# An underappreciated mechanism for the failure of tailings dams

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**ABSTRACT**

In at least two out of the three recent major failures of tailings dams, two in Brazil and one in Australia, where incipient failure due to other causes has been evident, the occurrence of small earthquakes or mine blasts immediately prior to the failure has been essentially ruled out as the principal trigger. This is in accord with the widespread belief that very short period / higher frequency motions are not "seen" by large earth structures. That may be true in many cases, but if there is an incipient failure due, for instance, to uncontrolled seepage, piping and erosion, the characteristic dimension of that feature will be much smaller and it is possible, even likely, that high frequency motions can impact the potentially unstable local structure and trigger a larger progressive failure. This phenomenon is illustrated with a simple example. The importance of correctly modeling progressive failure is also addressed.

**Keywords:** tailings dams, small earthquakes, unstable structure, triggering, progressive failure

## 1 INTRODUCTION

There have been three dramatic failures of tailings dams in recent years. Two of these, the Fundão and the Feijão failures occurred in Brazil in the State of Minas Gerais. The Feijão Dam I was located near the town of Brumadinho and is often referred to by that name. The Fundão Dam was located at the Samarco facility and is sometimes referred to by that name. The NTSF Embankment failure at the Cadia Valley Operations occurred in the State of New South Wales in Australia.

In each case a detailed report has been prepared by an expert panel. See Morgenstern et al. (2016) and (2019) and Robertson et al. (2019), all of which are publicly available on the Internet. These are all excellent reports although it should be noted that they were all prepared for lawyers representing the operators of the respective facilities.

All three failures were similar in that they were of embankments constructed by the "upstream" method with somewhat erratic sequences of construction that resulted in various uncontrolled seepage issues. They also contained at least patches of saturated loose cohesionless materials which might be susceptible to liquefaction under static loadings if those loadings caused a deformation sufficient to trigger static liquefaction and then progressive failure. See the panel reports and Pyke (2019) for further discussion of this general mechanism. Thus, in each case, the embankment was an "accident waiting to happen". However, from the panel reports it is not totally clear what the final trigger was that provoked the failure at the time that it happened.

From the practical engineering point-of-view, exactly what the trigger was might be less important than the fact that these were accidents waiting to happen and that good engineering practice and effective regulation should avoid the development of these kinds of situations. It is nonetheless of some interest to examine both the trigger and the mechanism of the subsequent progressive failure. Although it is unlikely that forward predictions of triggering will ever be made with sufficient accuracy to design or operate tailings storage facilities which are at risk but will not trigger. They need to be designed and operated so that triggering is not an issue.

## 2 CASE HISTORIES

### 2.1 Feijão

Of these three case histories, the Feijão Dam I failure is the least likely to have been triggered by earthquakes or mine blasts. The panel report concluded: *The Panel's investigation focused on possible triggers for a sudden and rapid strength loss capable of causing the global failure seen in the video. <u>It was recognized that the triggers could be relatively small, given the high shear stresses and brittle nature of the tailings within the dam prior to failure.</u> It also was recognized that the triggers could be due to the cumulative effect of multiple small events. No earthquakes were recorded in the region on the day of the failure. Although blasting occurred in the open pit mines in the area, there was no blasting* *recorded by the closest seismograph to Dam I on January 25, 2019, prior to the failure. Hence, earthquakes and blasting were not triggers of the failure.*

Thus, although questions remain about the triggering mechanism proposed by the panel and the possible role of the drilling of horizontal drains and a vertical borehole shortly before the failure, earthquakes or mine blasts do not appear to be likely triggers of the failure. But note the sentence that is underlined in the quote from the expert panel report. Relatively small triggers may be all that is needed to set a progressive failure in motion in embankments which are already close to failing.

