Seismic Design of Embankment Dams

25 March 2008

Presented by

Dr Gamini Adikari
Principal Engineer Dams
SMEC Australia

Seminar Outline

- ANCOLD Guidelines on Seismic Design
- Design Earthquake for dams
- Defensive design principles
- Liquefaction and its effects on dams
- Measures to improve liquefaction resistance
- Assessment of seismic stability of dams
- Case study on seismic rehabilitation of an embankment dam

Guidelines for Design of Dams for Earthquake

Guidelines cover:

- An introduction to earthquake hazards in Australia
- Selection of Design Earthquake
- Seismic design of embankment dams
- Liquefaction assessment
- Seismic stability assessment
- Analysis and design of concrete dams
- Appurtenant structures

Design Earthquake

- Operating Basis Earthquake (OBE)
  - > Minor damage to the structure permitted
  - > Structure should remain functional
  - > Damage should be easily repairable
- Maximum Design Earthquake (MDE)
  - > The maximum level of ground motion for which the dam should be designed or analysed
  - > Extensive damage possible
  - > Should not cause catastrophic failure and downstream flooding

Selection of Design Earthquake

- Deterministic Approach
  - > More widely used
  - > OBE and MDE are quantified
  - > Probability of failure not taken into consideration
- Probabilistic Approach
  - > Used less often due to cost and time constraints
  - > Based on Risk Assessment
  - > Probability of failure estimated, backed by experience, judgement and limited case histories

Effect of Earthquakes on Dams

- > settlement and cracking
- > reduction of freeboard and possible overtopping
- > slope instability
- > differential movement between the dam and structures (increased likelihood of leakage and piping)
- > liquefaction in the dam or foundation
- > movement/instability in the faults in foundation
- > overtopping due to reservoir seiches
- > overtopping due to landslides around the reservoir
- > damage to appurtenant works (eg: outlets) leading to potential piping erosion

"Defensive" Design Principles

- Provide ample freeboard
- Use well designed and constructed filters downstream of the earthfill core
- Provide ample drainage zones
- Avoid, densify, drain or remove potentially liquefiable materials in the foundation and in the dam

Other Design Measures

- Well graded filter zones upstream of the core, particularly in the crest area
- Provide crest details which will minimise erosion in the event of overtopping
- Provide filters downstream of contacts between dam and structures
- Locate core to minimise saturation of materials
- Stabilise slopes around reservoir rim
- Provide special details along foundation faults or seams if movement is likely
- Site dam on rock foundation where possible
- Use well graded, plastic core material

Liquefaction

All phenomena giving rise to a loss of shearing resistance and to the development of excessive strains as a result of transient or repeated disturbance of saturated cohesionless soils

Grading Limits of Liquefiable Soils

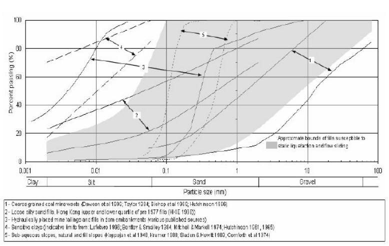


Figure – Particle size gradation of soils susceptible to flow liquefaction under static and earthquake loading (Hunter and Fell 2003a, b).

Measures to Improve Liquefaction Resistance

- Change operational procedures
- Improve in-situ foundation conditions
- Structural solutions
- Drainage solutions

Measures to Improve Liquefaction Resistance

Change Operational Procedures

- Lower the FSL of the reservoir
- Limit public access to the area downstream
- Institute early warning systems downstream

Measures to Improve Liquefaction Resistance

Improve Foundation Conditions

- Removal of potentially liquefiable soils
- Densification and increase in in-situ lateral stress
- Mixing in-place materials with additives
- Grouting or chemical stabilisation

Measures to Improve Liquefaction Resistance

Structural Solutions

- Addition of berms - they have the effect of increasing the effective vertical stress,thereby increasing the cyclic shear strength and shear modulus. They also reduce the static shear stress, improving the post earthquake stability. They can also be used to increase freeboard by raising the crest level of the dam
- Contain the liquefiable materials so that they cannot move
- Reconstruction of the dam

