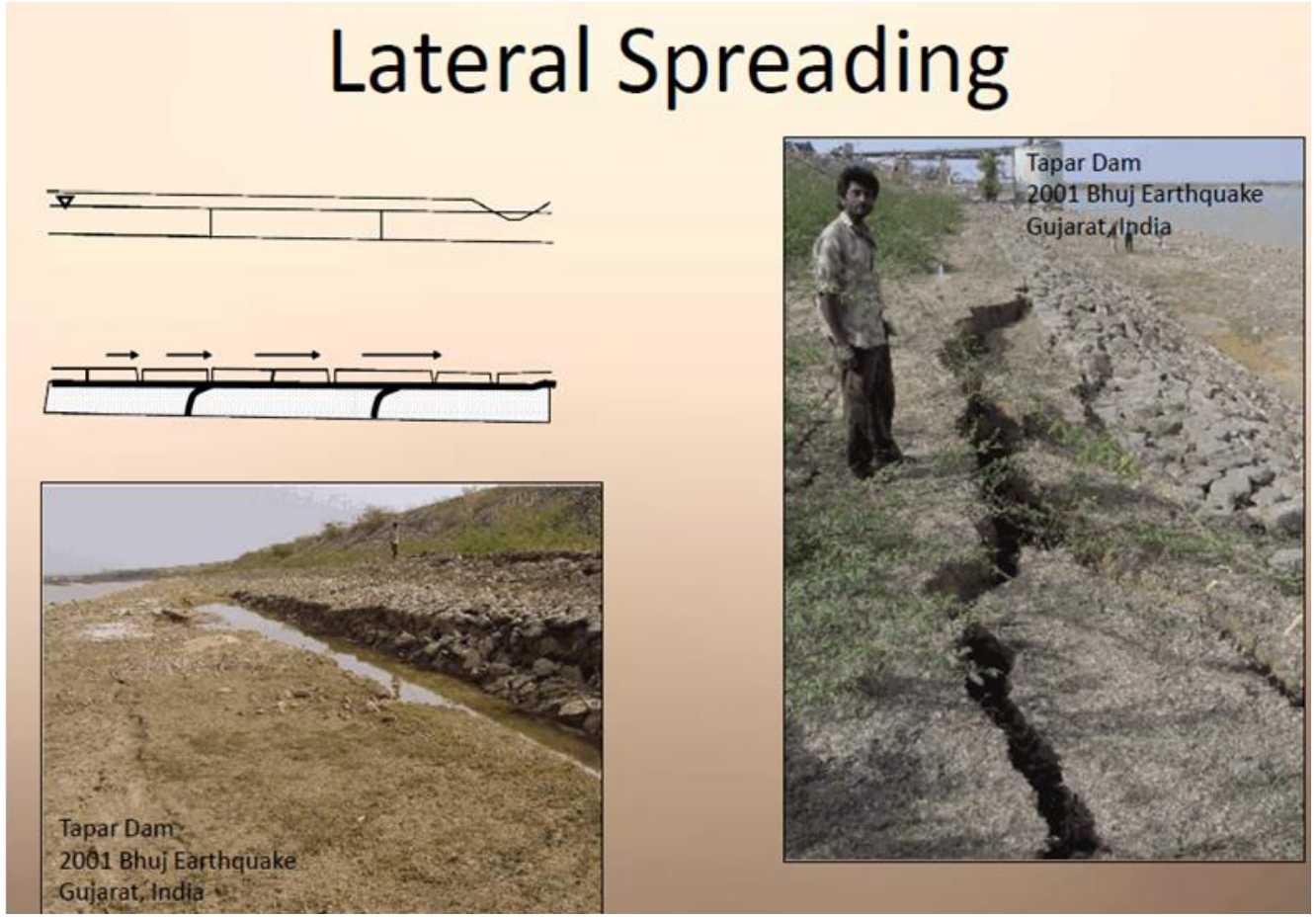


Effect of Earthquakes on Embankment Dams

2. Lateral Spreading and cracking of the embankment.







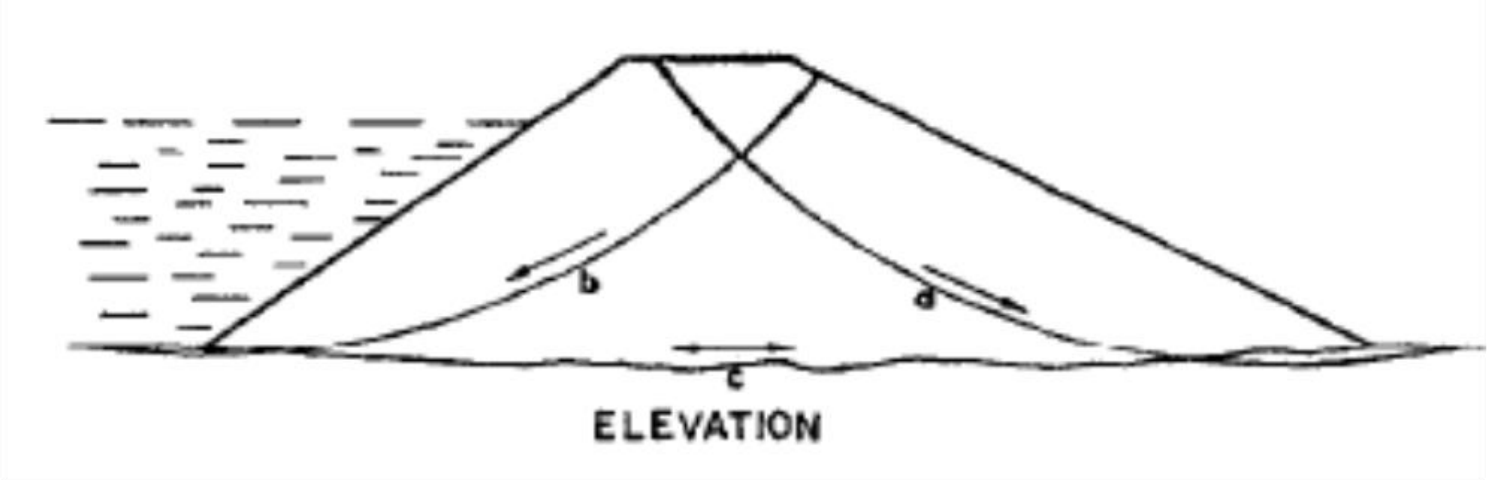
Effect of Earthquakes on Embankment Dams

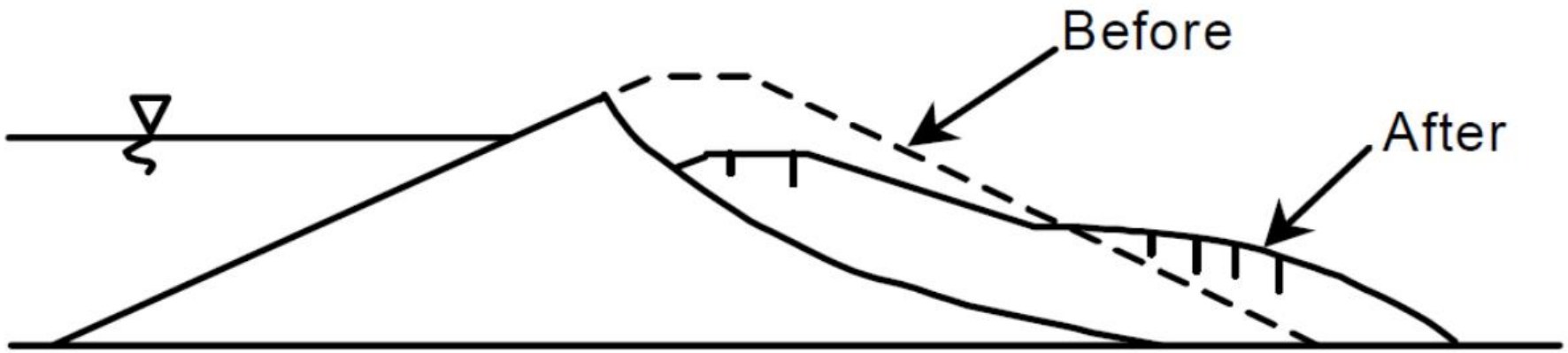
3. Liquefaction or loss of shear strength due to increase in pore pressures induced by the earthquake in the embankment and its foundations.

Lower San Fernando Dam after Upstream Slope Slide in Earthquake of Feb . 9, 1971 – M = 6.6 San Fernando earthquake produced about 0.55 g peak acceleration at the dam crest.

