APPENDIX K

Potential Failure Modes and Triggers
Appendix K

Potential Failure Modes and Triggers

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K1 FAILURE MODE SCREENING

A systematic methodology was employed for identifying potential failure modes—mechanisms known to have caused other tailings dam failures as applied to specific conditions of Fundão. Each such candidate failure mode was examined in detail to determine whether or not it could have been operative, following essentially a process of elimination. Those that survived this initial screening were then subjected to more detailed examination. For screening purposes, failure is defined as breach of the dam resulting in uncontrolled release of the retained tailings and water.

Initial failure mode identification yielded the following mechanisms and processes:

1. overtopping
2. internal erosion
3. starter dam foundation or embankment sliding
4. liquefaction

These are considered below in turn.

K1.1 Overtopping

Overtopping can occur either under flood or operational conditions. Flood overtopping results from precipitation inflows that exceed the capacity available to store and/or discharge them, allowing water to flow over the crest of the dam, erode, and breach it. Operational overtopping produces the same effects from improper water management practices.

Figure K1-1 provides daily precipitation recorded at the Germano Dam station from October 1, 2015 through the date of failure on November 5, 2015. The last significant precipitation event occurred on October 27, nine days prior to failure. Flood overtopping as a causative failure mode can be ruled out on this basis.
Similarly, for operational overtopping, the dam crest at the left abutment on November 5, 2015 was El. 901.1 m and the water level at El. 892.5 m, leaving 8.6 m of freeboard. Operational overtopping therefore did not occur.

**K1.2 Internal Erosion**

Internal erosion is a process of particle transport by concentrated seepage to produce voids and cavities that work back from the seepage discharge point, enlarge, and cause breach of the dam. Internal erosion can occur due to inadequate filters or in association with pipes or conduits that penetrate the embankment.

Internal erosion was manifested in the Fundão starter dam during the 2009 piping incident, as evidenced by the deposit of transported material and filter defects visible on Figure K1-2. In addition, the ITRB reported that cavities within the Starter Dam were indicated by geophysical investigations following the incident.
During the initial stages of failure, two eyewitnesses at the toe of the dam not far from the location of Figure K1-2(a) reported a dark or reddish coloration to water ponded there. However, they also reported that the Starter Dam remained intact even while tailings released from above were cascading down on their vehicle. These observations indicate that internal erosion within the Starter Dam did not initiate failure.

Moreover, there are no eyewitness reports of sinkholes or related features to suggest that internal erosion developed independently at the left abutment or within fill surrounding the outlet of the Secondary Gallery. On this basis, internal erosion is excluded as the cause of the failure.

**K1.3 Starter Dam Foundation or Embankment Sliding**

Failure by foundation sliding would have been manifested in the Starter Dam and would require the presence or development of shear surfaces within the natural foundation materials. This concerns in particular the phyllite schist and weathered phyllite schist, since overlying residual soils were removed from beneath the Starter Dam prior to construction. A pre-construction geologic profile through the Starter Dam foundation on Figure K1-3 indicates the location and extent of these materials.

Similarly, embankment sliding would involve the development and propagation of shear surfaces within the embankment fill itself.
Again, the same eyewitnesses at the toe of the Starter Dam reported that it did not move during failure initiation, ruling out foundation failure as the causative mechanism. The same is true of sliding within embankment fill materials of the Starter Dam.

**K1.4 Liquefaction**

Liquefaction is the process by which cohesionless material loses strength and flows like a fluid. Three conditions must be present for liquefaction to occur. First, the material must be contractive, with a propensity to reduce in volume during shearing. Second, shearing must occur rapidly enough to develop undrained conditions. And third, the material must be saturated. All of these conditions were present for the tailings at the left abutment. A flowslide is the physical manifestation of liquefaction and constitutes incontrovertible evidence for its occurrence.

Without exception, eyewitness descriptions are consistent with liquefaction of the tailings and consequent flowsliding. Particularly indicative of the transformation from solid to fluid are accounts of left abutment coming down “like a wave” and “melting”. The violent turbulence of the fluidized mass “going in somersaults” graphically and unmistakably characterizes the behavior of liquefied materials. One witness found himself “swimming” in the liquefied tailings as he clung to a tree.

Based on these accounts, it is concluded that liquefaction was the operative failure mode in the failure of Fundão Dam.