Measures to Improve Liquefaction Resistance

Drainage Solutions

These set out to relieve pore pressure build up during cyclic loading by providing drainage paths or by dewatering the soil to a partially saturated condition

- Pressure relief wells
- Drainage layers - vertical and/or horizontal drains
- Dewatering and air injection

Assessment of Seismic Stability

- Pseudo-static analysis
- Simplified methods of deformation analysis
- Post liquefaction analysis
- Numerical modelling techniques (total stress, effective stress)

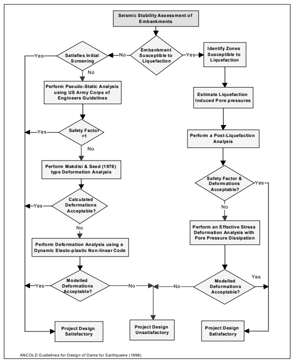
Assessment of Seismic Stability

Divided into two streams

- Dams susceptible to liquefaction
- Dams not susceptible to liquefaction

ANCOLD recommends a staged approach to seismic assessment of dams

Embankment Seismic Stability Assessment Flowchart



Assessment of Seismic Stability

Initial Screening Test of USBR (1989)

- Is the dam well constructed, and peak accelerations at the base of the dam less than 0.2g; or is the dam constructed of clay, on clay or rock foundations, with peak accelerations of less than 0.35g?
- Are the batters flatter than 3:1?
- Is the pre-earthquake factor of safety greater than 1.5?
- Is the freeboard greater than 2% of dam height, or a minimum of 0.9m?

Assessment of Seismic Stability

USACE (1984) Pseudo-Static Method (also known as Haynes-Griffin and Franklin method)

Perform a conventional slope stability analysis under static load, together with a seismic loading using seismic coefficient as half the peak acceleration of the base rock. Strength parameters are factored down, usually between 10% to 20% to allow for seismic effects. Potential crest settlements are determined as below, and checked against the available freeboard at FSL.

- For a calculated factor of safety greater than 1, the maximum permanent crest settlement would be less than 1m, and should freeboard be adequate, no further analyses is required.
- For a calculated factor of safety less than 1, a permanent settlement of greater than 1m is possible, and a more substantial deformation analysis is required.

Assessment of Seismic Stability

Makdisi and Seed (1978) Analysis

- Simplified deformation analysis, developed from Newmark (1966)
- Involves assessment of ground response, calculation of yield acceleration, and an estimate of permanent crest displacement by a Newmark double integration process
- Assess if the loss of freeboard exceeds the available freeboard and/or displacements are excessive

Is a more rigorous analysis required?

Assessment of Loss of Freeboard

- Swaisgood (1998) method - correlation between crest settlement and peak ground acceleration developed using data obtained at 54 dams worldwide

Assessment of Loss of Freeboard

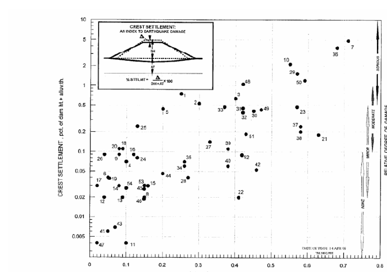


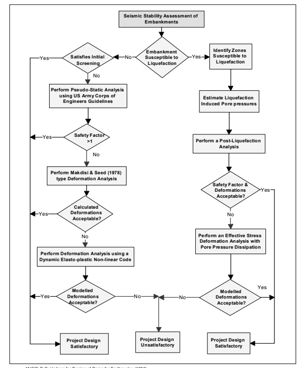
Figure – Relative crest settlement versus peak ground acceleration (Swaisgood, 1998).

Assessment of Seismic Stability

Numerical Methods (total stress)

- Perform deformation analysis using a dynamic Elasto-Plastic Non-Linear code (eg: DIANA, ANSYS, FLAC)
- Are modelled deformations acceptable?

Embankment Seismic Stability Assessment Flowchart



ANCOLD Guidelines for Design of Dams for Earthquake (1998)

Assessment of Seismic Stability

For dams susceptible to liquefaction

- Identify zones susceptible to liquefaction
- Evaluate earthquake induced pore pressures in the materials susceptible to liquefaction
- Conduct a conventional limit equilibrium stability analysis using the estimated pore pressures and residual undrained strength for liquefied materials. For clayey materials consider a strength reduction factor of 15%

Are safety factors and deformations acceptable?