Effect of Earthquakes on Embankment Dams

4. Instability of the upstream and downstream slopes of the dam

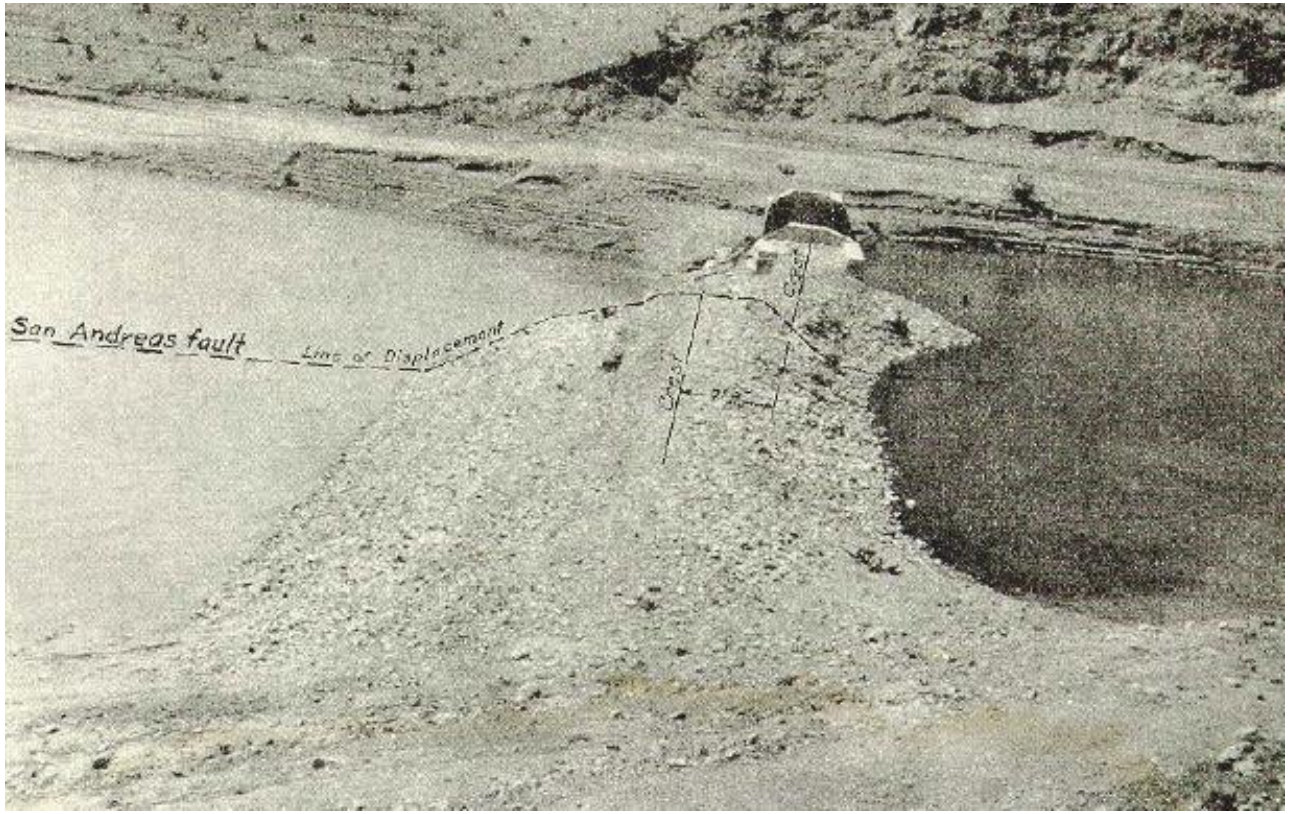




Effect of Earthquakes on Embankment Dams

5. Differential movements (rupture) on active faults passing through the dam foundation.

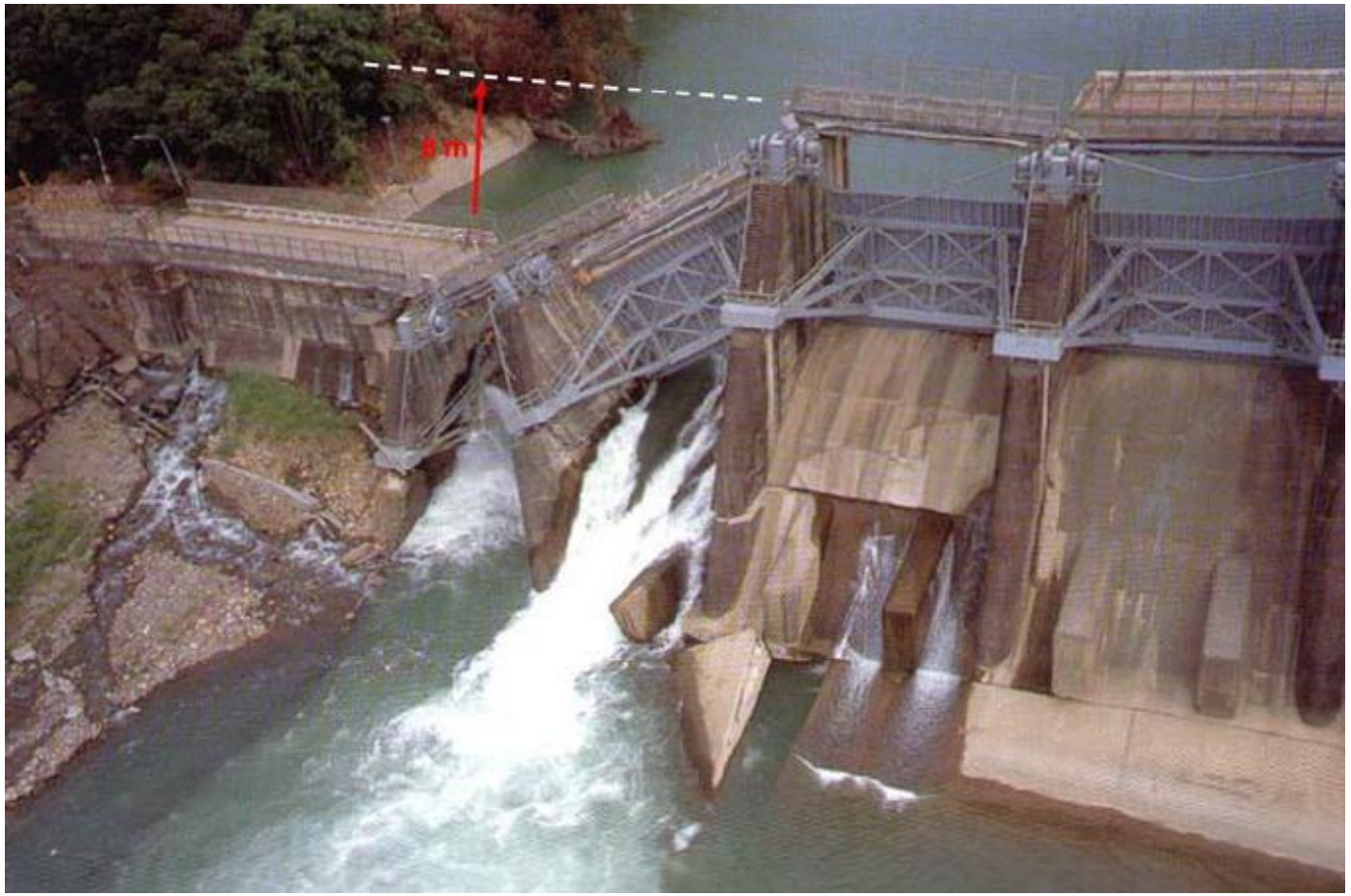
San Andreas Dam, CA (1906) Fault Rupture
The devastating magnitude Mw 7.7–7.9 San Francisco



Effect of Earthquakes on Embankment Dams

5. Differential movements (rupture) on active faults passing through the dam foundation.

Chelungpu-thrust-fault-Chi-Chi-Taiwan-1999-earthquake-Shih-Kang-Dam

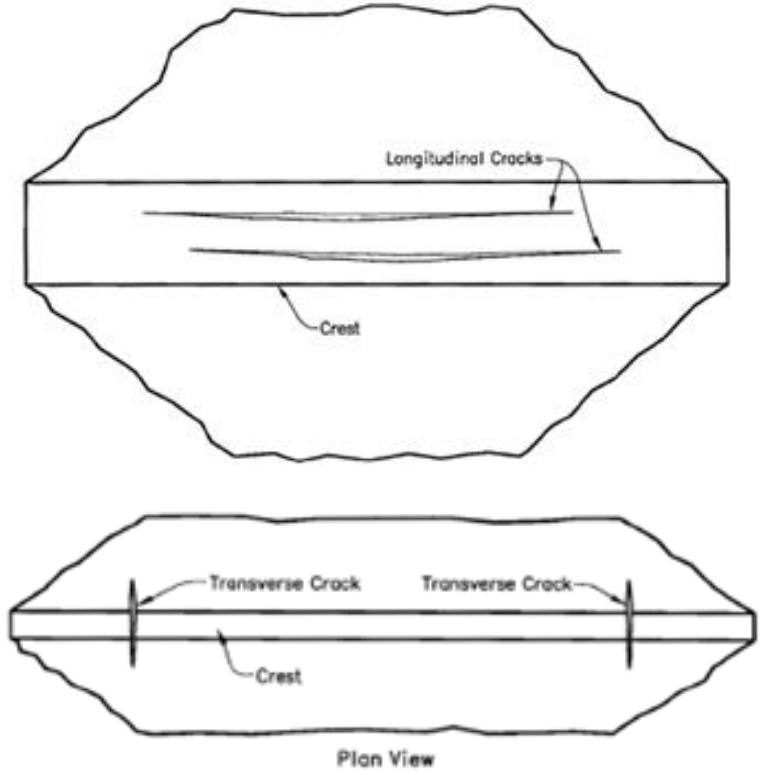


Effect of Earthquakes on Embankment Dams

6. Overtopping of the dam by waves due to earthquake induced landslides into the reservoir from the valley sides.
7. Damage to spillways and outlet works passing through the embankment leading to leakage and potential piping erosion of the embankment.

