Seismic Stability Analysis of Sangan Iron Ore Mine Project Tailings Dam

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Agenda

- Introduction
- Sangan Iron Ore Mines (SIOM) Tailings Dam
- Staged Development
- Stability Assessment of Tailings Dam
- Seismic Stability Analysis with Numerical Methods
- Conclusion
Why TSFs?

- TSFs are constructed not only to minimise or reduce the adverse environmental impacts associated with tailings, but also to play a key role in recycling of process water and freshwater conservation.

- A failure of a tailings dam can be much more harmful than a failure of a water retaining dam. So, they are more sensitive to natural disasters like earthquakes and floods.
Tailings Dams Failures

• The current rate of major tailings dam failures has been estimated as being of the order of 2 to 5 per annum. As addressed yesterday by the keynote speaker Professor Andy Fourie, there are extra failures that have not been included in the statistics, because they have not been reported! For example there are some unreported cases in Brazil and Iran.
Tailings Dams Design

• It is not unusual to design a tailings dam in low risk seismic areas using a ‘pseudo-static method’.

• This method of analysis is very popular for seismic analysis of embankments/dykes due to the simplicity of the method, but such a design is not sufficient, in high risk seismic areas like Iran.

• The response of dams to ground shaking is determined by the properties of the constituent material, the geometry, and the nature of the ground motion.
Sangan Iron Ore Mines (SIOM) Tailings Dam

- Sangan Iron Ore Mines (SIOM) is located in north east Iran and is the second largest iron ore recourse and third largest iron ore operation of the country.
- Total mineral resources of the SOIM in three regions (W, C & E) were estimated to be 1.2 bt

- The existing TSF of Sangan has been designed for storage of 45 Mm$^3$ equivalent to 74 Mt of tailings

- Capacity of concentrator plant is 2.6 Mt/a (Phase 1)

- Expansion of the project to 15 Mt/a is underway.
TSF Design Background

- SIOM located in a region of the Iranian Plateau that exhibits diverse geological formations and seismicity.

- The original TSF for the project designed by Klohn-Crippen Consultants in 1998.

- Further design considerations to support the FS efforts developed by AMEC (AMEC, 2007).
As there are no specific regulations for the design of tailings embankments in Iran, the regulations developed by the Canadian Dam Association, International Commission on Large Dams has been considered for dam design.
Sangan Iron Ore Mines (SIOM) Tailings Dam
TSF’s Staged Development

- Development of the TSF can be sequenced and built in stages (Kerr and Ulrich, 2011). This causes deferral of some of the capital costs over the life of the mine.
- TSF of Sangan Project was designed to be developed in three phases.
- The three-celled TSF was located approximately 3 km south-east of the processing facility.
In FS, due to the gentle sloping alluvial plain on which the TSF is located, a combination of excavation and earth-filled embankment configuration was determined to be the most logical and feasible method of constructing the TSF.

- Stage 1: Two years of tailings storage (3.5 Mm$^3$)
  (constructed using downstream dam raise methodology)
- Stage 2: Four years of tailings storage (6 Mm$^3$)
- Stage 3: Eleven years (6.6 Mm$^3$)
Embarkment Configuration

• Downstream slope of the Cell 1/Stage 1: 2H:1V
• Upstream slope of the embankment: 1.5H:1V.
• Subsequent stages of Cell 1 will also have an upstream slope of 1.5H:1V
• Downstream slope will be slightly flattened to 2.5H:1V to maintain an acceptable factor of safety (FoS).
• Crest width of each development stage will be 10 m.
Characteristics of Material Used in Embankment Construction