### 2.2 Cadia

As part of the panel's work on the NTSF Embankment failure, Dr. Gail Atkinson conducted an excellent study of the seismicity of the site. The embankment failure at Cadia was noticed the day after two events of M = 3.0 (10 seconds apart) on March 8, 2018. The response spectrum for an M = 4.3 event that occurred the previous year is shown in the report and the maximum amplitudes occur at frequencies as high as 100 Hz.

Both 1D and 2D response analyses and Newmark deformation analyses conducted by Klohn Crippen Berger using motions based on the recordings of the M = 3.0 and 4.3 events gave the conventionally expected results. The shear strains that were developed in the site response analyses were not large enough to generate significant excess pore pressures and the Newmark analyses did not show significant displacements.

The panel report describes a complex failure mechanism and concludes: "The Event was a mobile slump that resulted in loss of containment of tailings from the NTSF in the vicinity of Ch. 1950. It has been considered as evolving in two phases. Phase 1 involved slow movements up to the time of evacuation of the worksite on March 9, 2018. This was followed by a rapid acceleration of movement (Phase 2) culminating in the slump feature subsequently identified a few hours later. The two phases are intimately linked. Had Phase 1 not developed, Phase 2 would not have resulted. Even if Phase 1 had terminated with only minor movements, it is conceivable that Phase 2 would not have resulted. Phase 2 is entirely the result of the magnitude of movements associated with Phase 1." The panel also stated that: "Two small earthquakes occurred the day before the Event, and their role has also been assessed in detail. As a result of a comprehensive laboratory and analytical studies the ITRB concluded that the earthquakes did not contribute to the onset of Phase 2. The Phase 1 mechanism was well-advanced prior to these two earthquakes."

However, as will be discussed with respect to the following case history, these may not have been the most appropriate analyses to conduct and it remains possible, even likely, that the small earthquakes did play a role in the initiation of Phase 2 of the failure.

### 2.3 Fundão

The full story here is also complicated. The panel report concluded that uncontrolled seepage, piping and erosion was not the critical factor in this instance and that the critical factor was that thin layers of slimes had intruded into the sand tailings and then subsequent extrusion of the slimes layer had reduced the lateral stresses in the sands and brought them close to failure by "static liquefaction".

The panel report also notes: *A related aspect of the failure was the series of three small seismic shocks that occurred about 90 minutes earlier. By then the left abutment of the dam had reached a precarious state of stability. Computer modeling showed that the earthquake forces produced an additional increment of horizontal movement in the slimes that correspondingly affected the overlying sands. Although the movements are quite small and the associated uncertainties large, this additional movement is likely to have accelerated the failure process that was already well advanced. With only a small additional increment of loading produced by the earthquakes, the triggering of liquefaction was accelerated and the flowslide initiated.*

In other words, the embankment was already in the process of failing as a result of another mechanism when the three small earthquakes occurred, but they may have pushed the process along. However, the analyses that were performed do not necessarily support this contention.

Dr. Gail Atkinson developed a suite of input acceleration histories that represents those that likely occurred at the Samarco site on November 5, 2015, prior to the dam failure at approximately 15:45 (local time). The sequence includes three earthquakes closely spaced in time: M = 2.2 at 14:12:15 (foreshock); M = 2.6 at 14:13:51 (mainshock); M = 1.8 at 14:16:03 (aftershock). Both 1D site response analyses and Newmark-type deformation analyses were conducted. Again, as expected, the site response analyses showed cyclic shear strains that were too small to generate significant excess pore pressures. The deformation analyses generated displacements of from 2-8 mm, but, given the limitations of this method of analysis, that is effectively zero. The Newmark method does not take the mass of the potential sliding mass into account so that even a tiny excursion of the applied acceleration above the yield acceleration accumulates some displacement, even though this would not occur in the field. The Newmark method can be useful for estimating the general magnitude of possible displacements under seismic loadings, but it is not very exact. The calculated displacements are likely to be exaggerated when they are small and may err on the low side when they are large. Additionally, the concept of looking at the deformation of a potential sliding mass, which is implied to be rigid, is just wrong in most cases, and in this case in particular.