Types of Cracks in Embankments

Generally there are two types of cracks:



Fell et al. (2015)

1-

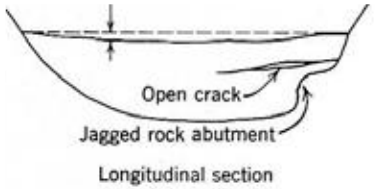
Vertical Cracks

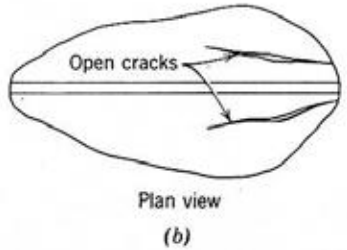
- **Longitudinal cracks**
- **Transverse cracks**
- **Diagonal cracks**

2-

Horizontal Cracks

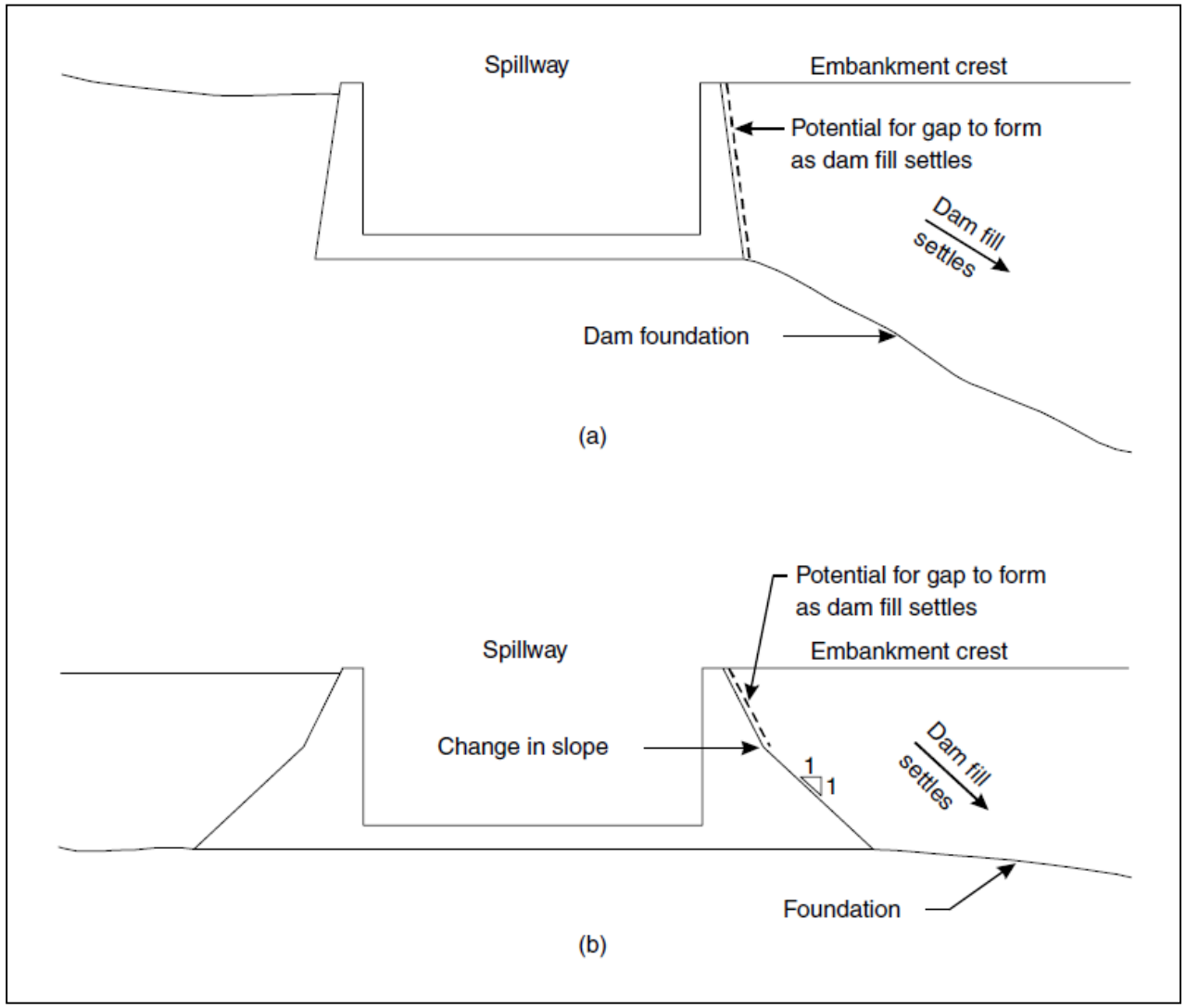
Arching Action and Hydraulic Fractures





Types of Cracks in Embankments

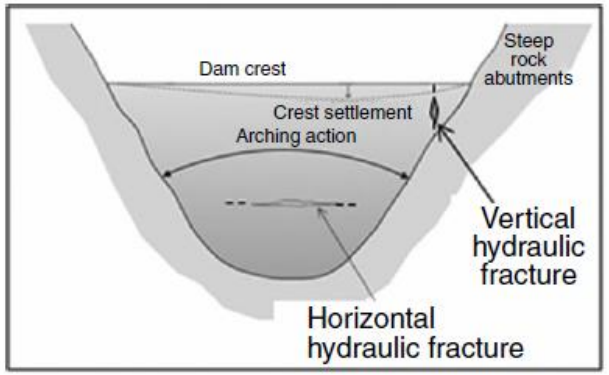
A very significant form of cracking is separation cracking; vertical crack occurs between two different units, for instance the embankment and a spillway wall (or a vertical abutment wall).

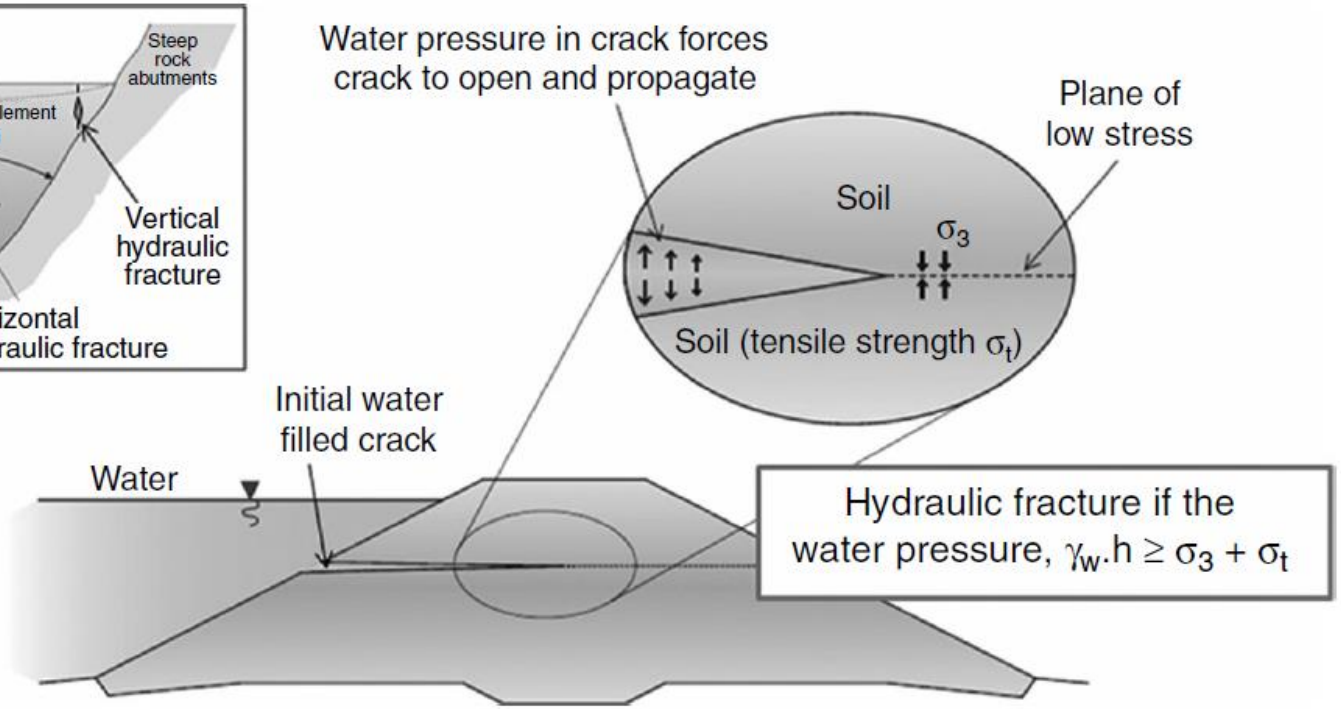


Types of Cracks in Embankments

Horizontal Cracks

Arching Action and Hydraulic Fractures





Darbandikhan Dam

- Darbandikhan dam is a multi-purpose rock-fill dam located on the Diyala river approximately 65 km south-east of Sulaymaniyah city and 230 km north-east of Baghdad city (Iraq).
- The dam has a height of 128 m, length of 445 m, and 17 m crest width at elevation 495 m. The construction of the dam was completed in 1961.
- The total capacity of the Darbandikhan reservoir is 3 km^3 at the normal pool level (El. 485.00 m).