<table>
<thead>
<tr>
<th>Title</th>
<th>Unit</th>
<th>Material</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry density</td>
<td>g/cm³</td>
<td>Dam</td>
<td>1.75</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Tailings</td>
<td>1.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Upper Layer &amp; Lower Layer</td>
<td>1.89</td>
</tr>
<tr>
<td>Permeability</td>
<td>m/s</td>
<td>Dam</td>
<td>2×10⁻⁶</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Upper Layer</td>
<td>1×10⁻⁶ - 7×10⁻⁵</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Lower Layer</td>
<td>1×10⁻⁷</td>
</tr>
<tr>
<td>Friction Angle</td>
<td>Degrees</td>
<td>Dam</td>
<td>33-35</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Tailings</td>
<td>33</td>
</tr>
<tr>
<td>Cohesion</td>
<td>kPa</td>
<td>Dam</td>
<td>7.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Tailings</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Upper Layer</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Lower Layer</td>
<td>15</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>-</td>
<td>Dam</td>
<td>0.35</td>
</tr>
<tr>
<td>Elastic Modulus</td>
<td>kPa</td>
<td>Dam</td>
<td>60000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Upper Layer</td>
<td>200000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Lower Layer</td>
<td>340000</td>
</tr>
<tr>
<td>Bulk Modulus</td>
<td>kPa</td>
<td>Dam</td>
<td>6.66667×10⁴</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Upper Layer</td>
<td>2.22222×10⁵</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Lower Layer</td>
<td>3.77778×10⁵</td>
</tr>
<tr>
<td>Shear Modulus</td>
<td>kPa</td>
<td>Dam</td>
<td>2.22222×10⁴</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Upper Layer</td>
<td>7.40741×10⁴</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Lower Layer</td>
<td>1.25926×10⁵</td>
</tr>
</tbody>
</table>
Typical Dam Sections and Details
Stability Assessment of Tailings Dam and Foundation

- Performance of slopes during earthquakes, seismic hazard analysis, ground motion characterisation; pseudo-static stability analysis and Newmark analysis are the most commonly used methods used for seismic analyses of slopes (Wyllie and Mah, 2004).

- Two general scenarios have been considered:
  - Scenario 1: strictly addresses the stability of Stage 1 during operations.
  - Scenario 2: both the operational and uncertain (a conservative phreatic surface was considered for stability assessment.)
Stability Assessment of Tailings Dam and Foundation

- Both static and pseudo-static analyses were completed for the downstream portion of the final embankment configuration of the Cell 1/Stage 3 embankment.
- There is no serious concern of the instability for the upstream portion of the final embankment as the downstream dam raise methodology is used and on the other hand, the upstream slope batters will be covered with tailings as impoundment is filled.
- Liquefaction of both foundation and embankment materials is not considered to be a threat to embankment stability at the Sangan site due to the in situ density of the foundation soils and prescribed density of the embankment fills.
Stability Assessment of Tailings Dam and Foundation

- According to the statistics published by ICOLD in United States in 2000, earthquake ranked as the second-most important cause for serious failure of tailings dams after instability of embankments.
Design Criteria

- FoS > 1.3 for short-term (static and pseudo-static stability analyses), construction conditions (when excess, construction-induced pore pressures might exist within the dam fill)
- FoS > 1.5 for long-term (Seismic stability analysis, steady state (ie closure) conditions.

A pseudo-static stability analysis for the downstream portion of Stage 3 of the dam was evaluated using a Peak Ground Acceleration (PGA) of 0.3 g and a design earthquake magnitude of 7.5.
All modeled soil types were assumed to behave as Mohr–Coulomb materials.
Stability Modelling Assumptions and Method of Analyses

Two analytical scenarios carried out for the Cell 1/Stage 3 (maximum height) during the stability assessment by AMEC were:

- Stage 3 end of construction with seepage entering the embankment from the tailings surface and exiting at the downstream slope two metres above the ground surface (high phreatic surface)
- Stage 3 end of construction with seepage from the tailings surface and exiting at the downstream toe (low phreatic surface).
Stability Modeling Assumptions and Method of Analyses

• These scenarios were completed for both static and seismic load (earthquake) conditions.
• For seismic evaluation, the seismic loading applied was from the PGA of 0.3 g was 0.12 g which is equal to 40 per cent of the peak ground acceleration of the design earthquake.
• The results of the stability assessment indicate that the structure would be stable for Cell 1.
Seismic Stability Analyses With Numerical Methods

- Due to complexity of soil behaviour, phreatic conditions, dynamic pore pressure fluctuations, applicable PGAs, etc, assessment of seismic responses for these structures is challenging.

