KINEMATIC ANALYSIS OF BEHAVIOR OF LARGE EARTH DAMS

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Introduction

Safety of earth dams depends on:

- proper design,
- construction, and
- monitoring of behaviour during the construction and during the operation

Most common causes of failure of the embankment dams are:

- internal erosion of fine-grained soils from the embankments,
- erosion under the foundation or abutment,
- stability problems resulting from the high pore pressures,
- hydraulic gradients, and
- overtopping of the dam or spillway.

Less common cause of failure is

development of high water pressures and possible liquefaction either in the foundation or embankment during earthquakes.

Role of monitoring

Major role of monitoring is to verify that the behaviour of the investigated dam follows the designed pattern.

Monitoring is important for a better and safer design of the future dams through the verification of the design parameters where the geotechnical parameters are of the highest importance.

Proper design of the monitoring scheme is crucial and should be based on deterministic model using, e.g. FEM.

Examples of earth dams

zoned embankment dams:

- Diamond Valley Lake, California,
- La Grande Hydroelectric Complex (phase I) La Grande 4 (LG-4) main dam;

concrete face rockfill dam (CFRDs):

- Toulnustouc Dam, Canada (Quebec).

Deformations of earth and rockfill dams

Deformations start occurring during the construction of the dam.

After the construction is completed, the movements can develop during the first filling of the reservoir.

Later, the rate of deformations decreases in time, with the exception of variations associated with the periodic variations of the level of the reservoir and, in seismic zones, with the earthquakes.

Geotechnical parameters

- geotechnical parameters of the earth and rockfill material play significant role in the stability of the dam.
- dams located in the seismically stable areas are built with material characterised by the geotechnical parameters, which allow for a dam to be more adaptable to the changes of loading conditions.
- parameters may be verified by comparing FEM results with measured values during construction and filing up a reservoir.

Design of Monitoring Scheme

The design of the monitoring surveys must include:

- determination of the minimum number and locations of the monitored points (points where the maximum displacements are expected),
- frequency of the repeated measurements, which depends on expected rates and magnitudes of the deformations.
- accuracy requirements.

In case when the area of a reservoir is located within the influence of active tectonic plates, the design of the monitoring surveys has to consider effects of earth crustal movements.

Monitoring (cont…)

Monitoring of the embankment dams may be divided into following groups:

- geotechnical,
- geodetic,
- environmental, and
- visual inspection.

Geotechnical monitoring may be divided into physical and geometric measurements.

Geodetic monitoring

Current geodetic technology utilises:

- RTS's with automatic target recognition,
- GPS, and
- other sensors.

One may achieve almost any instrumental resolution and precision, full automation and real-time data processing.

Example: a fully automated system ALERT developed for data collection, data processing and displacement analysis.

Integrated monitoring systems

- Geotechnical instruments once placed within the structure mass can not be rechecked or calibrated.
- Geodetic measurements, through redundant measurements and possibility of the statistical evaluation of the data quality provide reliable results.
- In most cases, it is recommended to use integrated monitoring systems in which geotechnical measurements are checked by comparing them with the geodetic data.

Deformation modeling using FEM

FEM is used in the analyses of behaviour through calculation of:

- displacements,
- strains, and
- stresses

in the structure caused by changeable:

- material parameters,
- loading, or
- boundary conditions.

Modeling using FEM

- Nonlinear behaviour of the material,
- Interaction between the structure and the underlying soil and rock strata,
- Influence of water load on the structure and on the foundation bedrock, and
- Effects of water saturation.

Types of investigated earth and rockfill dams

zoned embankment dams:

- Diamond Valley Lake, California,
- La Grande Hydroelectric Complex (phase I) La Grande 4 (LG-4) main dam ;

concrete face rockfill dam (CFRDs):

- Toulnustouc Dam, Canada (Quebec).

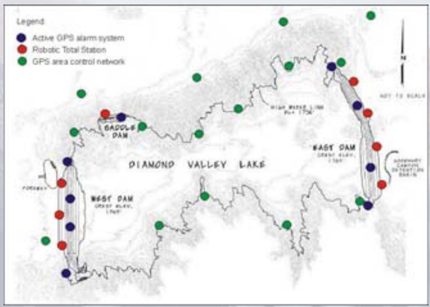
Diamond Valley Lake, California

DVL project consists of three dams constructed from soil and rock located within the interaction zone between the North American and Pacific tectonic plates.

The San Jacinto and San Andreas faults are located about 10 km and 30 km, respectively, from the reservoir.