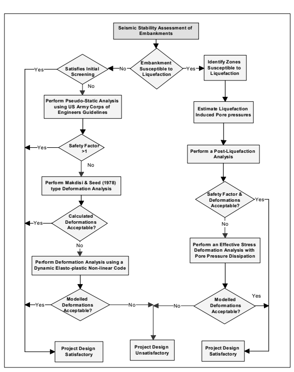
Assessment of Seismic Stability

Numerical Methods (effective stress)

- Uncoupled, semi-coupled, fully coupled deformation analyses (depending on how the pore pressures are treated)
- Computer codes of varying complexity exist for all methods of analysis

Are modelled deformations acceptable?

Embankment Seismic Stability Assessment Flowchart



ANCOLD Guidelines for Design of Dams for Earthquake (1998)

Wartook Dam

- Constructed in 1886 on the Mackenzie River in the Grampians National Park
- 11m high and 1200m long, impounding a reservoir of 29,400 ML
- Primary water supply source for the Rural City of Horsham
- Constructed of silty fine sand of medium density , with an upstream face of stone pitching set on a layer of gravel overlying a thin plastic clay blanket
- Foundation material comprising sands and gravel up to 3m thick, overlying sandstone bedrock
- Safety review undertaken in the mid 1990's identified embankment and foundation material susceptible to liquefaction under design earthquake, in-service factors of safety under static loading conditions below the recommended minimum values

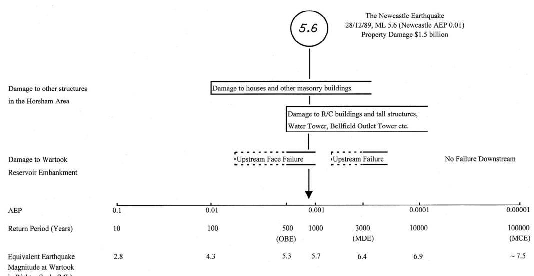
Wartook Dam

Wartook Dam

Design Earthquake

- Level of ground motion, thus the earthquake risk, at Wartook Reservoir is below the Victorian average for short return periods but approaches average for long return periods (SRC, 1991)
- Deterministic approach based on ICOLD (1989) and Hinks and Charles (1992)
- OBE - 1 in 500 AEP
- MDE - 1 in 3,000 AEP

Earthquake Damage to Structures



Wartook Dam

Embankment Rehabilitation Options Studied

- Reduce pore pressures in the embankment
- Increase effective stress by increasing overburden pressure
- Confine saturated sand so that it cannot flow
- Increase strength parameters by increasing relative density
- Construct a new dam downstream

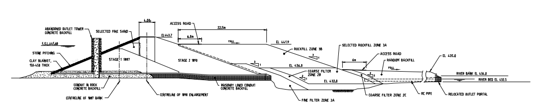
Wartook Dam

Embankment Rehabilitation Options Studied

- Impermeable membrane constructed on the upstream face of the existing embankment
- Upstream clay blanket coupled with downstream stabilising fill
- Upstream & downstream stabilising fills (5 versions considered)
- Impermeable membrane coupled with downstream dewatering pump
- Heavy tamping of the embankment and foundation material
- Vibro-compaction of the embankment and foundation material
- Plastic concrete diaphragm wall coupled with foundation dewatering pump
- Construction of a new dam downstream (5 versions considered)

Wartook Dam - Remedial Measures Implemented

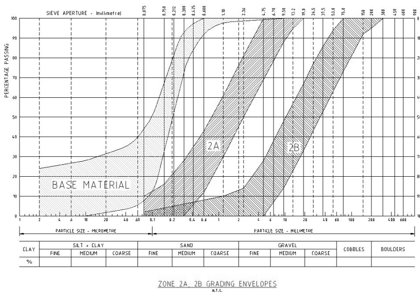
- Downstream rockfill berm and filters, to alleviate liquefaction, slope stability and piping problems
- Remodelled spillways and outlet works