- FLAC 2D software with different features such as measuring large deformation, using different constitutive models and pore pressure has been used for seismic analyses of Sangan Project’s TSF.

- Before seismic analyses, the embankment should be statically stable in various scenarios.
Modeling by FLAC 2D Software

Geometry of the Model
Modeling by FLAC 2D Software

Apportion Material
Modeling by FLAC 2D Software

Fixed Boundaries

[FLAC 2D software screenshot showing fixed boundaries]
Modeling by FLAC 2D Software

Model Balancing
Seismic Stability Analyses with Numerical Methods

- In FLAC, earthquake load can be applied in one of the following ways:
  - an acceleration history
  - a velocity history
  - a stress (or pressure) history
  - a force history
Seismic Stability Analyses with Numerical Methods

In accordance with the ICOLD Guidelines:

1. Safety Evaluation Earthquake (SEE),
   - Maximum Credible Earthquake (MCE),
   - Maximum Design Earthquake (MDE),
2. Design Basis Earthquake (DBE),
3. Operating Basis Earthquake (OBE),
4. Construction Earthquake (CE),
Seismic Loading

➢ In this study, seismic loading has been applied to the model by using recorded accelerograms for Tabas (Iran-1978) and Chi Chi (Taiwan-1999) earthquakes.

➢ At the moment of wave propagation in soil environment during seismic analysis, there is a possibility that numerical distortion may occur under undesirable condition.

➢ The amount of applied frequency to environment and wave velocity could affect numerical accuracy of wave transfer condition. In order to have the accuracy in wave transferring at soil or stone continuous environment, it is necessary that the recommended condition satisfied by Kuhlemeyer & Lysmer (1973).
Seismic Loading

These two researchers have suggested that the size of existing zones in the continuous environment should lower than the equation:

\[ \Delta l \leq \lambda /10 \]  \hspace{1cm} (Eq. 1)

and \( \lambda \) is given by

\[ \lambda = CT \]  \hspace{1cm} (Eq. 2)

Where:

\( T \) = the period for the incident wave;
\( C \) = speed of propagation associated with the mode of oscillation;
\( \Delta l \) = spatial element size;
\( \lambda \) = the wavelength associated with the highest frequency component that contains appreciable energy.
Seismic Loading

- For the selected earthquakes, the wavelength is 25.8, which means the size of biggest elements should be lower or equal to 2.58 in order to prevent numerical distortion.

- Considering that elements selected for foundation of model and dam are 2 m and 1 m respectively, in this model, it is predicted that numerical distortion will not occur and the recommended condition by Kuhlemeyer & Lysmer is maintained.
Characteristics of studies earthquakes

Characteristics of studies earthquakes have been listed in the Table:

<table>
<thead>
<tr>
<th>Row</th>
<th>Earthquake Name</th>
<th>Since the Earthquake</th>
<th>Location</th>
<th>Ms</th>
<th>M</th>
<th>ML</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Tabas</td>
<td>1978.09.16</td>
<td>Tabas - Iran</td>
<td>7.4</td>
<td>7.4</td>
<td>7.7</td>
</tr>
<tr>
<td>2</td>
<td>Chi-Chi</td>
<td>1999.09.20</td>
<td>Chi-Chi - Taiwan</td>
<td>7.6</td>
<td>7.6</td>
<td>7.3</td>
</tr>
</tbody>
</table>
Characteristics of studies earthquakes

The PGA of Chi-Chi and Tabas earthquakes recorded 0.958g and 0.798g respectively.
Damping Type

Damping type used in Sangan tailings dam analyses is Rayleigh damping which is based on two parameters:

- Natural frequency of model that could be measured by analysing model in seismic state and load weight and oscillation of a point is evaluated. Vibration frequency of this point could be intended as natural frequency of structure. In this study, natural frequency of Sangan dam in its construction has been measured 2.5, 2 and 1.5 Hz for the first, second and third stages respectively.

- The second parameter, damping ratio, was considered 5%. What is normally attempted in a seismic analysis is the reproduction of the frequency-independent damping of materials at the correct level. For geotechnical materials, damping commonly falls in the range of 2 to 5% of critical.
Site Seismics

- In the area of 100 km radius of the site, 23 faults have been recognized.

