Design of Dams and Bridges

Training Programme for Andhra Pradesh Human Resources Development Institute, Bapatla, Guntur, AP

Kayum Mohammad
Director CMDD (NW&S)

Central Water Commission
Ministry of Water Resources, River Development & Ganga Rejuvenation
ROCKFILL DAMS

- Rock fill dam
- Central core,
- Inclined core
- Zones, stability analysis, behaviour during EQ
Types of Rockfill Dams

(b) Rockfill Dam with a Centrally Located Core
- Outer Shell
- Inner Shell (Transition)
- Core
- Core Trench
- Filter
- Curtain Grouting

(c) Rockfill Dam with an Inclined Core
- Filter
- Random Shell
- Drain
- Core
- Curtain Grouting

(d) Rockfill Dam with a Facing
- Facing
- Shell
Components of Rockfill Dam

Most common feature adopted for Rockfill dam:

- Central impervious core
- u/s & d/s rockfill Shell
- Transition zones between impervious core and rock fill
- Transition filters between overburden in dam seat and rock fill
- Inclined filter
- Horizontal filter
- Rock toe and
- Toe drain
CORE: BORROW AREA MATERIAL

- Investigation are undertaken to determine quality and quantity of available material.
- Most suitable material are selected based on index properties, **Strength Properties (c & φ)**, gradation curve and permeability characteristics.
- For high embankment dams **modulus of compressibility** of materials for predicting total settlements and differential movements are required.
- Determination of foundation modulus of elasticity is not required for earth and rock fill dam, however shear modulus of foundation material may be required for response analysis of seismic loads.
All shear test results for earth dams should be obtained from triaxial shear test as far as possible.

Various types of shear test:
- Q test = unconsolidated undrained test
- R test = consolidated undrained test
- S test = consolidated drained test
# Suitability of Soil for Core

<table>
<thead>
<tr>
<th>Relative suitability</th>
<th>Rockfill dam (impervious core)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very suitable</td>
<td>GC</td>
</tr>
<tr>
<td>suitable</td>
<td>CL, CI</td>
</tr>
<tr>
<td>Fairly suitable</td>
<td>GM, GC, SM, SC, CH.</td>
</tr>
<tr>
<td>poor</td>
<td>ML, MI, MH</td>
</tr>
<tr>
<td>Not suitable</td>
<td>OL, OI, OH, Pt</td>
</tr>
</tbody>
</table>
STABILITY ANALYSIS

Stability analysis is made to avoid:

I. **Shear Failure**: to evaluate margin of safety of embankment section for various loading and seepage condition.

II. Failure due to **excessive deformation**

III. Failure due to **liquifaction**

- Result of stability analysis are reported as Factor of Safety (FOS)
- Embankment section is designed as per IS 7894–1975
SATBILITY ANALYSIS

Failure surface geometry:
- Plane Surface (very steep slopes)
- Curved Surface (circular— for relatively flat slopes)

Stability Analysis:
1. Assume a dam section with given soil properties (c & Φ)
2. Adopt failure surface geometry
3. Guess a failure surface
4. Draw FBD, compute FOS = s / τc
5. Guess another surface until we get FOS min which is FOS of the assumed section
6. If (FOS) obtained in not matching the standard value for that loading condition, then modify the section.
7. Modify the section by changing the slopes of embankment and/or introduction of berms, replacing the fill material to get desired FOS.
Filters: Safe passage for Seeping water

- **Inclined or vertical filter** : To collect seepage emerging out of core/Transition zone and keeping downstream shell dry.
  - Top level of inclined filter = FRL
  - Minimum thickness = 1 m

- **Horizontal filter** : collects seepage from inclined filter, dam body, foundation and carries to toe-drain.
  - Minimum thickness = 1 m
  - Slope = 1 in 100.
BEHAVIOUR DURING EARTHQUAKE

Embankment failure due to earthquake excitation:

1. Liquifaction or softening of sand foundation. (generation of high excess pore-water pressure by application of cyclic sheer stress and large deformation and vertical displacement in foundation)

2. Sliding and cracking of embankment body resting on hard foundation.
BEHAVIOUR DURING EARTHQUAKE

a) Homogeneous earth fill dam: a wedge type soil block is formed in the crest, and it grows up gradually as the excitation increases, causing deep circular sliding.

b) Homogeneous rock fill dam: the extent of falling down of rock particles along slope moves down from crest to toe, leading to a flat circular crest and lowering of the fill. Shallow surface sliding also appears during this process.

c) Centrally located core type rock fill dam: core zone is exposed at the crest due to settlement and drag of surrounding shells, causing decrease in lateral constraint and opening cracks.
FAILURE MECHANISM BY EQ

