$10 Million Tuff “Pods” in the Dam Foundation

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MWH is currently providing final engineering investigations, analysis, and design for various structures in support of a large Tailing Storage Facility (TSF) for a mine located in southern Peru.

- **Saddle Dam:** 80 m (262 ft) rockfill with upstream core
- **Ultimate TSF Embankment:** 310 m (1,020 ft) cycloned tailing sand embankment
- **Starter Dam:** 165 m (540 ft) central earth core rockfill
- **Auxiliary Water Supply Dam:** 60 m (197 ft.) central earth core rockfill

See page for additional details.
TSF Configuration

Jacking header and tailing discharge lines

Tailing fines ("overflow" or slimes) deposited as a slurry

"Cycloned" tailing sand ("underflow") embankment, deposited as a slurry and compacted.

Central core, rockfill "Starter Dam"

Photo of existing cycloned sand TSF

“Starter Dam” footprint

Diagram showing the layout and components of the TSF configuration, including the jacking header, tailing discharge lines, and the "Starter Dam" footprint. The diagram illustrates the deposition of tailing fines as a slurry and the formation of an embankment.
Project Geologic Setting

1) Granitic Gneiss

2) Meta-shale/quartzite

3) Granite

4) Diorite, granodiorite, monzodiorite

5) Granodiorite

Saddle Dam

Auxiliary Water Dam

Seepage Collection Sump

Main Dam

Spring

Rhyolite Tuff
Site Conditions:

- Fractured granodiorite and diorite intrusive bedrock across the majority of the proposed foundation and most of the impoundment.
  - Generally high quality foundation conditions and permeability that improves with depth.
  - Faults/shears, hydrothermal alteration, and/or fracture zones in the main dam area and seepage collection sump.
- Spring near the upstream foundation toe (related to K contrast b/t Granite and Diorite).
- Gypsum infilling of fractures within the rock mass.
- Rhyolitic Tuff “Pods” in the Starter dam and ultimate TSF Embankment footprint.
1 – Initially, ash accumulated in the in stream channels, swales, and on top of paleo-soil deposits and cooled quickly (may have been followed by a period of quiescence).

2 – Significant eruptive event resulted in thick pyroclastic accumulations (poorly welded tuff) along the stream channels, swales, and on top of the ash and/or paleo-soil deposits.

3 – Erosion removed the rhyolite tuff along the main stream channels resulting in discontinuous “pods” of this material left in place along the flanks of the valley slopes.
Feasibility Level Field Investigations

- Identification and detailed mapping of the spatial extent of the “pods”.
- Test pits excavated around the tuff “pod” perimeters
- One (angled) drill hole to understand the geometry and engineering conditions of the “pods”
Feasibility Level Field Investigations

- **Colluvium**
- **Ash**
- **Diorite**
- **Tuff**
- **Alluvium**
- **MASW-100**

**Poorly welded rhyolitic lapilli tuff:** (weak (500 to 2000 psi), low density, high absorption and porosity, with open and continuous joint sets)

**Unwelded/friable ash**
(silty sand / sandy silt (SM to ML), non-welded (friable and unconsolidated))

**Fractured diorite**
(Generally highly permeable in the upper 5-10 m and then it gets tighter and higher quality with depth)

Corrected thickness of tuff = 36m
Potential seepage pathway through or under “pods”:  
- Pods are discontinuous U/S–D/S, however:  
  • Irregular seepage gradients in the foundation  
  • Piping of the underlying ash layer, or  
  • Contamination/plugging of under-drain system.

Potential liquefaction at base:  
- The underlying, fine grained silty sand (SM) ash could potentially liquefy under seismic loading resulting in settlement or deformations under the dam.

Potential slope instability:  
- Ash layer could represent a basal slip surface and stability issues may develop due to loading and saturating of basal contact.

Potential collapse or differential settlement:  
- Uncertainty about the ash response due to loading and saturation (i.e. collapsibility of air-fall type deposits)
Estimated Removal Costs

- Very costly to fully remove the pods
- Material is not useable (i.e. weak, low def. modulus, porous, unacceptable for rockfill, aggregate, or filters)
- Limited space for additional disposal
- Significant delays relating to construction schedule

Is it possible to leave all or partial tuff pods in place under the TSF Embankment?

The extent, geometry, and engineering properties of the rhyolite tuff and ash must be characterized in the pods located in the area of the Main Dam.
Final Design Level
Field Investigations

- Additional drilling
  - HQ core
- In-situ testing
  - SPT, MC, water pressure testing
- Test pits
  - sand cones
- Geophysics
  - refraction, MASW
- Lab testing
  - strength, consolidation, index properties, XRD
Drill Data

- **Tuff**: $2.5 \times 10^{-3}$ cm/sec (high)
- Basal ash layer: $1 \times 10^{-4}$ cm/sec
- Underlying upper fractured diorite (to about 5 m): $5 \times 10^{-4}$ in near surface, highly fracture zones.
**Drill Data**

- **Basal Ash Layer - N_{field} / Inch**
  - \( N_{field} = 68 \) blows / 6”
  - \( N_{field} = 146 \) blows / 6”
  - \( N_{field} = 209 \) bl
  - \( N_{field} = >300 \) blows / foot

- Anything greater than 4.2 blows/inch is equivalent to >50 blows / ft.

- **Drill/SPT data results of suggest material at base is very/extremely dense (hard) and is not likely to collapse.**
- **SPT data indicates a relative strength of \( \phi = 35^\circ \) to 40°.**
- **Liquefaction potential of basal ash layer is considered to be extremely low (i.e. non-liquefiable).**

- **Range of SPT-N_{1(60)} values in ash >>30.**
Test Pits & Material Characterization

Test pits (hand dug) excavated around the perimeter of the rhyolite tuff pods in the starter dam area.