Darbandikhan Dam

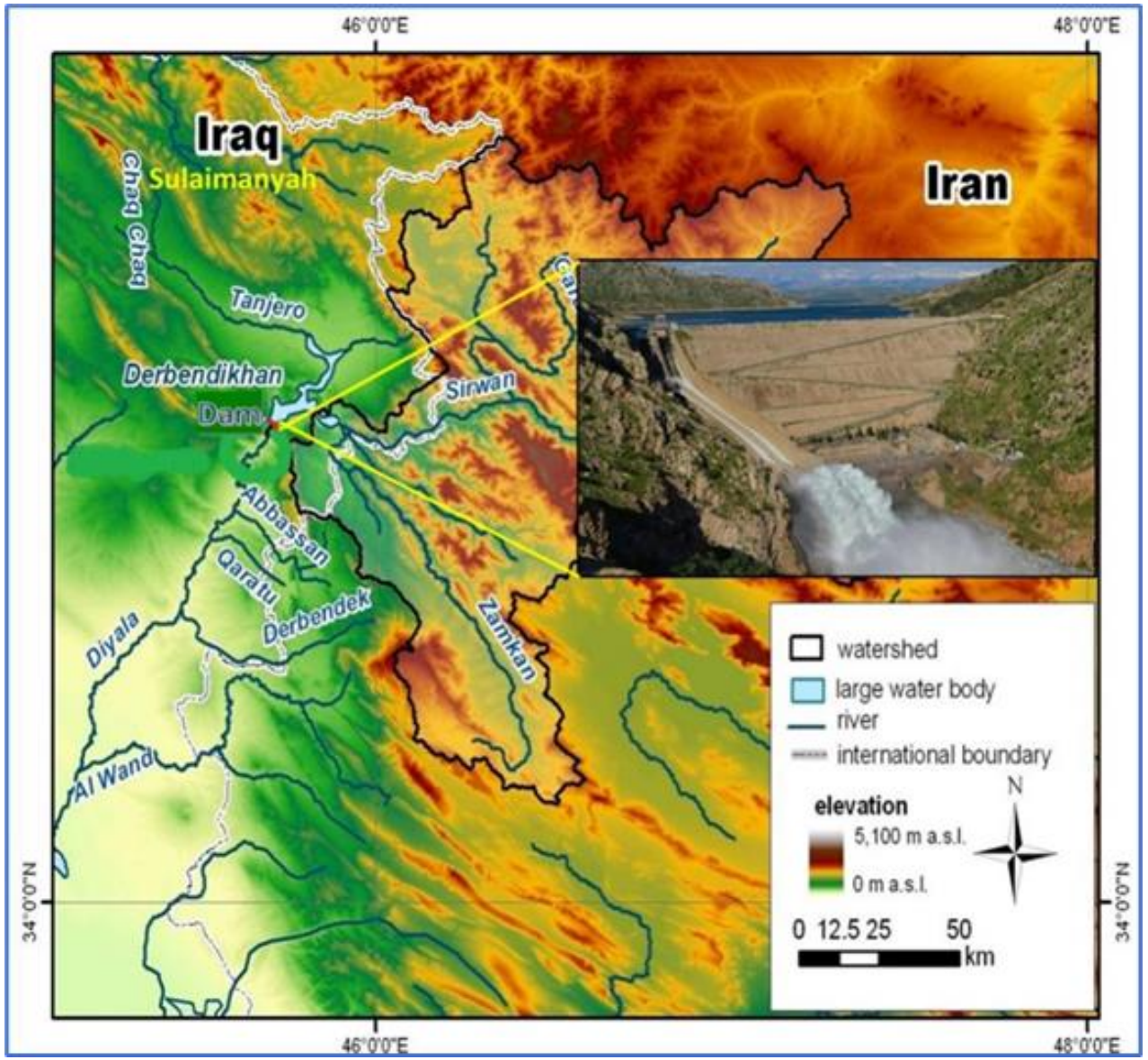


Figure 1. Darbandikhan dam location/ Iraq

Darbandikhan Dam

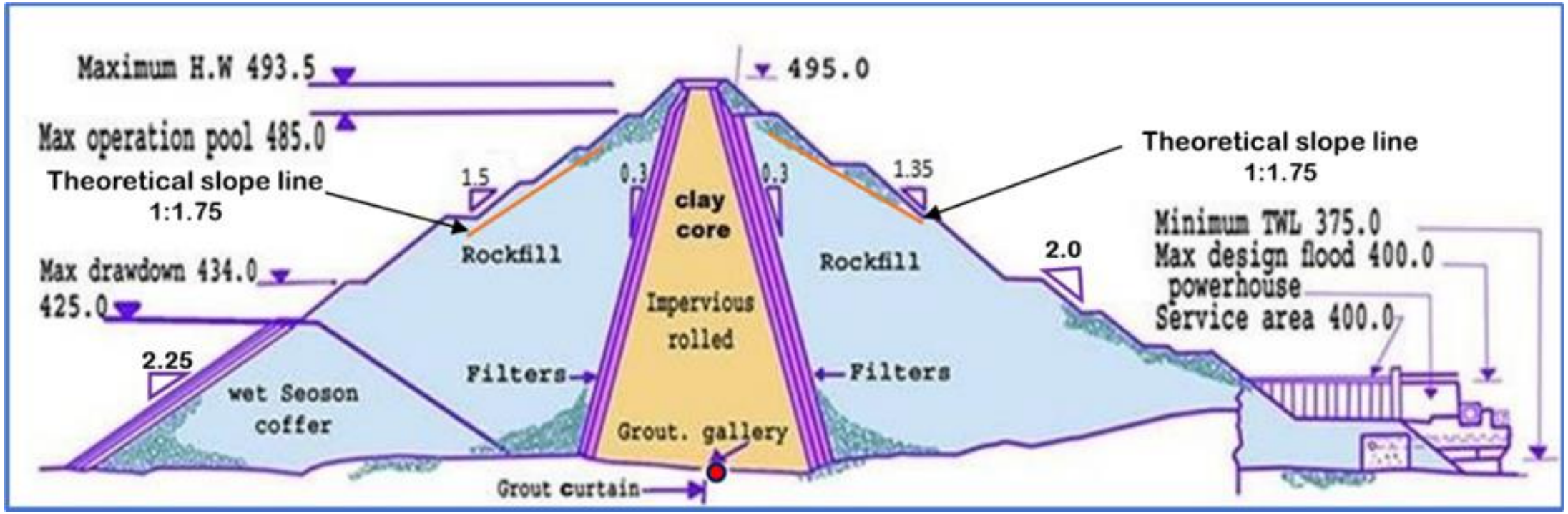
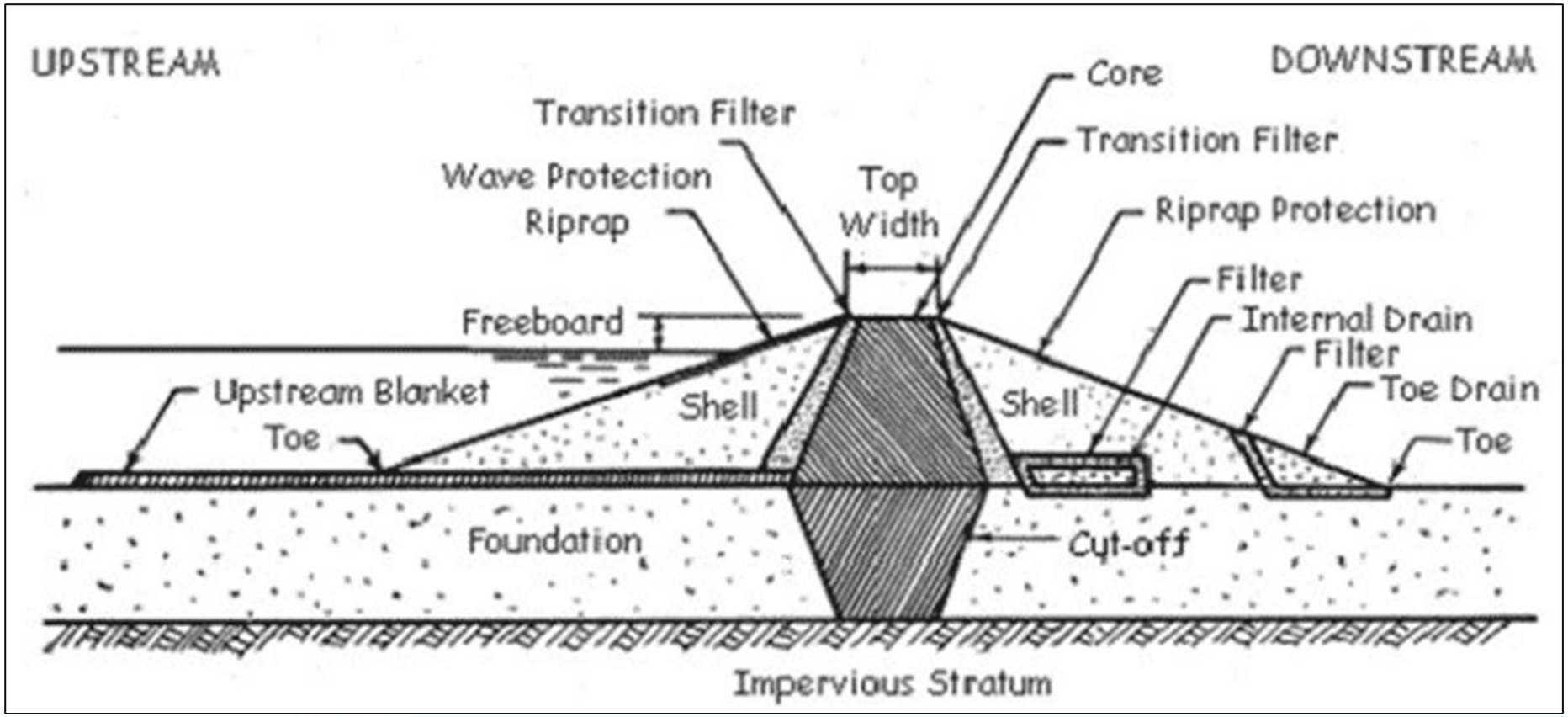


Figure 2. Maximum cross section of Darbandikhan dam.