Possible damaging effects of earthquakes on rockfill embankments:

- Slope failure because of inertial loading and/or softening of material strength
- Permanent deformation of dam body or foundation soils
- Crest settlement
- Fault displacement under foundation
- Piping and internal erosion
Failure Mechanism of Rockfill Dam on Hard Foundation
Failure Mechanism due to Liquefaction of foundation

Embarkment Failure due to Liquefaction of Foundation
Field investigation and lab testing

For seismic design of rock fill dam extensive field investigations, lab tests and office studies are required with active involvement of:

- Geologist
- Seismologist
- Geotechnical engineer

The entire effort can be grouped into four main areas:

- Field investigation
- Site characterization
- Analysis
- Evaluation
1. Geotechnical investigation:
Investigations for geological formations, soil deposits and rock in and around the dam site for assessing their behavior during earthquake shaking and ability of a structure to resist earthquake including evaluation of liquefaction potential.

2. Seismological investigation:
Study of past occurrence of earthquakes in the region of site to make an estimate of probability of future earthquake.
Site Characterization

Series of drill holes in gorge and abutments to get the information on site geology e.g.

i. Topographic conditions
ii. Description of geology
iii. Composition and structure of foundation soil, borrow area soil and bedrock
iv. Nature and depth of overburden
v. Depth of fresh and sound rock
vi. Depth of stripping/foundation grade
vii. Permeability of foundation rock & need for grouting
viii. Description of weak zones, its implications and remedial treatment.
Seismological/Earthquake hazard investigation

- The site specific seismic study: understanding of seismic scenario including geological setting of the area, tectonic features and the history of earthquake occurrence in the region. The study enables evaluation of designed ground motion based on identifiable seismic zones and appropriate ground motion attenuation laws.

- The largest possible earthquake with a Specific Seismic Source (SSZ) in a given seismo-tectonic frame work is known as Max. Credible Earthquake (MCE) for that SSZ.

- Design Base Earthquake (DBE) represents ground motion at dam site at which only minor repairable damage is accepted.
1) **Ground motion** can be characterized by peak value of acceleration, velocity and displacement.

2) **Response spectrum** represents in absolute acceleration, velocity and displacement as a function of natural time period.

3) **Acceleration time histories**: Seismic parameters in terms of peak values and spectral characteristics are sufficient for analysis of many dams, however in case of high dams or high hazard potential the specification of earthquake motion in time domain (Acceleration time history record) is also required.

- To arrive at these parameters **National Committee on Seismic Design Parameters (NCSDP)** has been constituted by MOWR, RD & GR. For dams more than 30m heights approval of NCSDP is mandatory.
Seismic effects on design

- **Pseudo-static approach:** (Seed & Martin 1966)
  In this method min FOS is calculated by including a static horizontal force (equal to seismic coeff $\times$ weight of sliding mass)

- **Dynamic response approach:** (Newmark 1965)
  Effects of earthquake is evaluated on the basis of deformations they produce rather than factor of safety.
2. METHOD OF ANALYSIS:

i. Liquefaction Evaluation
ii. Pseudostatic method
iii. Newmark method
iv. Dynamic Analysis
    (Finite element/Finite Difference analysis)
LIQUIFACTION EVALUATION DURING EARTHQUAKE

- Embankment failure due to earthquake excitation by:
  Liquifaction or softening of sand foundation (generation of high excess pore-water pressure by application of cyclic shear stress) and large deformation and vertical displacement in foundation.
- Therefore, evaluation of foundation for such behaviour is very essential before seating a dam on sandy foundation.
- Remedy/treatment:
  Foundation treatment/improvement
**Foundation Treatment?**

- To increase bearing capacity and stability (avoid failure)
- To reduce post construction settlements foundation and thus the overall settlement of the top of the dam
- To reduce liquefaction risk (seismic area)
- To reduce leakage through the dam foundation
- To reduce seepage erosion potential
Various steps involved in Improvement of Foundation

- Preparatory works, Excavation, Surface treatment
  - Sealing Measures (Curtain Grouting / Cut Offs/ Core etc.)
  - Drainage Measures (Drainage holes/ Filters)
  - Strengthening Measures (Consolidation Grouting/dental treatment/Stabilization)
Main Improvement Techniques

Temporary
e.g. dewatering or ground freezing, where the improvement is only during the application.

Short-term
e.g. some forms of grouting, or use of diaphragm walls for ease of construction with longer term benefits.

Long-term
e.g. soil nailing, vibro-replacement, curtain grouting of a dam, where the treatment is integral to the permanent works.
Main Improvement Techniques:

- by vibration
- by adding load
- by structural reinforcement
- by structural fill
- by admixture
- by grouting
- by specialist dewatering
Effect on the Ground

Change of state;
  i.e. the same ground but made stronger, stiffer, denser, more durable.