In-situ - Sand Cone Densities of Unwelded Ash in Test Pits

<table>
<thead>
<tr>
<th>Test Pit ID</th>
<th>Wet Density (g/cm³)</th>
<th>Moisture Content (%)</th>
<th>Dry Density (g/cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TP-33b</td>
<td>1.49</td>
<td>0.50%</td>
<td>1.48</td>
</tr>
<tr>
<td>TP-34</td>
<td>1.46</td>
<td>0.40%</td>
<td>1.45</td>
</tr>
<tr>
<td>TP-35</td>
<td>1.40</td>
<td>1.30%</td>
<td>1.38</td>
</tr>
<tr>
<td>TP-40</td>
<td>1.47</td>
<td>1.30%</td>
<td>1.45</td>
</tr>
<tr>
<td>TP-41</td>
<td>1.38</td>
<td>0.60%</td>
<td>1.37</td>
</tr>
<tr>
<td>Average w/o TP-36</td>
<td>1.44</td>
<td>0.82%</td>
<td>1.43</td>
</tr>
</tbody>
</table>

Lab - Relative Density Tests (Sand Cone Material)

<table>
<thead>
<tr>
<th>Trial</th>
<th>Min Densities (g/cm³)</th>
<th>Max Densities (g/cm³)</th>
<th>Max Densities (pcf)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>67.76</td>
<td>91.02</td>
<td>1.458</td>
</tr>
<tr>
<td>2</td>
<td>68.23</td>
<td>90.81</td>
<td>1.455</td>
</tr>
<tr>
<td>3</td>
<td>67.83</td>
<td>90.92</td>
<td>1.46</td>
</tr>
<tr>
<td>Average</td>
<td>67.94</td>
<td>90.92</td>
<td>1.46</td>
</tr>
</tbody>
</table>

Targeted “Remolded” Densities for Shear Strength Tests

<table>
<thead>
<tr>
<th>Target Density (g/cm³)</th>
<th>Relative Density</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.40</td>
<td>≈95%</td>
<td>Field Sand Cone Density, Very Dense</td>
</tr>
<tr>
<td>1.30</td>
<td>≈90%</td>
<td>Medium Dense</td>
</tr>
</tbody>
</table>
## Test Pits & Material Characterization

<table>
<thead>
<tr>
<th>Density (g/cm³)</th>
<th>Test</th>
<th>Condition</th>
<th>c' (kPa)</th>
<th>Φ'</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.30 (90%)</td>
<td>Direct Shear</td>
<td>Dry</td>
<td>33</td>
<td>38°</td>
</tr>
<tr>
<td>1.30 (90%)</td>
<td>Direct Shear</td>
<td>Saturated</td>
<td>44</td>
<td>34°</td>
</tr>
<tr>
<td>1.29 (88%)</td>
<td>CU Triaxial</td>
<td>Saturated</td>
<td>218</td>
<td>31°</td>
</tr>
<tr>
<td>1.39 (95%)</td>
<td>Direct Shear</td>
<td>Dry</td>
<td>76</td>
<td>34°</td>
</tr>
<tr>
<td>1.39 (95%)</td>
<td>Direct Shear</td>
<td>Saturated</td>
<td>23</td>
<td>37°</td>
</tr>
<tr>
<td>1.37 (94%)</td>
<td>CU Triaxial</td>
<td>Saturated</td>
<td>192</td>
<td>36°</td>
</tr>
</tbody>
</table>

1) potentially “destroys” the pre-existing granular structure in remolded soil testing – currently we are testing ash collected from MC liner samples at UC Berkeley.

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### Remolded Ash Shear Strength Parameters

![Graph showing shear stress vs. normal stress for remolded ash](image-url)
Currently we are performing consolidation/collapse testing on additional tuff samples.
SM material collected from test pits excavated around the perimeter of the pods
ML (SM) material collected from drill hole A3-5 and A3-24 (additional results pending)
samples collected from ash under the middle portion of the tuff “pod”

• Consolidation/collapse and grain crushing has already occurred.
• Washing out of fines from the perimeter.
• Weathering and mineral degradation is greater internally under the pod.
Geophysics (Refraction & MASW)

Compression Wave Velocity:
Base of Tuff: ~1600 to 1800 m/s
Diorite: >2000 m/s

View is looking uphill, to the SE
We are currently in the process of performing additional stability and seepage analysis for the overall structure and optimization of the design geometry.
Poorly-welded rhyolite tuff “pods” are 20 to 50 m thick and underlain by a 20 cm to 2 m thick layer of unconsolidated (un-welded) ash classified as a silty fine sand (SM) to sandy silt (ML).

The poorly welded tuff has very high hydraulic conductivity along open and continuous fractures.

The ash has a lower hydraulic conductivity than the overlying tuff and the underlying fractured diorite (a potential barrier to seepage along the base).

“Pods” are discontinuous. (But irregular/undesirable seepage gradients could be realized if left in place around the core).

Ash is very dense.

There is a low potential for liquefaction of the underlying ash layer.

Tuff and ash are consolidated with a low potential for additional consolidation/collapse or differential settlement.
1 - Tuff and ash **must** be completely excavated from below the core and filters/transition.

2 – Additional seepage/stability modeling could show that there is little risk with leaving the tuff “pod” A under the main embankment alignment. However, at this time we are recommending removal of this “pod”.

3 - The upper 3 m of the tuff “pods” under the Main TSF sand embankment should be removed, but otherwise left in place under the dam.