The Weak & Strong Points in Darbandikhan Dam

Weak Points

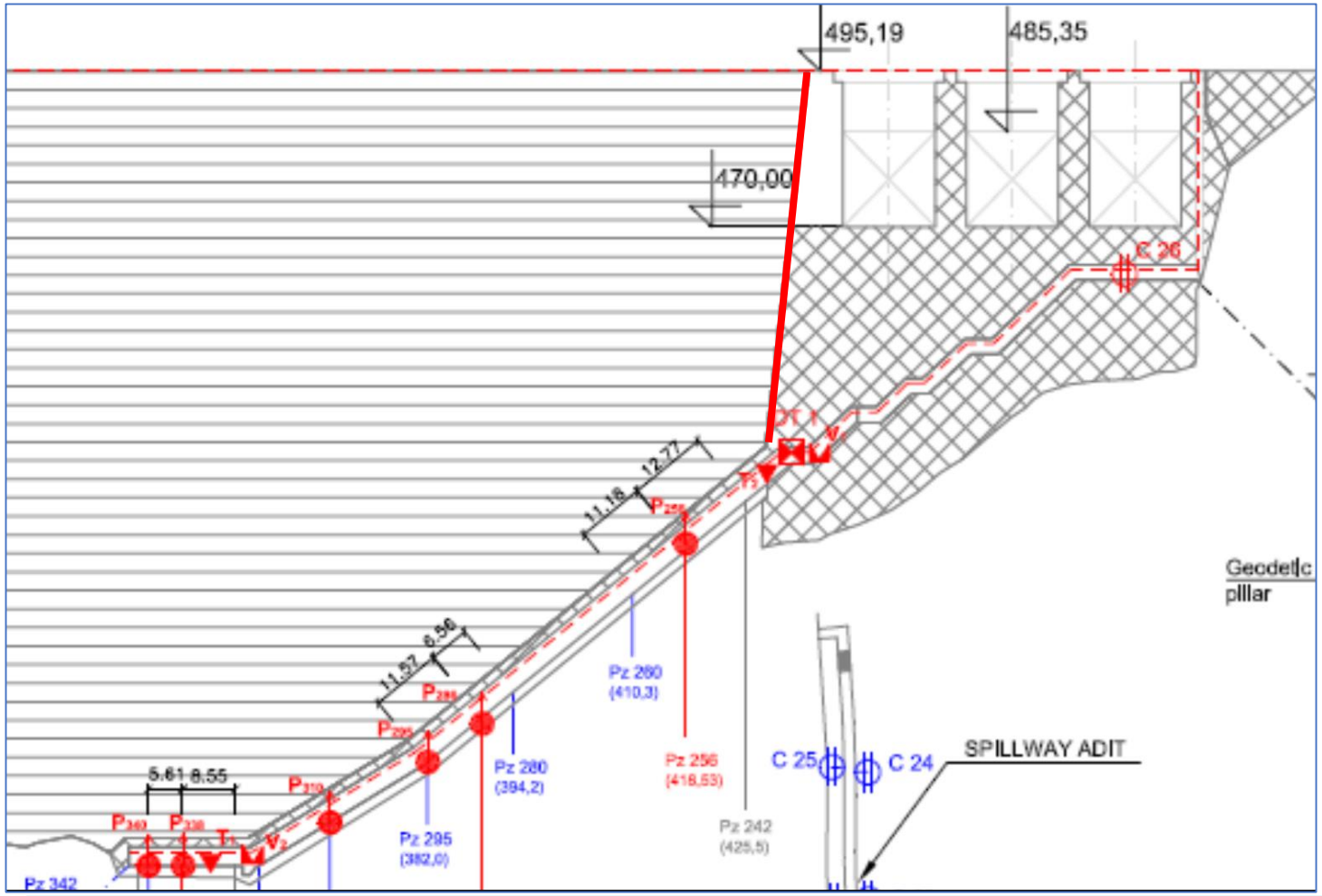
1. There is no Toe Drain which is essential for the Inspection of seepage through the dam body.



The Weak & Strong Points in Darbandikhan Dam

Weak Points

2- Spillway-Embankment interface

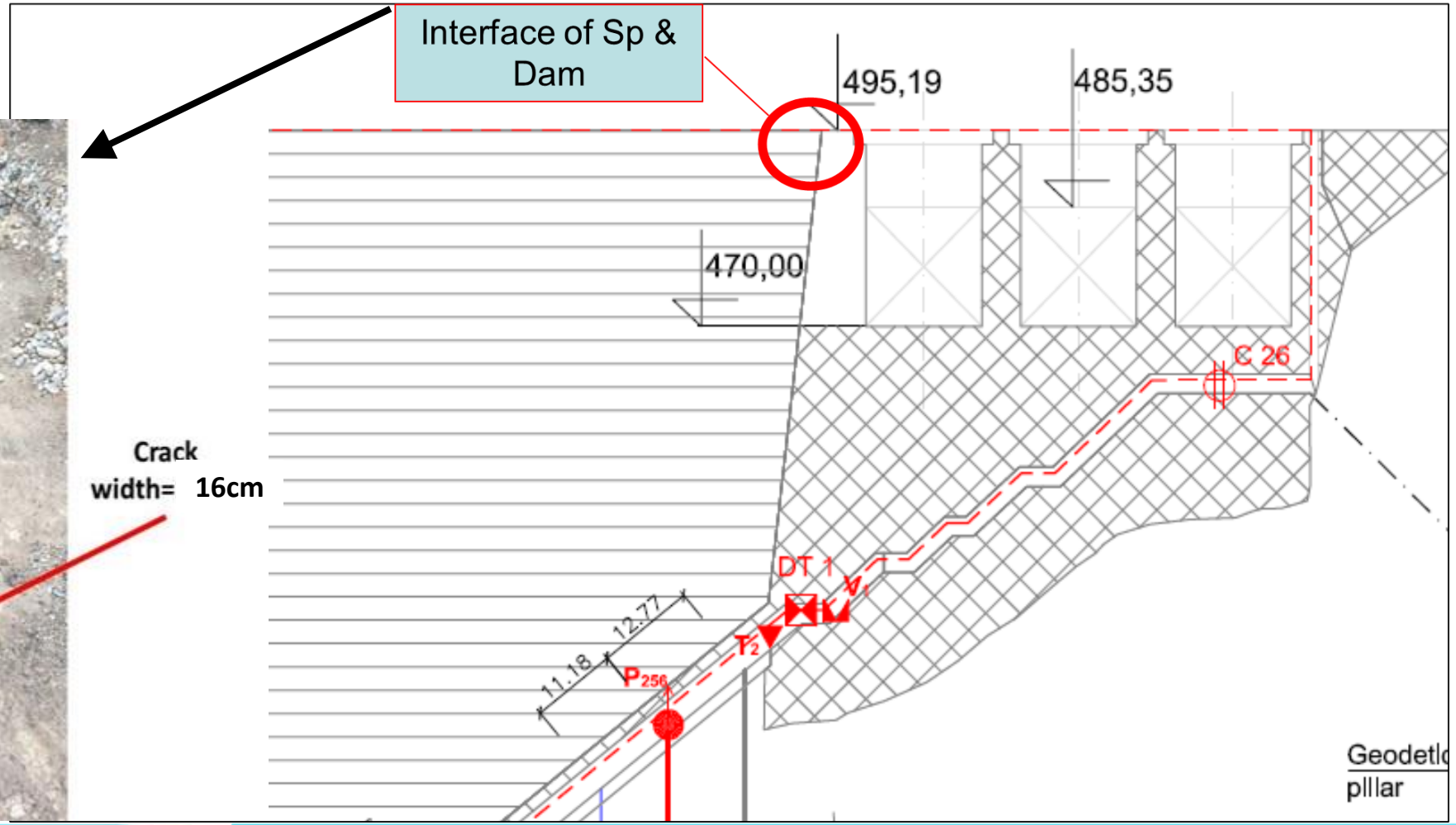


The Weak & Strong Points in Darbandikhan Dam

Weak Points

2- Spillway-Embankment interface

Crack
width= 16cm



The Weak & Strong Points in Darbandikhan Dam

Strong Points

1. Generally, the dam has been designed and built accurately.

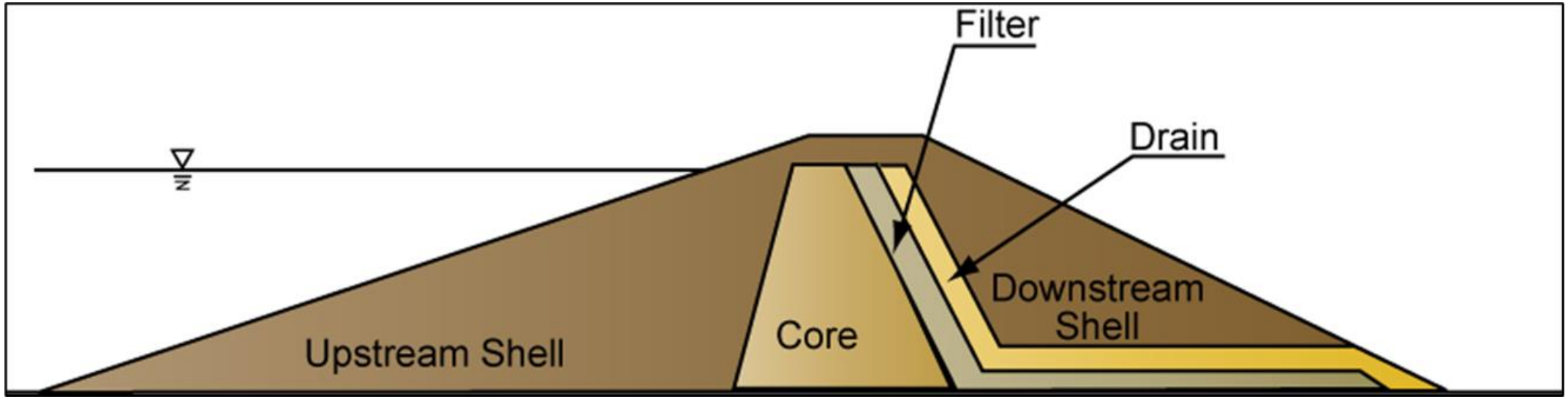
2. One of the strongest points in the dam is its filter & drains.