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**Figure K1-3 Geologic profile beneath Starter Dam**[66]

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weathered phyllite schist

phyllite schist
K2 LIQUEFACTION TRIGGERING

K2.1 Fault Tree

In addition to the antecedent conditions described above, liquefaction requires some process or mechanism to initiate, or trigger, the solid/fluid phase transformation. A variety of such mechanisms have been proposed, mainly in connection with past liquefaction failures. Understanding of the Fundão liquefaction failure requires that its operative trigger mechanism be identified. This is aided and illustrated by the fault tree for liquefaction triggering provided on Figure K2-1, which is restricted to the left abutment where failure initiated.

The fault tree of Figure K2-1 is a logic diagram and is used to help structure the process of liquefaction trigger identification and screening. It works back through the failure sequence starting with the failure, then through the contributing events and conditions necessary for failure to have occurred, and finally to the basic events that initiated the failure process. Developed as a tool for system reliability analysis, the related algebraic manipulations and formal symbology they require are not necessary or applied here. Rather, as before for failure mode screening, the fault tree is used as a heuristic device, first to inventory potential triggering mechanisms, then to determine which can be eliminated as the operative trigger.
On Figure K2-1, the top event is liquefaction flow failure. Underneath this, the next tier of events portrays the two possible mechanisms by which liquefaction is known to occur: cyclic liquefaction and static liquefaction. Cyclic liquefaction is the process by which cyclic loading, a series of reversals of the direction in which applied stresses act, causes pore pressures to increase to the point that either the material loses its strength altogether or experiences very large and essentially unrestricted deformations. Static liquefaction, on the other hand, represents the same end result—loss of strength and/or unlimited mobility—but without the stress reversals inherent to cyclic loading.

In the framework of Figure K2-1, static liquefaction and cyclic liquefaction are mutually exclusive; that is, failure can be attributed to one or the other, but not both. However, even if cyclic liquefaction was not the exclusive cause of failure, cyclic loading may still be a contributing factor to one or more static liquefaction triggers.

Saturation of the sand tailings is a necessary condition for cyclic liquefaction, shown by the event highlighted in blue. Given that saturation exists, potential trigger mechanisms are arrayed along the bottom of Figure K2-1 as basic events. Here, three possible triggers are identified:

- equipment vibration;
- mine blasting; and
- seismic shaking.

Turning to static liquefaction, there are four subsidiary events highlighted in blue. From left to right, these are: saturation of the sand tailings; slimes deposition due to beach encroachment; the alignment setback; and increased height of the left abutment setback embankment. Events pertaining to the alignment setback and height increase are further decomposed into the enabling events responsible for their occurrence.

Potential static liquefaction triggers along the bottom of Figure K2-1 have been identified from previous tailings dam failures and accidents. These include:

- static pore pressure increase;
- excess pore pressure in slimes;
- Secondary Gallery collapse;
- solution feature collapse; and
- tailings pipeline break.

An additional trigger, static load increase, is subdivided into two possible mechanisms, both of which might occur either with or without any pore pressure effects induced by cyclic loading. This decomposition of static loading can be structured as follows:

- static load increase:
  - undrained shearing:
• with cyclic pore pressure (e.g., earthquake); and
• without cyclic pore pressure.

• deformation extrusion:
  • with cyclic pore pressure (e.g., earthquake); and
  • without cyclic pore pressure.

Each of these potential liquefaction triggers portrayed on Figure K2-1 is discussed individually in the sections that follow.

**K2.2 Cyclic Liquefaction**

**K2.2.1 Equipment Vibration**

Heavy equipment such as bulldozers left idling on saturated tailings have been known to sink into the tailings due to local liquefaction caused by engine vibration. This has led equipment vibration to be proposed as a cause of large-scale liquefaction failures, although well-documented cases are rare or nonexistent.

When the Fundão failure occurred, workers on the left abutment setback were on break, and there was only one piece of heavy equipment present. By contrast, most construction equipment and activity was at the drain on the right abutment, which is not where failure initiated. Furthermore, heavy equipment had been routinely present on the Fundão embankment throughout all phases of its construction, and equipment vibration did not cause liquefaction failure at any previous time. Equipment vibration as the operative liquefaction trigger is accordingly ruled out.

**K2.2.2 Mine Blasting**

Two blasts from Vale’s nearby mine were instrumentally recorded on November 5, 2015 prior to the failure, and blasting records from both Samarco and Vale confirm that these were the only such blasts on that day. The timing, moment magnitude and distance of these blasts from Fundão, along with the three subsequent earthquake shocks, are shown on Table K2-1 below.