- Among the 23 faults, three of them, Khaf, Behdadan and Daruneh, have the potential to induce earthquake with magnitude of 7 to 7.4.

- The highest PGA in the site because of earthquakes made from expected activity of these three faults have been 0.349g, 0.31g and 0.237g respectively. All these three faults are reverse.
Calculation Shear Stress

- In this study, acceleration data have been scaled in SeismoSignal software according to maximum acceleration in the construction range of tailings dam (0.349g) and the maximum acceleration will get raise to 0.349g.

- Velocity data from this software (during earthquake time) convert to shear stress using equation 3 and they applied to bottom boundary of model.

\[ \sigma_s = 2(\rho C_s) v_s \]

and Cs is given by

\[ C_s = (G/\rho)^{1/2} \]

\( \sigma_s \) = applied shear stress (Pa), \( \rho \) = density (kg/m\(^3\))
\( C_s \) = speed of s-wave propagation through medium (m/s)
\( v_s \) = input shear particle velocity (m/s) \( G \) = shear modulus (Pa),
Shear Stress

- Shear stress was applied to bottom of the model in every three stage
Seismic analyses displacement results are summarised in the Table:

<table>
<thead>
<tr>
<th>stage</th>
<th>Horizontal Tabas (Iran - 1978)</th>
<th>Vertical Tabas (Iran - 1978)</th>
<th>Horizontal Chi-Chi (Taiwan - 1999)</th>
<th>Vertical Chi-Chi (Taiwan - 1999)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>19</td>
<td>6</td>
<td>2</td>
<td>0.4</td>
</tr>
<tr>
<td>2</td>
<td>25</td>
<td>10</td>
<td>2.25</td>
<td>3</td>
</tr>
<tr>
<td>3</td>
<td>60</td>
<td>35</td>
<td>20</td>
<td>12.5</td>
</tr>
</tbody>
</table>
Vertical displacement of the third stage after applying the Tabas earthquake
Horizontal displacement of the third stage after applying the Tabas earthquake
Results of Shear Strain Increment

Shear strain increment in Seismic Analysis of the Sangan Tailings Dam are summarised in the Table:

<table>
<thead>
<tr>
<th>stage</th>
<th>shear strain increment</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Tabas (Iran - 1978)</td>
</tr>
<tr>
<td>1</td>
<td>0.035</td>
</tr>
<tr>
<td>2</td>
<td>0.09</td>
</tr>
<tr>
<td>3</td>
<td>0.1</td>
</tr>
</tbody>
</table>
Pore Pressure at the Depth of 6m after Applying Tabas Earthquake

- The maximum pore pressure occurred in the maximum shear stress of the Tabas earthquake between the seconds 2 and 3.
Conclusion

✓ The crest and the upstream portion of the embankment were not experienced significant horizontal displacements during earthquake period, but the downstream portion of the embankment showed maximum horizontal displacement of 60 cm at the Stage 3 of the Cell 1 embankment. Also maximum vertical displacements by Tabas earthquake was 35 cm.

✓ Comparison the results of the embankment response to Tabas and Chi-Chi earthquakes showed that displacement, shear stress and pore pressure by the Tabas earthquake were higher than the case of Chi-Chi earthquake. Higher energy of Tabas earthquake and the higher frequency near to the natural frequency of Tabas earthquake could be the reasons of this difference.
Conclusion

✓ With respect to outcomes of this study, by applying Tabas (South Khorasan Iran) earthquake as the Maximum Design Earthquake (MDE), displacement of the dam crest as well as the shear strain of the embankment were higher than the case of Chi-Chi earthquake.

✓ The results of this case study confirm that if the studied tailings dam impacted by an earthquake of a similar magnitude to Tabas, the dam will be seismically stable and the developed strains will not exceed allowable thresholds as defined in the earthquake bylaw (Iranian 2800 standard).

✓ It should be noted that two-dimensional (2D) analyses were utilised and there will be some beneficial three-dimensional (3D) to any strain surface which will be performed in future.
Any Questions?

Thank you for your attention