Change of nature;
  i.e. the ground becomes a different material by inclusion of other materials.

Change of response;
  i.e. through the incorporation of other materials, the ground becomes a composite material with enhanced load-carrying or deformation characteristics.
## Foundation Treatment Techniques

<table>
<thead>
<tr>
<th>Cohesive soil</th>
<th>Without added materials</th>
<th>With added materials</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peat, clay</td>
<td>1 Drainage</td>
<td>4 Dynamic replacement</td>
</tr>
<tr>
<td></td>
<td>2 Vacuum</td>
<td>5 Stone columns</td>
</tr>
<tr>
<td></td>
<td>3 Dynamic consolidation</td>
<td>6 CMC</td>
</tr>
<tr>
<td></td>
<td>4 Vibroflottation</td>
<td>7 Jet Grouting</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Soil with friction</th>
<th>Without added materials</th>
<th>With added materials</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand, fill</td>
<td>3 Dynamic consolidation</td>
<td>4 Vibrflottation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5 Stone columns</td>
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<td>7 Jet Grouting</td>
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<td></td>
<td></td>
<td>8 Cement Mixing</td>
</tr>
</tbody>
</table>
Seismic slope stability of rock fill dam is influenced by:

1. Cyclic stress induced by earthquake shaking
2. Cyclic stress–strain behaviour

Potential instability during earthquake is caused by:

1. Inertial effect
2. Cyclic softening of soils
SOIL PROPERTIES

- Since **earthquake loading is rapid**, stability for rock fill dam is usually considered under **undrained conditions**.
- Soil properties used in analysis should reflect **softening** because of **pore water pressure generation and strain development and cyclic strength degradation**.
1. Pseudo static slope stability analysis
2. Sliding block method
3. Dynamic analysis (simplified or rigorous)

Pseudostatic slope stability analysis:
- Slope stability analysis is similar to that for static condition except for the application of horizontal and vertical inertial forces on every portion of potentially unstable soil mass. This approach is based on obtaining inertial force due to earthquake by multiplying the weight of potential sliding mass with these seismic coefficients.
- Horizontal seismic coefficients = free field peak ground acceleration corresponding to design label of earthquake shaking
- A limit of factor of safety = 1.0 is considered acceptable.
- E.Q forces shall not be normally included in stability analysis for construction stage or reservoir empty condition. However, for sudden drawdown of reservoir E.Q forces should be considered.
Failure surface geometry:
- Plane Surface (very steep slopes)
- Curved Surface (circular— for relatively flat slopes)

Stability Analysis:

i. Assume a dam section with given soil properties
ii. Adopt failure surface geometry
iii. Guess a failure surface
iv. Draw FBD including a static horizontal force (equal to seismic coeff \(X\) weight of sliding mass)
v. Compute FOS = \(s/\tau c\)
vi. Guess another surface until we get \(FOS_{\text{min}}\) which is FOS of the assumed section
vii. If (FOS) obtained is not matching the standard value for that loading condition, then modify the section.
viii. Modify the section by changing the slopes of embankment and/or introduction of berms, replacing the fill material to get desired FOS.
The dynamic analysis essentially involves estimation of the deformation of behavior of an rock fill dam using finite element or finite difference method.

Dynamic analysis is recommended for important dams the involving high level risk and located over active fault zone.

The results of such analysis are sensitive to input seismologic parameters and engineering properties.

Hence, thorough seismo tectonic assessment and detailed site and material characterization are pre requisite for dynamic analysis.
Dynamic analysis employs a **Non linear stress–strain relationship**.

Hence, this approach requires an **accurate characterization of stress–strain behavior of dam and foundation material**.

It also requires a **suitable earthquake time histories** representing design earthquakes.
The procedure usually involve the following:

1. **Determine pre earthquake static stresses** using a static numerical model for initial effective normal stress and shear stress along the potential failure surface.

2. **Evaluate dynamic soil behavior** from in-situ and cyclic laboratory test for input soil properties.

3. **Evaluate dynamic response of the dam-foundation system** using different stresses computed in step 1 as the initial condition using either linear or non-linear procedures.

4. **Evaluate embankment deformation** or strain potential for the individual element.

5. **Calculate total deformation** on the basis of gravity loads and softened material properties to determine whether they are in the acceptable limits.
In the design of remedial measures there is continuing change and the state-of-the-art advances such as:

- Use of Geotextiles (Geofilters and Geomembrans)
- Improved techniques to install concrete cutoff walls through techniques and materials such as increased pressure, microfine cements and vide variety of grout additives
- Automated monitoring systems
Thanks!