<table>
<thead>
<tr>
<th>Local time</th>
<th>Moment magnitude $M_w$</th>
<th>Distance from Fundão</th>
<th>Identification</th>
</tr>
</thead>
<tbody>
<tr>
<td>1:01:49PM</td>
<td>2.1</td>
<td>2.6 km</td>
<td>mine blast</td>
</tr>
<tr>
<td>1:06:06PM</td>
<td>2.3</td>
<td>2.6 km</td>
<td>mine blast</td>
</tr>
<tr>
<td>2:12:15PM</td>
<td>2.2</td>
<td>&lt; 2 km</td>
<td>earthquake (foreshock)</td>
</tr>
<tr>
<td>2:13:51PM</td>
<td>2.6</td>
<td>&lt; 2 km</td>
<td>earthquake (main shock)</td>
</tr>
<tr>
<td>2:16:03PM</td>
<td>1.8</td>
<td>&lt; 2 km</td>
<td>earthquake (aftershock)</td>
</tr>
<tr>
<td>3:45PM</td>
<td></td>
<td></td>
<td>Dam failure</td>
</tr>
</tbody>
</table>
Although the magnitudes and distances of the mine blasts are similar to those of the earthquakes, the blasts occurred almost three hours prior to the failure and approximately one hour before the earthquake sequence. For the mine blasts themselves to have triggered cyclic liquefaction after a three-hour delay is considered to be implausible, especially considering their small magnitudes. Additionally, any cyclic loading effects produced by the mine blasts would have been exceeded by those from the subsequent earthquakes that occurred much closer in time to the failure. On this basis, mine blasting is ruled out as a cyclic liquefaction trigger.

K2.2.3 Earthquakes

Cyclic loading produced by earthquakes is a well-known cause of liquefaction failure for upstream-type tailings dams. Earthquake performance of operating tailings dams, predominantly in Chile and Japan, is summarized on Figure K2-2.

From Figure K2-2, it is significant that no failure of an upstream tailings dam has been reported for magnitude less than 5.5 despite the large number of such dams exposed to smaller earthquakes, especially but not exclusively in highly-seismic areas.

As described in Appendix B, a systematic review of post-failure imagery in areas unaffected by the Fundão failure was undertaken in order to identify the presence of sand boils diagnostic of cyclic liquefaction. The results were inconclusive. Nevertheless, it is significant that no damage was reported to any of the other tailings dams in the Germano complex from the November 5, 2015 earthquakes, including structures with tailings foundation stratigraphy and saturation conditions at least as conducive to cyclic liquefaction as Fundão.
The process of cyclic liquefaction reduces initial undrained strength to some much lower post-liquefaction strength. Figure K2-3 shows stability analyses performed by the Panel that assign a post-liquefaction undrained strength ratio of 0.07 to saturated tailings for right and left abutment sections. The resulting factor of safety at the steeper right abutment (0.37) is lower than the left (0.44). Hence, had cyclic loading triggered liquefaction, the right abutment would have failed before the left, the opposite of what actually occurred.

![Figure K2-3 Post-liquefaction comparison of right (top) and left (bottom) abutment sections](image)

On the basis of this evidence, cyclic liquefaction alone, in and of itself, is ruled out as the operative trigger mechanism. However, this does not preclude some contribution of cyclic loading to other mechanisms, as subsequently explained.

**K2.3 Static Liquefaction**

**K2.3.1 Static Pore Pressure Increase**

The classic experiment of Eckersley (1990) showed how increase in pore pressure due to a rising piezometric surface can trigger static liquefaction, even when the externally-applied load remains unchanged. This potential trigger was evaluated by examining piezometric trends at the left abutment prior to failure.
Figure K2-4 shows the locations of piezometers at the left abutment on three sections designated 01, 02, and 03.

The figures on the following pages show readings from these instruments, with readings subsequent to August, 2015 highlighted in blue shading.
Figure K2-5  Piezometer readings, Section 01

Figure K2-6  Piezometer readings, Section 02
Piezometric behavior prior to failure is similar at all three sections. Despite the continuing increase in reservoir level indicated by the upper blue line in the figures, the readings peak shortly after the beginning of August, 2015, then either remain constant or decline slightly. This effect is attributed to the influence of the newly-constructed left abutment blanket drain at El. 860 m when it intercepted and arrested the rise of the piezometric surface at a time coinciding with the peak readings.

Thus, the El. 860 m blanket drain precluded this liquefaction trigger because it prevented further increase in the piezometric surface within the left abutment. On this basis, increase in static pore pressure is removed from consideration as a static liquefaction trigger.

**K2.3.2 Excess Pore Pressure in Slimes**

A potential liquefaction trigger mechanism is the generation of excess pore pressures within individual slimes layers. These pore pressures would inhibit the gain in undrained strength that would otherwise occur at the same time applied load from the overlying embankment was increasing. Because the rate of pore pressure dissipation varies as the square of the vertical layer dimension, the thickness of individual slimes layers is a key factor in this assessment.

