Seismic Analysis of Concrete Dams Workshop

Field investigations and foundation material properties

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Foundation deformation modulus

• For analysis purposes, approach used at Reclamation is to reduce the laboratory modulus or use an empirical equation (often based on borehole properties)
  – Does your organization use plate bearing, dilatometer, or other in situ testing to estimate modulus, and if so, how do you account for the fact that the results pertain to specific portions of the foundation?
  – It is known that the use of a modulus that is unrealistically low can lead to overdamping, but the use of the dynamic modulus is often discouraged. Should the dynamic modulus be used for seismic analysis, and if so should a reduction be applied?
  – Is dynamic response analysis the only realistic means of selecting a foundation deformation modulus with confidence?
Shear strength of Dam-Fnd. contact

• Direct shear testing is a good option for measuring the basic friction angle along a rock joint (subject to a large scale roughness correction) or between adjacent concrete blocks. The basic friction angle of the rock concrete interface is often assumed.
  – Does your organization perform laboratory testing to determine the basic friction angle of the rock concrete interface? If so, how sensitive would those results be to differences (e.g. degree of bonding) between the laboratory model and prototype?
  – In a sliding or toppling problem involving the ability of the concrete blocks to move independently, how do you adjust the shear strength of the dam foundation contact to account for potential locking between the monoliths?
Shear strength of Dam-Fnd. contact
Geologic Investigations

- Once they have been identified, Reclamation typically models the controlling discontinuities as continuous and then addresses the issue of actual continuity in a risk analysis context.
  - How does your organization model or address the question of joint continuity?
  - Can a potential wedge be identified on the basis of borehole data alone or should field mapping always be performed?
  - Can large scale roughness be quantified on the basis of borehole data alone?
  - How should the geologic investigations be focused when the foundation consists of hard but very blocky rock?
Geologic Investigations

Fairly closely spaced but generally tight planes of parting (developed at the time of crystallization of the rhyolite) are wide spread and diversely oriented. The rhyolite at the site is conspicuously jointed. The major joint set is high angle (70° to 80° dip) and trends about N 60° E (Drawing No. 121-D-5). This major joint set can be seen on aerial photographs, and appears to affect outcrop alignments and vegetation. The spacing of the joints ranges from 6 inches to 3 feet. Another steeply dipping joint set trends about normal to the major set and has about the same spacing. A minor set of joints strikes northerly and dips at low angles toward the east. These joints are spaced from 6 inches to 2 feet apart. Most of the joints on the surface are tight or are filled with chloritic materials. However, on some rock surfaces weathering has opened or accentuated the joints. Percolation tests in the lower part of the damsite indicated that some of the joints are open, even at depth [2].

Hydrothermal alteration of the rhyolite is very prominent in the reservoir area, and in a few areas near the dam [3]. The rhyolite bedrock at the damsite has been altered and considerably softened along and near the joints by hydrothermal solutions. Along the joints are films and thin (1/16 inch to 1/2 inch) seams of nontronite, formed by the ascending hydrothermal solutions. Nontronite is a soft, yellow to green, wax-like clay mineral of the montmorillonite group. Since the main alteration of the rock has been by hot ascending solutions, the rock does not improve appreciably with depth. Near the surface weathering has altered the nontronite to a soft rusty brown, clayey material [4].

Most of the rock at the damsite is relatively hard. In most areas, the rock is just as competent within a few inches of the surface as it is with depth. However, in a few areas weathering extends to a depth of 2 to 3 feet. Rock in the upper portion of the left abutment is very hard and dense and only slightly fractured; however, in the lower portion, which was covered with slopewash, some of the rock is moderately fractured. Drill holes across the valley bottom indicated that the rock is lightly to heavily fractured. The rock in the right abutment is lightly to moderately fractured. During the keyway excavation it was reported that generally the rock in the left abutment was much harder, and less weathered than rock in the right abutment [2].
How to model the foundation

• When a hard rock foundation is joint controlled, the key discontinuities must be defined as sliding surfaces in the finite element model before the analysis is run.
• When a foundation is weak or soil-like, can potentially model is as a continuum (e.g. using the Hoek-Brown failure criterion) within the finite element model.
• Questions arise when a foundation lies somewhere between these extremes:
  – Whether to formulate the analysis in terms of stresses or forces
  – How to account for friction between foundation blocks
  – How to identify the likely mode of failure of the rock mass
  – Whether to account for cohesion between foundation blocks
Stresses versus forces in the analysis of blocky rock masses
In a *blocky rock mass*, the mathematical construct of “a state of stress” can be hard to apply, except when discussing the behavior of individual blocks.

So, our profession has developed tools to work directly with *forces and displacements between blocks*. Then, if desired, we can calculate the stress distributions *within individual*, relevant blocks.
This approach can be (and has been) enlarged, as appropriate, to discuss: cracking within blocks, and the stability of the whole system under water and frictional forces – using, block theory, DDA, DEA and new developments in older, available tools.
Dealing with friction forces between blocks
Most of our problems involve friction. This immediately complicates any analysis because the analysis becomes piecewise non-linear since:

- all friction forces have to be assigned a direction that opposes incipient motion;
- but one generally does not know the directions in which to apply the friction forces until the analysis has already been made;
- and, each subsequent iteration may continue to produce a new result, with different force vectors in new directions.