Almost certainly this was a progressive failure in which the initial failure occurred in a small, localized area and then propagated from that location and ended up encompassing a much larger body of soil. In a situation like this the micro-earthquake does not have to drive the entire final sliding mass, it only has to trigger the initial failure of an element that sets off the progressive failure. If everyone agrees that it was a progressive failure, shouldn't the triggering mechanism be analyzed in the context of a progressive failure? Thus, although it seems to be possible, even likely, that the series of small earthquakes might have had some effect in triggering the ultimate failure, neither of the seismic analyses that were conducted provide persuasive support for that.

A different and plausible argument regarding the Fundão failure has in fact been made by Stark et al. (2023), who postulate that the cumulative effect of the three small earthquakes was to raise the excess pore pressures in one patch of silty sand, not to 100 percent excess pore pressure, but sufficiently to initiate a failure. Although other workers might model the development and dissipation of the excess pore pressures differently, this is a valid mechanism to put forward, and if the patch in question had a size and stiffness such that it was more sensitive to higher frequency motions, that would have increased the cyclic shear strains and the rate of excess pore pressure development, as discussed further below.

## 3 EXAMPLE CALCULATION

The panel evaluations miss a key consideration. The widespread belief that very short period / higher frequency motions are not "seen" by large earth structures is largely supported by the studies conducted by the three panels. However, if, for instance, there is an incipient failure due to uncontrolled seepage, piping and erosion, or a stress state has developed in which a small perturbation can trigger static liquefaction, there may well be somewhere in the embankment a patch of material that is on the verge of collapsing and the characteristic dimension of that patch would be much smaller. So that it is possible, even likely, that high frequency motions could impact the unstable local structure, cause it to collapse or otherwise fail, and trigger a larger progressive failure.

- Consider a dam 100 m tall. Assume it has an average shear wave velocity, $v_s$, of 400 m/sec.
- The maximum deformations and strains will result from waves having a quarter wavelength equal to the height. So, wavelength L = 4 x 100 m = 400 m
- For this case the critical frequency, f = $v_s$/L = 400 m / 400 m = 1Hz
- Typical strong shaking from earthquakes has maximum energy around 1-5 Hz
- So, there is a match for 1 Hz but not for 100 Hz, which is why the conventional thinking is that the embankment does not "feel" higher frequency motions.

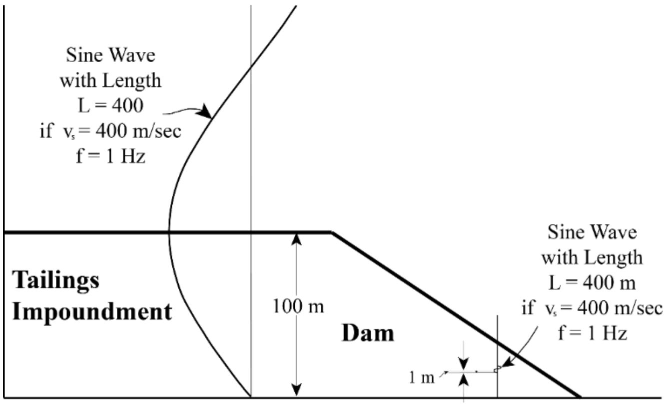


Fig. 1. Sketch to illustrate example calculation.

But what if uncontrolled seepage, piping and erosion has created an unstable structure with much smaller dimensions?

- Say there is a patch close to or at the point of collapse with a characteristic dimension of 1 m (shown in Figure 1 as the small dot in between the dimension lines towards to the toe of the dam).
- Then the critical wavelength, L = 4 x 1 m = 4m
- And the critical frequency, f = $v_s$/L = 400 m / 4 m = 100Hz
- Thus, if this patch sees motions at 100 Hz, those motions will tend to promote resonance and might well trigger local collapse of the soil

fabric and/or the initiation of static liquefaction and then progressive failure of the entire face of the dam.

