# Transcript of Video Presentation by Dr. Peter K. Robertson, Ph. D., Chairperson of the Expert Panel on the Technical Causes of the Failure of Feijão Dam I

My name is Dr. Peter Robertson. I am a retired professor of geotechnical engineering, and I'm the chair of a Panel of four geotechnical experts assembled to investigate and determine the technical causes of the tailings dam failure on January 25, 2019. As experts, we used our professional judgment and expertise in conducting our investigation and in reaching our conclusions.

At the outset, I want to say that all of us serving on the expert panel fully appreciate the important responsibility that we have undertaken. Fortunately, in doing our work, the expert panel had access to an enormous quantity of data about the dam — including full, clear videos of the dam collapse. That wealth of information has allowed us to reach certain conclusions. But I caution that we are engineers, trained to understand and explain how things work — not experts on corporate and risk management. For that reason, our mission was limited to determining the technical causes of this failure. Others will address the question of any responsibility as well as make recommendations to prevent such tragedies in the future.

As this video shows, shortly after noon on January 25, 2019, an iron ore tailings dam near Brumadinho in Brazil suffered a sudden and catastrophic failure, resulting in a mudflow that travelled rapidly downstream.

As shown on this slide, the technical findings of the Expert Panel can be summarized as follows: the dam failed when the tailings experienced a sudden and rapid strength loss known as flow or static liquefaction. The dam was essentially too steep and too wet, and the material in the dam was loose, saturated, and very heavy and brittle. The failure of the dam was due to internal creep strains that when combined with a small reduction in strength in areas of the dam due to infiltration from accumulated heavy rainfall caused the flow liquefaction to occur. Now let me explain what all of that means.

Our assessment of the technical causes should start with an understanding of what this dam was. Most people think of dams as earthen or concrete structures designed to retain water in reservoirs. In water-retention dams, the structure must <u>not</u> allow water to pass through — it must be water-tight or, as we say, impermeable to retain the water. That's not the kind of dam we are talking about here. This was a tailings dam. It was designed to create a retention area to store mine tailings, which was the waste product of the iron ore refining process. In fact, most of the dam itself was made of tailings.

A tailings dam like this one should be designed and constructed to be sufficiently permeable to allow drainage of water out from behind the dam, particularly because the stored tailings contain a lot of water that must be allowed to drain, or in other words, allowed to slowly flow or migrate out from behind the dam. This slide shows a cross section of the dam, showing the high-water level in the dam. The absence of proper drainage creates a higher water level in the dam that reduces the ability of the material to resist load. This can undermine the stability of the dam. In short, water is the enemy in a tailings dam like this.

Construction of the dam started in 1976. It was subsequently heightened — or "raised" — several times by adding new layers on top of old ones. These raises increased the capacity of the retention area to allow storage of additional tailings. The 10th raise in 2013 was the last. Each raising used the upstream method of construction. That means that each raising was moved upstream or back from the starter dam, which was the original layer constructed in 1976. As a result, each successive dam raise was constructed over tailings that had been previously deposited behind the dam.

The original design and construction of this dam by Ferteco, a mining company acquired by Vale in 2001, did not allow for proper drainage. The starter dam itself was constructed to be essentially impermeable — it retained water instead of allowing it to drain. As the slide shows, the starter dam and the other raises combined with layers of fine tailings had low permeability, resulting in the water level being close to the surface at the toe of the dam. Also, the dam was located where a lot of water flowed into the retention area behind the dam and on to the dam due to runoff from the surrounding area, underground springs, and seasonal heavy rains.

Another flaw in the dam's original design was that its slope was very steep. When a dam has a steep slope, greater stress is placed on the material in the dam than if the slope was less steep. After the third raising, as you can see on the slide, a setback was constructed to reduce the overall slope of the dam, but the slope remained quite steep. Hence, maintaining the stability of the dam was a continuing challenge over the life of the dam because its original design and construction was not robust: essentially it was too wet and too steep.

The failure of this tailings dam was unusual because it was captured on high quality video. This slide from the image analysis of the video shows the location of the earliest visible movements of the failure. The initial visible failure began at the crest and continued down to an area above the starter dam. The failure extended throughout much of the face of the dam, and was over in 10 seconds. Nearly 10 million cubic meters of tailings were released in less than 5 minutes. These images show that the dam collapse was a flow liquefaction event. The heavy tailings material essentially turned into a liquid, collapsing the dam and flowing out rapidly.

The conditions necessary for flow liquefaction to occur are set forth on this slide and were present in this dam. The tailings in the dam were loose, largely saturated and were contractive – that is, they had a tendency to compress or contract when subjected to high shear stresses in the downward slope of the dam. The dam also had high internal shear stresses because it was too wet and too steep.