In any large, sophisticated model with friction forces, iterations are required to circumvent this difficulty.
To make a fully satisfactory analysis in any significant rock mechanics application, we must be able to predict and identify the correct applicable modes of failure.

A failure mode is dependent on the structure and arrangement of component rock materials and importantly depends on the intimate details of material interfaces.
Initial motion of the key block may be in response to: \textit{shear; tension; torsion, bending; cracking; } or other mechanisms.

As soon as the motion has initiated, new block movement-opportunities may arise, allowing continued block motion in an \textit{altogether different mode}. The failure process thus involves a path of \textit{incrementally adjusting or changing failure modes}.
Geological work in the field may be able to establish a *likely mode of failure* based on the record of natural failures in the same or similar rock formations.

In my opinion, this should be a primary responsibility of the geological engineer and field geologist – by means of geological observations and studies of case histories in the region. Some examples follow:
Rock mass mode of failure
It makes little sense to proceed with an analysis that is not responsive to the most likely mode(s) of failure. Why? Because, in such cases, the method of analysis may call for input of inappropriate properties for the rock mass --

without even suspecting that the central focus of the analysis is being misdirected.

Further, it will tend to create a false expectation that the geologic problem is being handled.
A process of failure in discontinuous rock can initiate in many ways, including:

- *Sliding of an initial, planar key block that releases, blocks behind it;*
- *Forward rotation of a key-block (toppling);*
- *Cracking of a non-convex block to create removable sub-blocks;*
- *Surface erosion that enlarges the space pyramid to expose new key-blocks;*
- *Torsion of a potential key-block about an axis through a block corner;* etc.
Rock strength is generally understood to vary with the shear and normal displacements on discontinuities.

However this conclusion is insufficient since these displacements depend not only on translations of blocks but on their general motions in space.
Figure 57: Types of block motion related to failure modes: (a) Lifting; (b) Single face sliding; (c) Double face sliding; (d) Rotation about an edge; (e) Rotation about a corner; (f) Rotational sliding on a plane – Torsional slide; (f) Slumping. Redrawn after Goodman & Shi (1985) and Goodman (1995).
A complete analysis of block motion requires consideration of additional potential inter-block modes as described by Dr. Markus Poetsch (*), including block translations or rotations along convex block edges.

(*) Markus Poetsch, (2011) *The analysis of rotational and sliding modes of failure for slopes, foundations and underground structures in blocky, hard rock*, (Tech. Univ. Graz, Inst. fuer Felsmechanik und Tunnelbau, V 42.) (This work also advances analysis of block rotation kinematics pioneered by Prof. Mathew Mauldon.)
Overview of constrained motion of single polyhedral blocks described by basic constraints.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Degrees of freedom</th>
<th>Number</th>
<th>Mode</th>
<th>Degrees of freedom</th>
</tr>
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<tr>
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<td>6</td>
<td>11</td>
<td>Sliding rotation of a plane while rotation point slides along line</td>
<td>2</td>
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<tr>
<td>Rotation about a corner which slides on a plane</td>
<td>5</td>
<td>12</td>
<td>Rotational slide of an edge with static rotation point</td>
<td>2</td>
</tr>
<tr>
<td>Rotation of an edge about an edge and sliding in contact point</td>
<td>5</td>
<td>13</td>
<td>Sliding of an edge along a line with rotation about the edge</td>
<td>2</td>
</tr>
<tr>
<td>Rotation about a corner sliding along a line</td>
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<td>14</td>
<td>Double plane sliding</td>
<td>1</td>
</tr>
<tr>
<td>Rotational slide of an edge with rotation about the edge</td>
<td>4</td>
<td>15</td>
<td>Edge rotation</td>
<td>1</td>
</tr>
<tr>
<td>Rotational slide of a plane about an edge</td>
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<td>16</td>
<td>Sliding rotation on a plane about a static corner</td>
<td>1</td>
</tr>
<tr>
<td>Rotation of an edge about a corner and sliding in contact point</td>
<td>4</td>
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<tr>
<td>Pure rotation about a static corner</td>
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<tr>
<td>Rotational slide of a plane</td>
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</tr>
<tr>
<td>Rotational slide of an edge with translation of rotation point and rotation about the edge</td>
<td>3</td>
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</tbody>
</table>
Cohesion between foundation blocks

• Cohesion along joints is sometimes conveniently ignored. This is a common, presumably conservative, approach because one cannot easily evaluate cohesion by normal methods of investigation used in engineering practice.

• Further, the great French dam engineer, Pierre Londe argued that introducing cohesion makes the problem of calculating the safety of rock blocks scale-dependent; whereas problems of calculating blocks with cohesionless connections (without rotations) have been treated as scale-independent.
Cohesion between foundation blocks

• Considering only sliding modes, Pierre Londe maintained that inter-block sliding, as opposed to rotation, is always the most critical mode - a finding that greatly simplifies engineering analysis.

• However this is not true when allowing rotational modes - if friction is large.
Fig. 12. Schematic view of the left bank — definition of a tetrahedron.