The Weak & Strong Points in Darbandikhan Dam

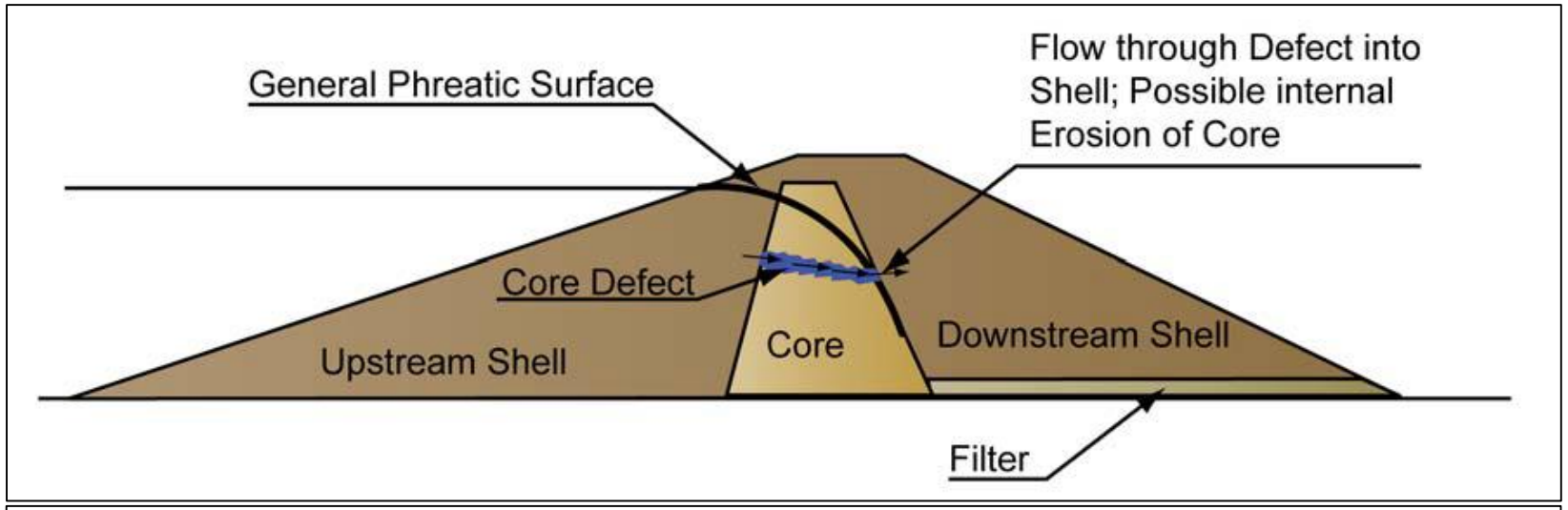
Strong Points

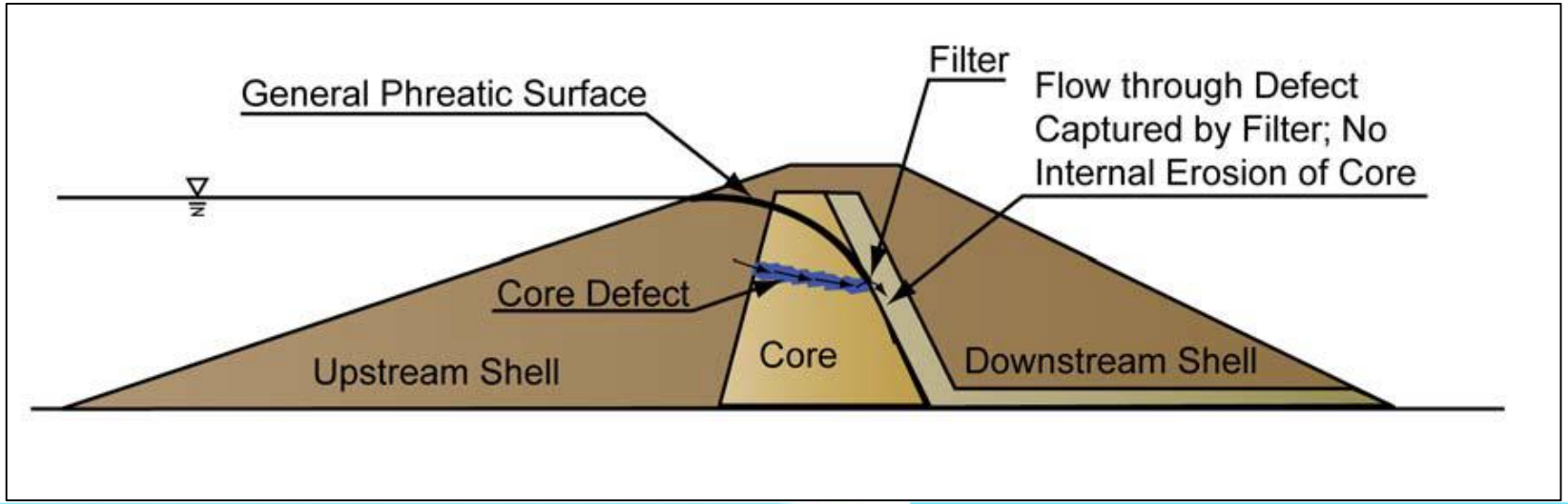
1. Over all the dam has been designed and built accurately

2. One of the strongest points in the dam is its filter & drains.



The Weak & Strong Points in Darbandikhan Dam





Strong Points

2. One of the strongest points in the dam is its filter & drains.

The November 12, 2017 Earthquake Properties

- A strong earthquake with a moment magnitude of 7.3 (Mw = 7.3) occurred on November 12, 2017, near the Iran-Iraq border (220 km northeast of Baghdad, Iraq) (**USGS, 2021**).
- The event commonly referred to as the Ezgeleh Earthquake and resulted in 500 victims and about 12000 homeless.
- It was the most disastrous earthquake that has affected the Iraq/Iran border since 1909 (**USGS**, 2021). The earthquake had lasted for about **30 seconds** (long duration).

The November 12, 2017 Earthquake Properties

Earthquake Properties

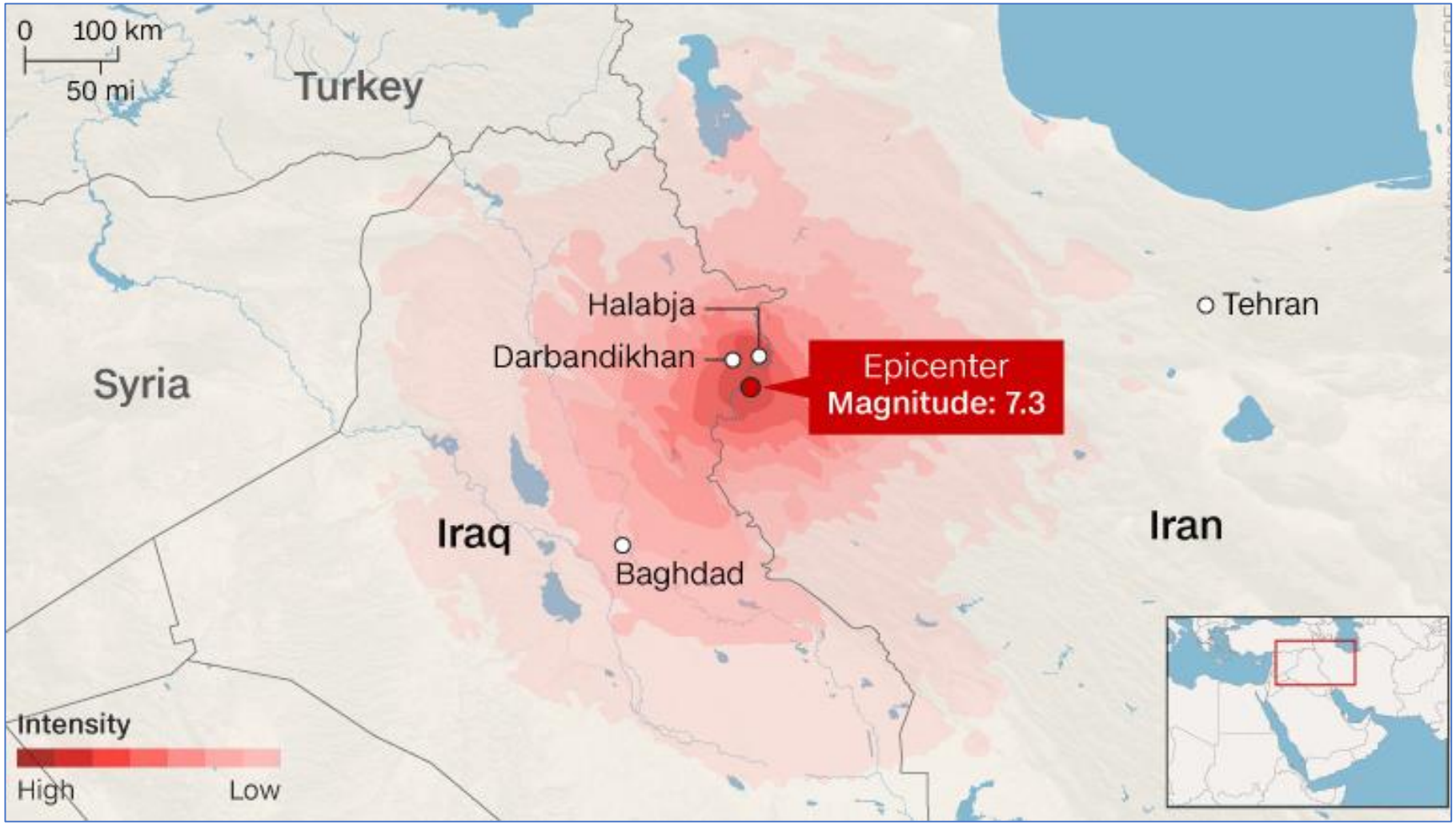


Figure 3: Earthquake intensity and extent (adapted from **USGS, 2017**)

The November 12, 2017 Earthquake Properties

Data Collection

- In the days following the Azgala earthquake, a team of engineers and geologists carefully surveyed the Darbandikhan dam.
- The data collected in two stages (i.e. **Visual inspection** & **Detailed Inspection**).
- The aim of the survey was to determine the locations of cracks, displacements, and abnormal appearances that caused by the earthquake.
- The horizontal and vertical offset of cracks were measured. The movements and settlements were determined relative to control points located on bedrock.

The November 12, 2017 Earthquake Properties

Visual Inspection

Figure 4. Visual inspection just after the earthquake.