However, no tailings had been deposited in the dam for over two years, and efforts to reduce the water level were succeeding, albeit slowly. In the months before the collapse, the dam was ***not*** showing any signs of distress or approaching failure. There was no cracking, horizontal deformations, or excessive seepage -- even in the days immediately preceding the failure. The challenge for the Panel was to determine what caused the sudden strength loss that resulted in flow liquefaction to occur when it did. In other words, what was the trigger that caused the dam to fail?

We were surprised to determine that the tailings in the dam had a very high iron content — more than 50% — and a very low quartz content. This material was quite different from the tailings material of many other tailings dams that have been studied. It also was very different from the natural soils that exist in the many case histories used to guide most designs. We also were surprised to find evidence of bonding between the tailings particles because of iron oxide. Material of this sort is extremely brittle. As this slide illustrates, material bonded in this way, has a high peak strength, meaning it can withstand higher stresses than would normally be expected for tailings that have little or no strength loss. But when material that is bonded in this manner is subjected to forces or stresses over time, it can at some point suddenly lose most of its strength under undrained conditions. The slide also illustrates that the amount of deformation, or strain, required to trigger strength loss in bonded material can be very small.

Importantly, materials of the sort found in this dam can experience high "internal creep" rates when subjected to shear stresses like those that were present in this dam being too steep and too wet. Internal creep is a constant but slow process. When a material is susceptible to internal creep like the material here, it is initially stiff and strong, but vulnerable to very slow deformation.

As creep proceeds, the resulting strain can cause such material to reach a breaking point at which it would become incredibly weak very quickly — this is known as creep rupture. It is like when the metal of a bridge rusts over time, the otherwise strong metal eventually becomes brittle, and when it does, it easily breaks and falls away. The last car to drive over such a bridge did not cause the bridge to fail; it was the metal rusting that slowly, constantly caused the bridge to lose its strength.

Significantly, the bonding of the tailings due to iron oxide had the effect of making the dam appear to be stronger and more robust than it actually was – without the normal signs of distress or imminent failure. Further, the internal creep movements were so small that they would not show signs of distress on the surface or be a predictor of failure.

The Panel performed computer simulations that showed that the combination of internal creep strains and a small reduction in strength in the unsaturated zone of the dam above the water level caused this wet, steep and marginally stable tailings dam to fail on January 25, 2019. The computer simulations identified that infiltration into the dam from accumulated heavy rainfall, including the intense rainfall toward the end of 2018 – although not the trigger in itself – contributed to the failure by causing a small reduction in strength in the unsaturated material above the water level. This effect is referred to as loss of suction. This loss of suction and its resulting small reduction in strength in the material above the water level when combined with the ongoing creep strains, led to the failure of the dam on that day. This slide shows the failure surface from a computer simulation that matches what was observed on the video.

To summarize, the bonding of the tailings because of iron oxide created a stiffer, more brittle material that only required a relatively small strain to trigger strength loss and failure. The stresses in the dam caused by the dam being too wet and too steep were sufficient to cause ongoing creep strains. The evidence shows that the failure on January 25, 2019 was caused by a combination of ongoing creep strains and a small strength reduction due to loss of suction from accumulated heavy rainfall, including the intense rainfall toward the end of 2018. This was confirmed by advanced laboratory testing and computer simulations. These findings are not something that we have seen before in connection with other tailings dam failures.

The panel report and its appendices detail these findings. As the panel report also details, all other potential triggers were **ruled out** based on the available evidence. However, I would like to discuss briefly three events mentioned as possible triggers or causes.

First, blasting in the open pit mine at the site has been raised as a possible trigger of the failure. However, as shown in this slide we determined from an analysis of seismograph data that the blast that occurred in the open pit mine closest to the dam on the day of the failure did not occur until **after** the dam had failed. Therefore, blasting was not the trigger that caused the dam to fail that day.

Second, on the day of the collapse, drilling of a vertical borehole was underway on the dam. That drilling was part of a project in progress for several months to test soil and to install more monitoring devices. These boreholes were very small, only 4.5 inches (or 114 mm) in diameter. Significantly, on the day of the failure, the borehole drilling on the dam had extended below the tailings and had reached the natural foundation soil. Computer simulations have confirmed that the drilling of that borehole did not cause the failure. The borehole drilling would have had only a small, localized impact on the dam. Therefore, it was not the trigger.

Third, beginning early in 2018, deep horizontal drains or DHPs were installed in the dam in an effort to reduce the water levels. When DHP number 15 was being installed in June 2018, it caused a flow of water and fine materials — that is, turbid muddy water — to seep out of the dam for several days. This incident did not cause the dam to fail at the time and computer simulations show that it did not cause the dam to fail seven months later. The computer simulations demonstrated that the incident likely caused a hydraulic fracture, but it was a localized event that was insufficient to trigger global instability in the dam. We also believe that this event did not create a condition in the dam that persisted at the time of the failure.

For more information about the work and conclusions of our expert panel, I refer you to the panel’s report and appendices, which have been made public and are available at www.b1technicalinvestigation.com.