This is similar to what happens in a modern high-rise building in an earthquake. The building structure is not affected by higher frequency motions, but sensitive equipment with higher natural frequencies might be.

This example is not proof positive of the mechanism of any particular past failure, but an illustration of the fact that the critical frequency, or range of frequencies, might well be quite different for a relatively uniform, well-constructed embankment or tailings impoundment, and one that has patches in it whose failure might lead to a larger progressive failure. Any individual case would likely require a very detailed and sophisticated numerical analysis to model both the triggering mechanism and the development of a progressive failure. It may be that discrete particle analyses would be helpful in this regard.

But such analyses will always be difficult, either as a forward prediction, when detailed explorations in the vicinity of an incipient failure might be challenging, or as a post-failure analysis, when the precise geometry and materials involved have disappeared.

However, this mechanism should not be excluded from the list of possible triggers of progressive failure, and it may have been significant in both the Cadia and the Fundão failures. And it illustrates one of the several reasons why it is desirable to avoid situations where the margin of safety against failure is very small and it is not possible to evaluate what that margin of safety is with any precision.

In addition to not recognizing that it is just small patches in a dam or tailings impoundment whose failure might trigger a much larger progressive failure, there are several other reasons why the significance of higher frequency motions has been downplayed in the past. Older strong ground motion records do not show frequencies as high as 100 Hz because the recording instruments that were used could not record them. However, modern instruments show that such frequencies exist at least at short distances from the source and in hard rock. An example is shown in Figure 2 which is taken from Gail Atkinson's contribution to the Cadia Panel Report. These spectra were constructed by Dr. Atkinson, as described in the report, and at the higher frequencies they are consistent with records obtained on three-component geophones at the site. However, those records had relatively low spectral accelerations at lower frequencies because of the diminished response of the geophones at lower frequencies so that lower frequency motions needed to be added to the recorded motions for use in subsequent analyses. These higher frequencies can also be recorded using modern digital seismic recording devices.

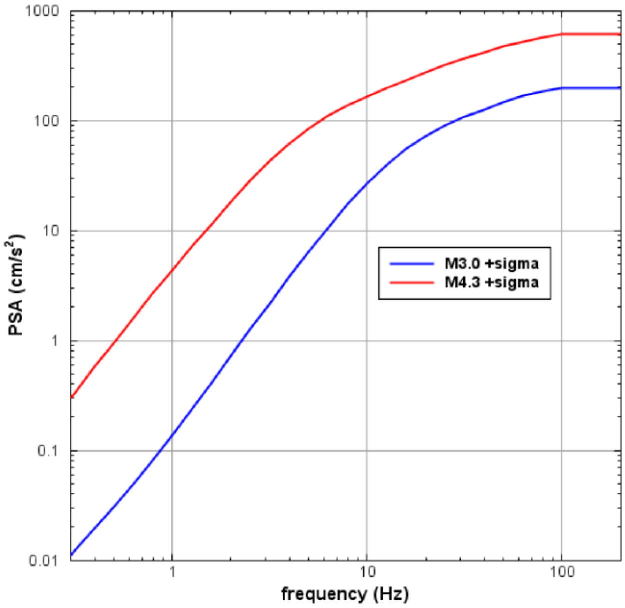


Fig. 2. Inferred spectrum in hard rock at the site for magnitude 3.0 and 4.3 earthquakes at a distance of 5 km. From Morgenstern et al. (2019).

Additionally, even if higher frequencies were included in the input motions applied in analyses of the response of earth structures they would normally be filtered out, either by the mesh that is used in the numerical model or by overdamping of high frequencies. This overdamping always occurs in equivalent linear analyses and may occur using many nonlinear soil models, particularly those that add viscous damping in order to model the damping at low strain levels which is observed in laboratory tests and can also be interpreted from field measurements. Thus, the conventional wisdom is that higher frequency motions do not affect earth structures, but while that might generally be true, it may not be true in specific instances.