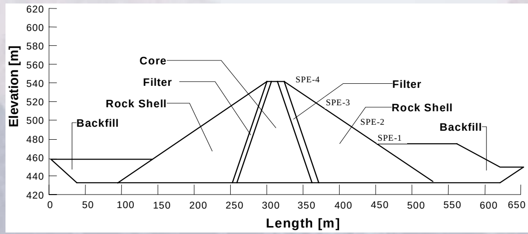
Diamond Valley Lake (cont…)

Fully automatic system using ALERT software with 8 RTS's, number of geotechnical instruments, and GPS



Diamond Valley Lake (cont…)

West Dam



La Grande 4 (LG-4) Dam, Quebec

Maximum height of 125 m and is 3.8 km long.

The dam is constructed almost entirely on bedrock.

La Grande 4 (LG-4) Main Dam, Quebec

Fig. LG 4 main dam—general arrangement.

LG-4 Main Dam

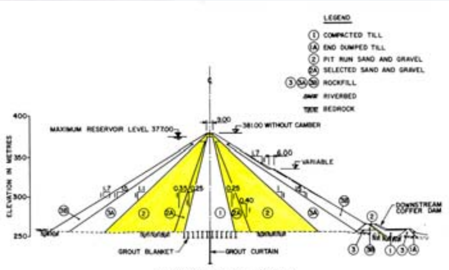
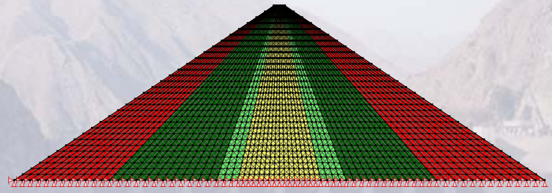


FIG. 2. Typical section in river valley.

Constructed almost entirely on bedrock composed of granite and gneiss

LG-4 main dam

- Height-125 m,
- Crest length - 3800 m



Constructed almost entirely on bedrock composed of granite and gneiss

Concrete Face Rockfill Dams (CFRDs)

In northern Canada, (northern parts of Quebec,) the use of CFRDs constitutes an alternative to zoned embankment dams.

Placement of rockfill is less sensitive to the variations of weather conditions and frost action.

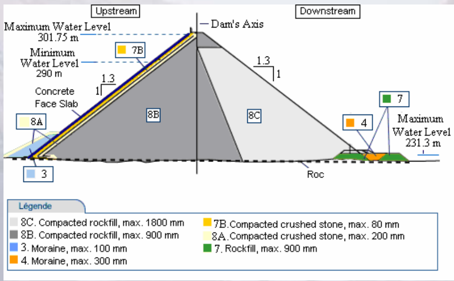
The total building time of a CFRD may be reduced by one year compared to the building of a zoned embankment dam.

Toulnustouc Dam, northern Quebec

CFRD Toulnustouc Dam

75 m height and 0. 575 km long built on bedrock foundation (gneiss).

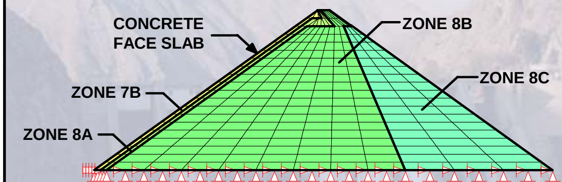
Thickness of the concrete face slabs = 0,3 m.



CFRD Toulnustouc Dam

100 m height and 0. 575 km long built on bedrock foundation.

thickness of the concrete face slabs = 0,3 m.



Safety of CFRD

- The main concern is the deformation of the concrete face slab.
- During the reservoir filling, the load of water and deformations of the rockfill produce a deformation of the concrete slab.
- The concrete slab acts as an impervious membrane and any development of cracks in the slab would allow for the water to penetrate the rockfill of the dam.

FEM analysis

Behavior of earth dams was analyzed in two stages:

- construction of a dam,
- the filling of the reservoir with water.

Geotechnical parameters used in the design of DVL dams differ quite significantly from the parameters used in LGC project

Assumptions:

Embankment dams

- LG4: for two assumed heights:
  - 84 m during construction and
  - 120 m on non-deformable bedrock.
- DVL- West Dam:
  - 87 m height on non-deformable bedrock.

CFRD dam

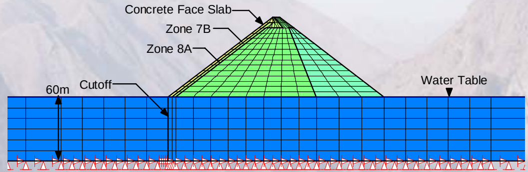
- Toulnustouc main dam:
  - 75 m height.