By simulating the loading history of the left abutment setback embankment beginning in 2012, consolidation modeling described in Appendix F calculates excess pore pressures that would be induced in slimes layers of different thicknesses. Results are shown on Figure K2-8.
Appendices B and C show that the greatest documented discrete slimes layer thickness beneath the embankment is approximately 2 m at boring SP-07. Figure K2-8 shows that corresponding excess pore pressures in such a layer beneath the embankment at El. 840 m to El. 850 m would be less than 1% of the effective overburden stress, an insignificant amount. On this basis, excess pore pressure in slimes layers is not a candidate trigger for static liquefaction.

**K2.3.3 Secondary Gallery Collapse**

The Secondary Gallery underlies the left abutment setback where failure initiated, making it a feature of interest that deserves particular attention. Specifically, it can be hypothesized that if the gallery had collapsed to allow entry of tailings, a rapidly-induced void ratio increase in the surrounding mass of saturated tailings could have triggered widespread liquefaction within it.

Figure K2-9 shows the left abutment setback at failure and the alignment of the buried Secondary Gallery. For reference, the gallery approximately follows the El. 810 m natural-ground contour, the plateau area is at approximately El. 860 m, and the dam crest is at El. 901 m.
Several events and conditions are relevant to this potential trigger mechanism. As shown on the figure, the downstream portion of the gallery is reported to have been filled with concrete to enable it to resist the stresses that would be imposed by raising the overlying embankment to its maximum design height at El. 920 m. However, the setback of the El. 920 m dam crest was not accounted for in establishing the terminus of this concrete-filled section, which resulted in the embankment being as much as 60 m above the open, unfilled portion of the gallery.

Another factor is the break in the Secondary Gallery that occurred on November 25, 2012 at the location indicated on Figure K2-9. The sinkhole itself is shown on Figure K2-10, illustrating the upward propagation of the resulting void to the surface of the overlying tailings.
Also of interest is piezometer 16LI017 at the location shown on Figure K2-9 and Figure K2-4. This instrument consistently showed anomalously low readings some 11 m to 13 m below the neighboring piezometers 16PI014 and 16PI015 on either side. If accurate, such a depression in the piezometric surface could be indicative of an underlying void or cavity.

These and other factors are considered in the following discussions.

1. **Secondary Gallery remnants.** Several exposed segments of the Secondary Gallery remained intact after the failure at the locations on Figure K2-9, one of which is shown on Figure K2-11. These intact sections demonstrate that gallery collapse did not occur—and therefore that the related liquefaction trigger could not have been operative—at these particular locations.
2. **Secondary Gallery filling.** To verify that filling of the indicated section of the Secondary Gallery did indeed occur, the Panel calculated the open volume of this section to be 1396 m$^3$ from design drawings. This was compared to concrete volumes reported in construction QC reports$^{[67-79]}$ that summed to 1199 m$^3$, for a difference of 197 m$^3$. This leaves 14% of the open volume unaccounted for. At least some of this deficit can be explained by volume occupied by bulkheads, pipes, and top voids. It may also result from recordkeeping errors. In any case, an equivalent loss of tailings would not likely be sufficient to trigger widespread liquefaction in the surrounding tailings mass.

3. **Piezometer 16LI017.** Post-failure interviews and information provided by Samarco indicate that the elevation of this piezometer was in error. The apparent depression of the phreatic surface is therefore also spurious.

4. **Previous behavior.** The behavior of the tailings during two previous gallery events provides insight into the propensity of such events to trigger widespread liquefaction. One such break in the Secondary Gallery shown on Figure K2-10 resulted in void formation that propagated to the surface by upward stoping, but did not produce a more generalized void redistribution that triggered liquefaction in the saturated tailings at greater depth. The second case was a collapse of the Main Gallery on July 9, 2010 that allowed tailings entry and produced a vortex in the water above. The feature that remained is shown on Figure K2-12. It is apparent that tailings flow into the Gallery left a conical depression but did not disturb the surrounding tailings or produce more generalized liquefaction beyond the limits of the material that flowed.

![Figure K2-12  Tailings depression resulting from break in Main Gallery][25]

5. **Eyewitness accounts.** There were no eyewitness reports of sinkhole formation or surface depressions in previous occurrences of tailings entry into the Galleries.