On the question of whether higher frequency motions can actually transmit through soils, it should be noted that higher frequency waves have small amplitudes and they generate relatively small or even zero hysteretic damping. Thus, they can propagate through soils. This is why downhole and crosshole measurements of shear wave velocity and other geophysical measurements can be made even in soft soils when the sources that are used generate waves with a dominant frequency in the order of 100 Hz. However, energy losses due to reflection, refraction and geometric damping are generally more significant than material damping. That is why micro-earthquakes are not felt at other than short distances from the source, but if these motions reach the site, they can propagate upwards into earth structures.

It does not matter for present purposes whether the mechanism of failure of the Fundão Dam was exactly that proposed by the expert panel, or by Stark, or whether there was a patch that was on the verge of failure as a result of uncontrolled seepage, piping and erosion. The point is that any of these mechanisms involve relatively small patches whose response to earthquake ground motions might be different from the response of the entire embankment, and that that patch is potentially more sensitive to higher frequency motions.

## 4 ANALYSES OF PROGRESSIVE FAILURE

All three of these failures have correctly been described as progressive failures in which static liquefaction likely played a major role. Progressive failure is a mechanism where a failure at one location causes load-shedding to adjacent materials and the failure surface progressively enlarges until there is a total collapse. This kind of failure can be modelled in large strain finite element or finite difference calculations or with the Material Point Method (MPM), but these methods of analysis are time-consuming and may require a much greater effort to collect appropriate data.

Progressive failure cannot be modelled in conventional limit equilibrium slope stability analyses because the factor of safety is, by definition, the same at the base of each slice in 2D analyses, or each column in 3D analyses. Conventional limit equilibrium analyses are not very helpful in studying the risk of progressive failure and both operators and regulators are basically just guessing what overall factor of safety is sufficient to reduce the risk of failure to an acceptable level. However, some insight into the progressive failure mechanism can be obtained by using the Ordinary Method of Slices (OMS) or Columns in which the local factor of safety can be obtained at the base of each slice or column. This method of analysis also has the advantage of not assuming that the potential sliding mass is a rigid block, something that is quite unlikely to be true for embankments constructed of tailings. Pyke (2017) provides some additional discussion of these points.

## 5 CONCLUSIONS

The three failures cited as case studies in this paper were located in regions that are not considered to have significant seismicity. This may explain why operators continued to use cheaper upstream methods to construct tailings disposal facilities when a combination of economic and regulatory actions had ended this kind of construction elsewhere.

The conventional wisdom that higher frequency earthquake motions are not “felt” by embankment dams or tailings impoundments is generally correct for well-constructed, relatively uniform embankments, but is not necessarily correct for a non-uniform embankment that includes patches that for other reasons might be on the verge of failure. It is plausible, even likely, that higher frequency motions generated by small local earthquakes played a role in triggering two of the three failures cited in this paper. The Fundão panel acknowledged this, and the only difference between their findings and the author’s opinion has to do with the modeling of the mechanism of the triggering of accelerated movement. In the case of Cadia, the small earthquakes occurred the day before the failure, but it is not unlikely that they contributed to the failure mechanism described by that panel. The Newmark analyses that are cited in the panel report as the basis for ruling out a seismic contribution to the triggering process are not persuasive.

These failures also provide good examples of why engineers should avoid getting in a borderline stability situation as a result of uncontrolled seepage or any other issue. Even in an area that does not have significant seismicity, small earthquakes or mine blasts may trigger progressive failures. Perhaps less frequently, this mechanism of failure might also apply to water-retaining embankment dams.

An even more general conclusion is that even with modern numerical analyses it is not easy to make accurate forward predictions and to assess the true margin of safety in borderline stability situations. That problem can best be controlled by commonsense design and construction procedures, but it is also why spending money on better site investigations and monitoring is generally a good investment.

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