Two models:

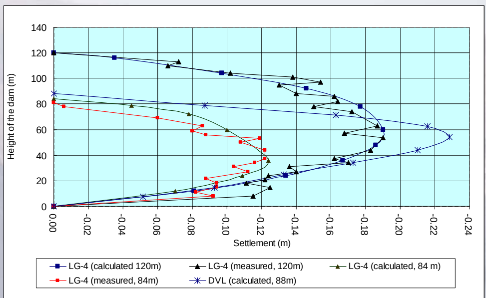
on bedrock foundation (real foundation conditions)

on a 60 m high foundation of dense till (moraine).

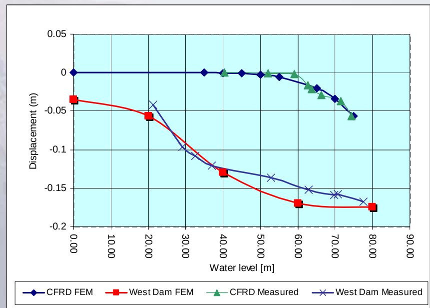
CFRD resting on the till foundation



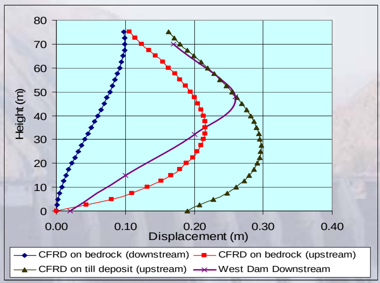
Settlements at the end of the construction of DVL and LGC dams



Vertical displacement of the crest (DVL and CFRD) during the filling of the reservoir



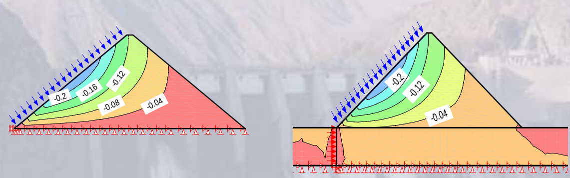
Displacements of CFRD and West Dam at the end of filling up a reservoir



Calculated settlements (m) at the end of the filling of the reservoir

Dam of 100 m high resting on:

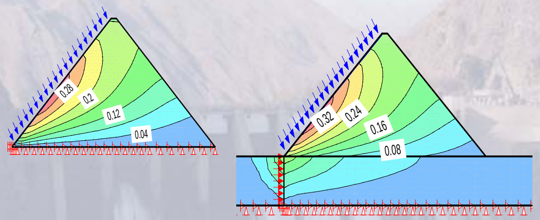
bedrock **40 m of till foundation**



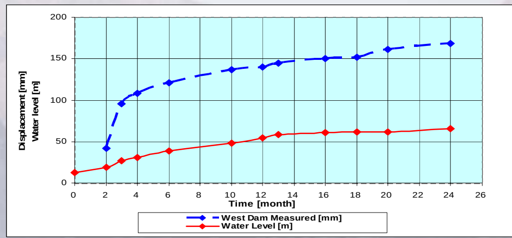
Calculated horizontal displacements (m) at the end of the filling of the reservoir

Dam of 100 m high resting on:

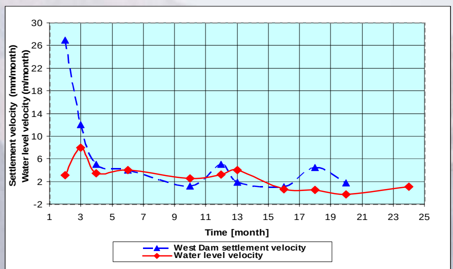
bedrock **40 m of till foundation**



Settlement of the crest of the West Dam during filling up a reservoir



Velocity of the crest settlement of West Dam during filling up a reservoir



Conclusions

- **Geotechnical parameters of the construction material play a significant role in the stability of earthen dams.**
- **The dams located in the seismically stable areas are built with the material, which allows for the dam to be more adaptable to the changing loading conditions caused by the tectonic activity.**
- **The dams built on stable (hard) bedrock are more stiff structures.**

Conclusions (cont…)

- **As shown by the examples of three dams, the predicted deformations of each dam and, particularly, the location of the maximum expected displacements significantly differ in each case.**
- **Therefore, one cannot develop detailed technical specifications for dam monitoring, which could serve as a standard for any type of the earth dam.**
- **In each case, a multidisciplinary approach is needed through a close cooperation between the structural, geotechnical, and geodetic engineers at the design stage of the monitoring surveys.**
- **Theoretically, this last conclusion seems to be very obvious. In practice, however, geodetic monitoring surveys are usually designed without any regard to the deterministic model of the expected deformations**