The November 12, 2017 Earthquake Properties

Visual Inspection

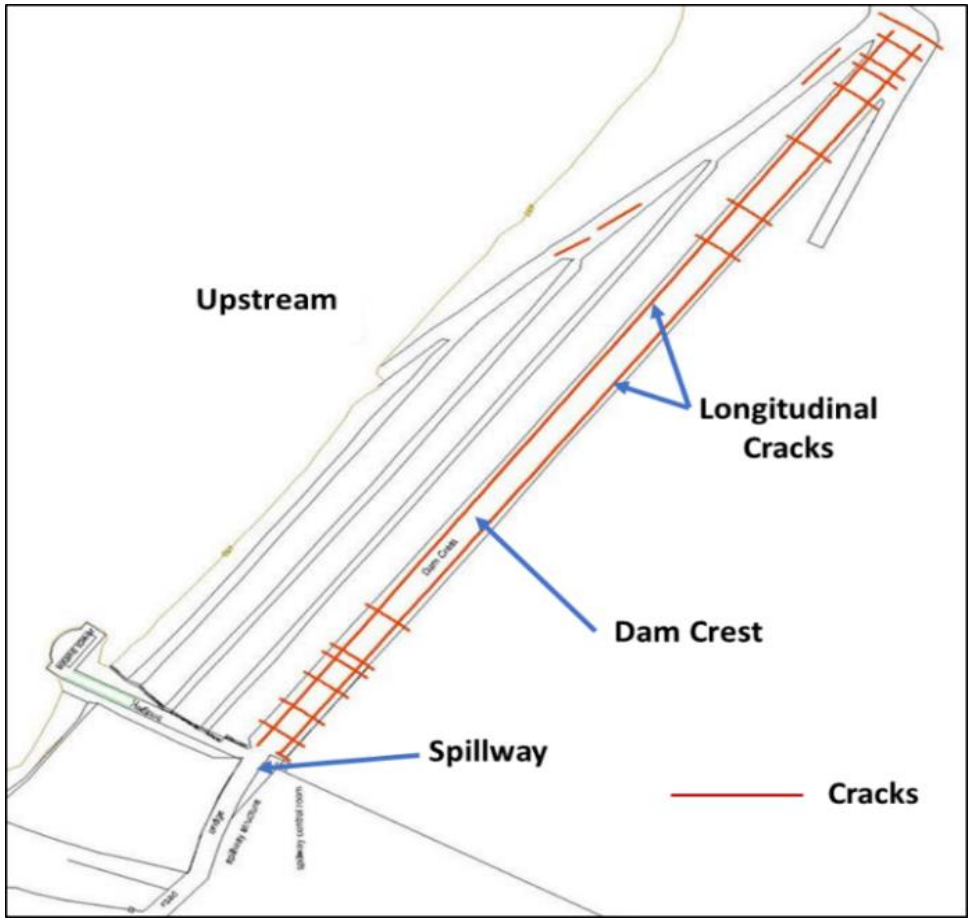


Figure 5. Crack pattern

The November 12, 2017 Earthquake Properties

Visual Inspection

Figure 6: **A**- The Control Room, **B**- Pieces of Rock Fall at the Spillway Chute.

The November 12, 2017 Earthquake Properties

Visual Inspection

Figure 7: Left & right bank sliding

Detailed Safety Inspections

The detailed safety inspections included the following actions:

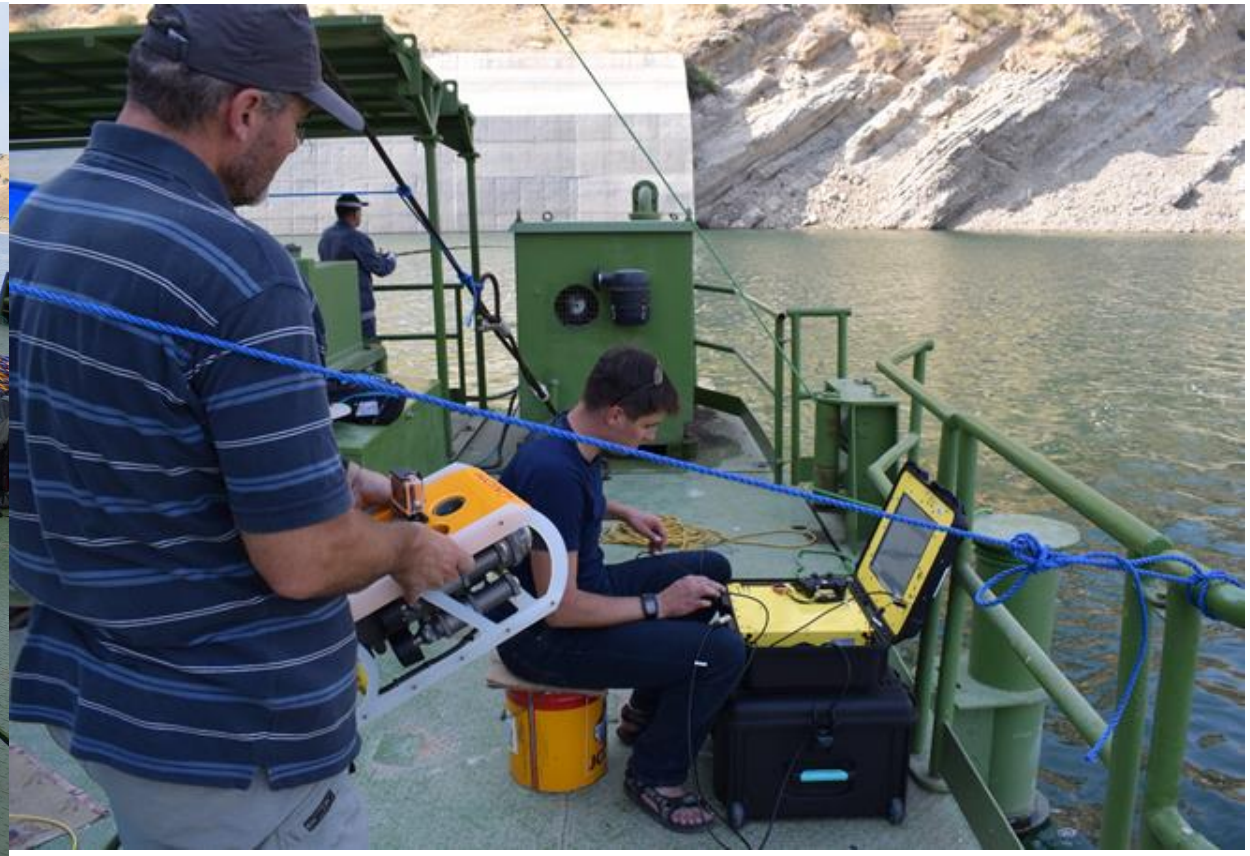
1. Geodetic survey **(48 cm, $\Delta H/H=0.38\%$).**
2. Geophysical investigation **(GPR & MASW)**
3. Test pits (Trenching)
4. Continues Drilling in the clay core
5. Seepage rates and piezometer readings
6. Underwater inspection **(CREA Co. Czech Republic)**

Detailed Safety Inspections

Continues Drilling in the clay core

Detailed Safety Inspections

Underwater inspection **(CREA Co. Czech Republic)**



How The Safety Of The Dam Was Assured?

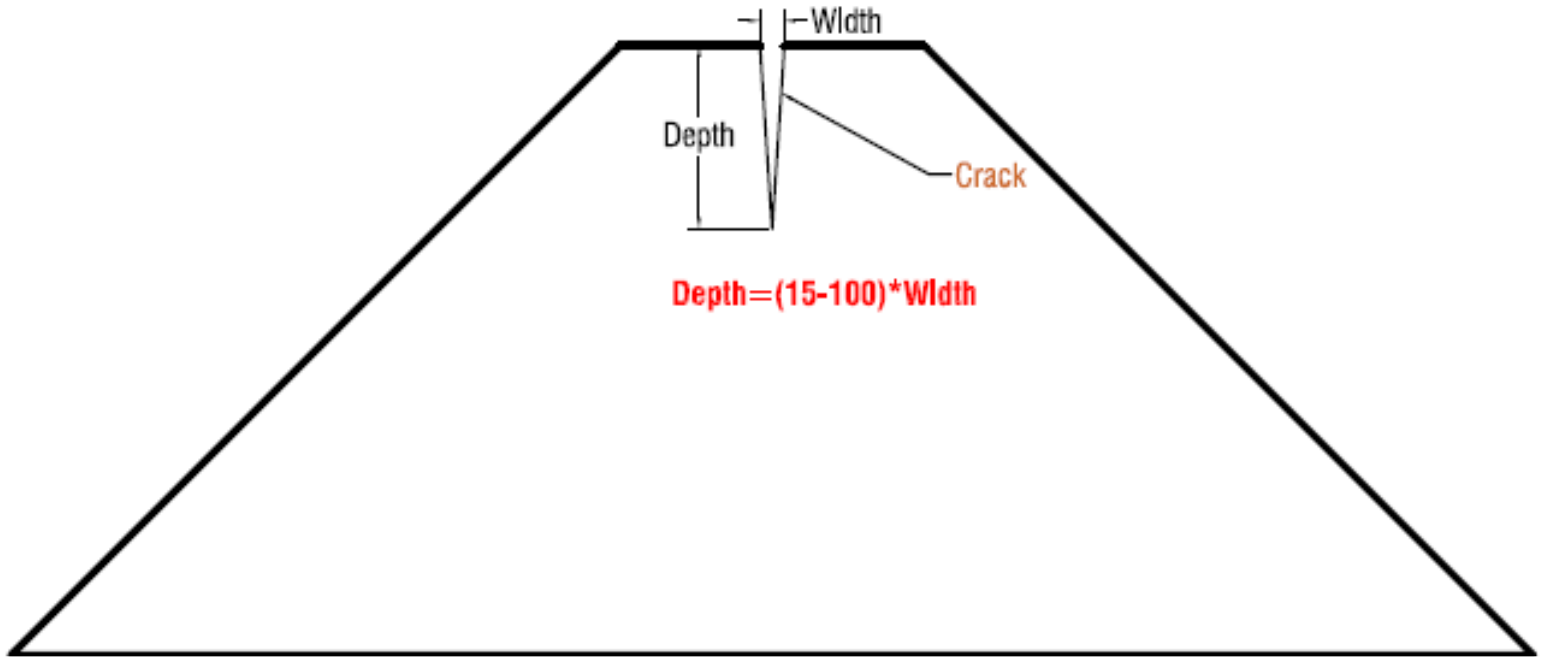
- Once the safety of the spillway and the bottom outlets has been checked, it was decided to lower the water level in the reservoir in order to investigate the lower parts of the dam and to reduce the water pressure applied to the dam.
- The water level in the reservoir was then gradually lowered from the elevation **471.9** m to the elevation **464** m (i.e. 7.9 m) in about two months.
- Due to the awareness and cautions about whether there were cracks in the lower parts of the dam or not, the water level was not allowed to rise above elevation 470 m in 2018.