To summarize the pertinent factors related to liquefaction triggering by Secondary Gallery collapse:

- Available evidence indicates that collapse did not occur within that portion of the Secondary Gallery that was filled with concrete, or if it did occur that the resulting volume would have been too small to have triggered generalized liquefaction in the surrounding tailings mass.
Previous incidents indicate that if collapse of the unfilled portion of the Gallery had occurred, the effect of tailings entry would have been void propagation to the surface rather than generalized void redistribution resulting in liquefaction triggering. No such indications of void propagation were reported by those who witnessed failure initiation.

Accordingly, Secondary Gallery collapse is ruled out as a liquefaction triggering mechanism.

K2.3.4 Collapse of Solution Cavities

Attachment K1 to this appendix describes the regional and local occurrence of solution cavities, their morphology and lithologies, and their overall geologic setting.

Cavities formed by dissolution of soluble rocks exist in the Iron Quadrangle of Minas Gerais, and 1226 have been documented. If present beneath the Fundão left abutment, their collapse might have caused the same effects postulated above for collapse of the Secondary Gallery: void ratio redistribution and liquefaction triggering in overlying saturated tailings.

As detailed in Attachment K1, iron-enriched laterites, or ferricrete, constitutes the preferred environment for cavity formation, accounting for almost half of all such features. By contrast, the Fundão area is underlain mainly by phyllites with low karstic potential.

There are 238 mapped cavities within a 5 km radius of Fundão Dam. The closest of these are shown on Figure K2-13.

Figure K2-13 Mapped cavities (circles) and associated lithologies in the Fundão vicinity
In the immediate Fundão vicinity, Figure K2-14 shows that iron-rich ferruginous phyllites that could provide a more favorable host for solution cavities are found mainly in the Grota da Vale area. To further investigate cavity presence, more than 300 drill holes were analyzed. From these, there were 41 cores with lithologies favorable to the formation of cavities, but none were beneath the Fundão Dam or tailings. No evidence of cavities was found in boreholes drilled for the Fundão Dam or in speleological studies performed in the area.

![Ferruginous Phyllite](image)

Figure K2-14 Location of ferruginous phyllite in the immediate Fundão vicinity (see inset Figure K2-13)

With reference to related material in Section K2.3.3 of this appendix, evidence regarding solution cavity collapse as a potential liquefaction trigger can be summarized as follows:

- Geologic studies and drill hole logs provide no indication of the presence of cavities beneath the Fundão left abutment.
- Had cavities been present and collapsed, the likely effect would have been void propagation by upward stoping manifesting as sinkholes rather than generalized void ratio redistribution in the overlying mass of saturated tailings. Eyewitnesses reported no such effects.

On this basis, collapse of solution cavities is ruled out as a liquefaction trigger mechanism.

**K2.3.5 Pipeline Break**

Rupture of tailings distribution pipelines or return-water lines on the crest have been the cause of past tailings dam failures and accidents. Accordingly, pipeline rupture or leakage might have eroded
the crest of Fundão Dam, breached it, and triggered liquefaction in the mass of unsupported tailings behind it.

Figure K2-15 shows that tailings were being discharged at the left abutment prior to failure from a tailings pipeline located on the tailings beach at the upstream edge of the dam crest.

At the time of failure, the piezometric surface was at least 15 m below the pipeline, so erosion would have to extend to this depth and more before reaching and releasing saturated tailings. This would have taken considerable time, allowing ample opportunity to be seen. Of the many observers on the dam, none reported an erosional breach on the crest. To the contrary, it was consistently reported that the failure started “from the bottom up,” beginning at the lower benches rather than on the crest where erosional breach from a pipeline break would have initiated. On this basis, it is concluded that pipeline rupture did not trigger liquefaction.
K2.3.6 Remaining Trigger Mechanisms

It is useful to revisit the fault tree of Figure K2-1 reproduced below as Figure K2-16 in order to review the status of the various candidate liquefaction trigger mechanisms. All of the potential triggers shaded in gray have been considered and rejected for cause per the preceding discussions, with the candidate triggers that have survived the process of elimination shaded in yellow.

![Fault Tree Diagram]

The sole surviving trigger on Figure K2-16 derives from static (as distinct from dynamic) load increase, and it can be subdivided into two forms. One is simple undrained shearing, whereby the loading imposed by embankment raising increased until exceeding the undrained shearing strength of the tailings. The other, termed *extrusion* (Jefferies and Been 2016), is a deformation process whereby load-induced strains triggered liquefaction. To the extent that strength and deformation are inextricably linked, these two mechanisms are complementary and not mutually exclusive. Both are carried forward in the text of this report. Figure K2-16 also shows that both of these mechanisms may or may not have been significantly influenced by the earthquake sequence described in Table K2-1, and this assessment is carried forward as well.