Risk Based Approach to Embankment Remediation

- downstream stabilising fill only
- 1890 bank permitted to collapse to upstream following earthquake
  - > minor damage to pitching at 1:200 AEP
  - > significant damage to pitching at 1:500
  - > stability failures in U/S shell at 1:1000
  - > collapse at 1:3000 AEP
  - > reconstruction of embankment required following 1:3000 AEP earthquake

Wartook Dam - Filter Grading Limits

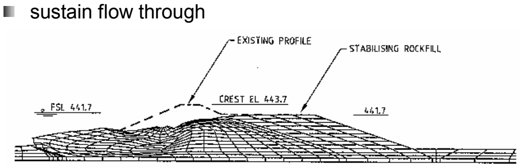


Wartook Dam Material Properties for Deformation Analysis

Zone	Modulus (Mpa)	Poisson's Ratio	Unit Weight (kN/m^3)	Cohesion (kPa)	Friction Angle (Degrees)
Embankment					
Zone 1 (static)	18	0.25	19	0	32
Zone 1 (post liquefaction)	18	0.49	19	0	4.1
Zone 2 (static)	20	0.25	19.5	0	35
Foundation					
Very loose silt (static)	5	0.30	18	0	23
Very loose silt (post liquefaction)	5	0.49	18	0	2.8
Loose sand (static)	18	0.25	19	0	32
Loose sand (post liquefaction)	18	0.49	19	0	4.1
H.W. sandstone	50	0.25	20	0	45
Stabilisation Works					
Sand filter	15	0.25	19	0	30
Downstream shell	30	0.25	20	0	35
Select backfill	18	0.35	19	10	23

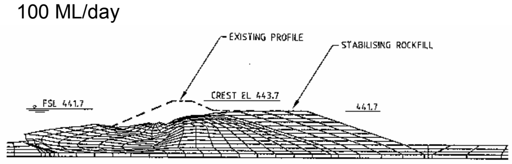
Downstream Stabilising Fill

- contain failed bank following 1:3000 AEP
- catastrophic collapse prevented
- sustain minor overtopping
- sustain flow through



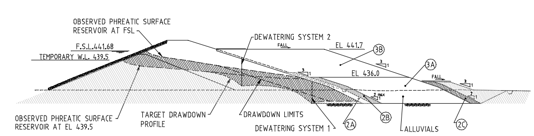
Downstream Stabilising Fill

- will remain stable post liquefaction
- no displacement of liquefied sand occurs from underneath the rockfill berm
- seepage following failure expected to be in the order of 100 ML/day



Downstream Stabilising Fill

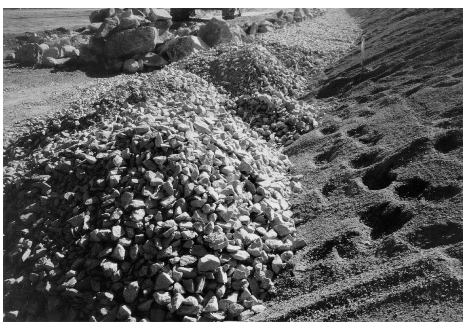
- stabilising rockfill, Zones 3A & 3B
- filters to prevent piping due to seepage & liquefaction
- total cost $ 5M compared to full rehabilitation option with upstream and downstream stabilising shells at $15M and new dam downstream at $25M



Wartook Dam

Wartook Dam

Wartook Dam



Wartook Dam

Wartook Dam

AERIAL VIEW OF THE COMPLETED WARTOOK EMBANKMENT REHABILITATION
Primary spillway and new outlet works in the foreground

Wartook Dam

- Risk based solution that is acceptable to client
- Client decision based on public safety, project cost and security of supply considerations
- ALARP (as low as reasonably practicable) principle in risk assessment

Seismic Design of Embankment Dams

Summary of main points covered

- ANCOLD Guidelines
- Design Earthquake for dams
- Defensive design principles
- Liquefaction and its effects on dams
- Measures to improve liquefaction resistance
- Assessment of seismic stability of dams
- Case study on Wartook Dam rehabilitation