How The Safety Of The Dam Was Assured?

- However, in 2019, based on the results obtained from the drilled boreholes and on the promised information regarding the behavior of Earth Core Rockfill Dams (ECRD) subjected to major earthquakes, it was decided to gradually raise the water level in the reservoir.
- The decision of rising water level in the reservoir in 2019 was based on the academic findings and observations mentioned in (Pells & Fell, 2002; Fell et al., 2008; **Zomorodian & Moghadam, 2011**).

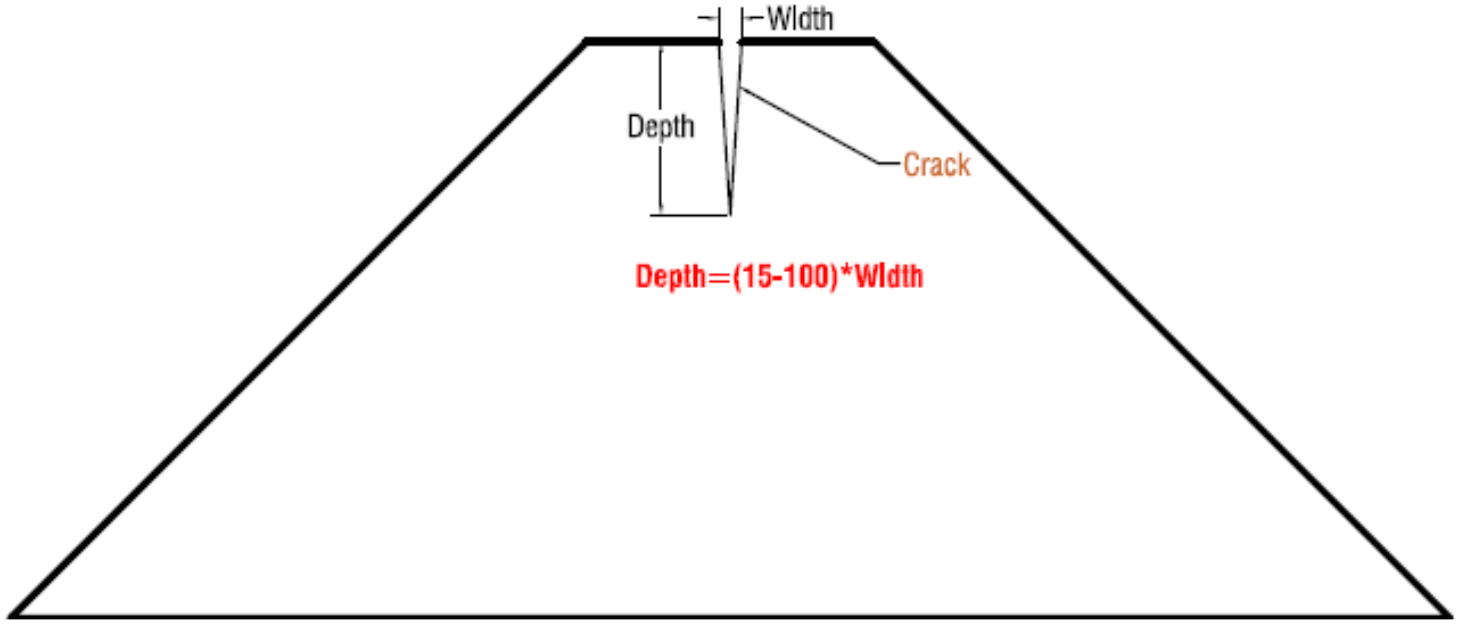
How The Safety Of The Dam Was Assured?

- According to a statistical analysis carried out by (**Pells & Fell, 2002**) the **depth of cracks** that occurred in embankment dams due to earthquakes ranges from **15 to 100** times the **width** of the crack at the crest.



How The Safety Of The Dam Was Assured?

For Darbandikhan dam, the width of the major transverse crack that occurred in the clay core next to the spillways structure was about **16 cm**. So, the estimated depth of this major crack should be between **2.4 m** and **16 m** from the top of the clay core (i.e. it may go down from elevation 490.6 m to elevation 479 m).



How The Safety Of The Dam Was Assured?

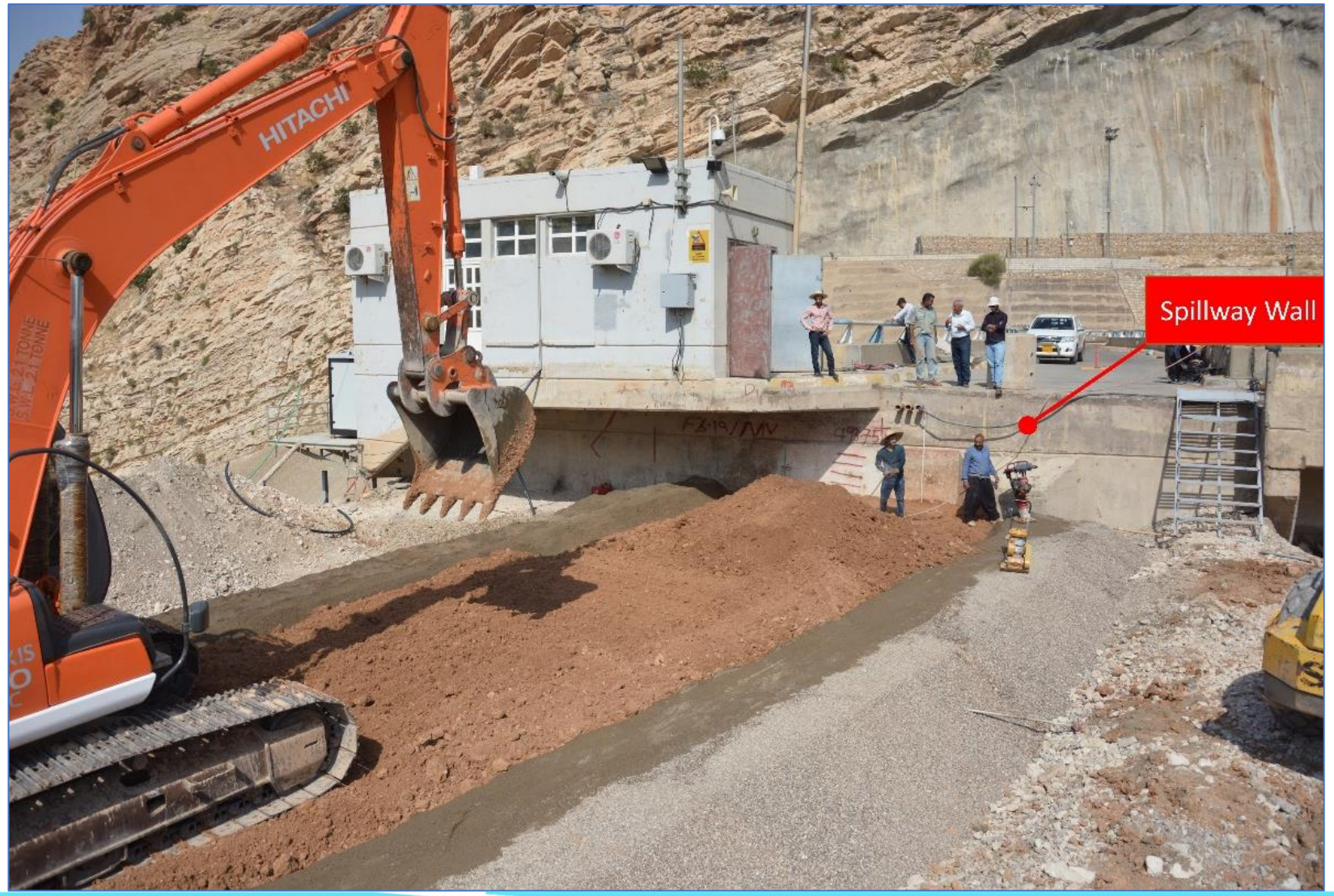
- Fell et al., (2008) as cited in (**USBR, 2015**) stated that erosion in clay cores in embankment dams may not occur until the following two conditions fulfilled;
- 1- The width of the transverse cracks reaches 1 or 2 inches and'
- 2- The hydraulic gradient approaches 0.5 or more.
- Furthermore, the width of possible cracks in clay cores may be reduced or closed due to swelling by the wetting process.

In Darbandikhan dam, the upstream and the downstream wide cohesionless filters will contribute to the crack filling or self-healing process should any crack exist in the core.

How The Safety Of The Dam Was Assured?

- From all of the above analyses and the results of the various investigations, the authorities of Darbandikhan dam concluded that there were no problems severe enough to threaten the safety of the dam and that the dam was safe and could store water to its full capacity.
- Accordingly, in May 2019, the water level in the Darbandikhan reservoir was raised to the elevation 484.28 m which is only 0.72 m below the maximum operational level (Normal Pool Level).

Rehabilitation



Conclusions

- From the results of the inspections and the evaluations, the following conclusions can be drawn:
- Adequate design and construction of dams can help them pass through even large earthquakes.
- The adopted measures used for evaluation and remediation of the earthquake-induced damages in Darbandikhan dam were dependable for checking dam safety.
- In high and steep sloped mountainous areas, it is advisable to locate all structures (if possible) outside the rockfall hazard zones, or they must be properly protected.

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