Remarks on Mariana and Brumadinho tailings dams' disasters (Minas Gerais, Brazil)

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Abstract. Inadequate layout and drainages galleries failures resulted in very poor tailings drainage in Mariana case. Seismic chocs of moderate magnitude occurred shortly before the reservoir rupture. Failure occurred at noon hours what allowed reasonable large escape of Bento Rodrigues village inhabitants and relatively small number of victims. At Brumadinho site a delayed and interrupted fill drainage process created a critical saturation state and sudden rupture by retaining water of the Feijao creek. A dangerously close location of the office and personal facilities provoked a large number of fatalities in this case. Heightening of the fill was interrupted at close to 80 meters.

Key words: *inadequate lay-outs in both cases, seismic shocks at Mariana site, deficient and poor drainage of erected fills in both cases*

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Краткий обзор катастроф, произошедших на намывных дамбах Мариана и Брумадиньо (штат Минас-Жерайс, Бразилия)

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Аннотация. Неадекватная планировка и отказы дренажных галерей привели к очень плохому дренажу хвостохранилищ в случае Марианы. Сейсмические удары средней магнитуды произошли незадолго до разрыва коллектора. Авария произошла в полдень, что позволило значительному количеству жителей деревни Бенту-Родригес спастись бегством, поэтому количество жертв было относительно небольшим. На участке Брумадинью отложенный и прерванный процесс дренажа при заполнении хвостохранилища создал критическое состояние насыщения и внезапный разрыв ввиду скопления воды из ручья Фейжау. Опасно близкое расположение офиса и частных домов спровоцировало при этом большое количество погибших. Глубина врезания в насыпь составила почти 80 метров.

Ключевые слова: *неадекватная планировка в обоих случаях, сейсмическое воздействие на дамбе Мариана, недостаточный дренаж на возведенных насыпях*

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Preliminary considerations

The Mariana dam disaster, also known as the Bento Rodrigues or Samarco dam disaster, occurred on 5 November 2015, when the Fundão tailings dam at an iron ore mine near Mariana, Minas Gerais, Brazil, suffered a catastrophic failure, resulting in flooding that devastated the downstream villages of Bento Rodrigues and Paracatú de Baixo, killing 19 people.

Three years after the Mariana dam disaster, on 25 January 2019, the tailings dam at the Córrego do Feijão iron ore mine, 9 kilometers of Brumadinho, Minas Gerais, Brazil, also suffered a catastrophic failure. The dam released a mudflow that advanced through the mine's offices, including a cafeteria during lunchtime, along with houses and farms downstream, resulting in 256 confirmed fatalities and 14 people missing.

The Fundão tailings dam, 110 meters high, was still in the process of rising, while the 81-meter-high Córrego do Feijão dam was already completed and in the process of maintenance and decommissioning with some complementary drainage services in progress.

Both tailings dams are located on rugged, mountainous terrain containing small but perennial watercourses that form the respective valley basins that were closed by the corresponding starter dams to accommodate the tailings reservoirs.

In the case of Fundão tailings dam, the starting dam was executed about 23 meters high [*Morgenstern et al., 2016*], and in the case of the Córrego do Feijão dam, the starting dam was approximately 18 meters high [*CBDB Publication and J.P. de Ávila, 2012*].

In both mines the iron ore was excavated by blasting and then transported for beneficiation.

The economically valuable ore was then concentrated by froth flotation, separating the inert and valueless waste, which was stored in reservoirs.

Water from the tailings portion used during transport evaporates into the atmosphere, seeps into the subsoil, and the remainder is drained superficially by system of horizontal and sloping drains and drainage channels built along the starting dam and usually repeated at the following elevations.

Otherwise, all the pulp is transported (drained or pumped) integrally to the reservoir tank where it initially experiences a coarse particle size separation between the weighted coarse solid phase (sand) or the underflow and the thin solid phase (clay) or the overflow.

The large portion or underflow is deposited in the reservoir near the crest, and the fine portion or overflow is freely drained over a low slope (beach) where selective deposition of the heavier grains occurs.

The remaining water evaporates, infiltrates or is drained out of the reservoir through an increased and effective surface drainage system.

Mixing of underflow and overflow material should be strictly avoided in these cases:

The first is a coarse, frictional and draining granular material $(u = 0)$, which is fluffy or medium in size.

The second is a thin, cohesive, waterproof $(u > 0)$ micro-granular material, plastic and yielding.

The mixture of these materials, if it occurs, makes the tailings mass mechanically heterogeneous, which favors the formation of shearbands, i.e., horizons of low shear strength, whose presence is detrimental to the stability of the tailings' regolitical mass.

Tailings dams have a dual function of retaining and waterproofing stored material, whether it is solid or liquid, or a mixture of both.

The structures which form the reservoir deposits of waste tailings from mining must integrate into their original environment in a stable, safe and durable manner.

The open pits that result from the dismantling of rock or ground masses by blasting are, in principle, the best place for the deposition of these tailings and residues of the beneficiation processes of ore extraction.

But existing availability and logistical interference often preclude doing so, resulting in the alternative choice of using existing natural depressions of the landscape for tailings disposal, or in the selection of new sites suitable for the establishment of these tailings deposits.

According to Jamialkowski [*2012*], flat areas, with large perimeter and surface, and located on layers of easily infiltrated and permeable soils, without natural watercourses, would be such an option.

But this solution is not always possible due to geographic, climatic, geotechnical and economic-financial reasons that cannot be ignored.

Thus, the implantation of tailings reservoirs in small valleys becomes an alternative to be considered.

In these cases, it should be noted that such sites considered for the implantation of the reservoirs generate a new geomorphological interference that is introduced in the environment and consists of:

(a) new configuration of the natural relief surface;

(b) new geostatic overload on the ground as a function of the stocked material height;

(c) adaptation of the drainage of the surface outflow of the inserted reservoir in the selected area;

(d) formation of the new water table and its regime by the insertion of the reservoir deposit in the chosen area.

Items (a) and (b) are quantities determined by the design of the dam itself and the reservoir that is intended to be implemented.

Item (c) is a semi-deterministic quantity due to the presence of the random factor of rainfall, and item (d) is a difficult, time-consuming and very expensive determination, which in practice almost always remains undefined and undetermined.

If any river basin has its surface and perimeter determined by the dividing points, the groundwater basin attached to it has the magnitude of its corresponding undetermined groundwater in terms of its extent and physical limits and magnitude, duration. and type of your percolation regime.

Thus, in small, relatively enclosed valleys that are used to receive the tailings reservoir, it is convenient to decouple the influence of the surface drainage and the subsurface groundwater from the tailings exclusively for the receipt of slurry or slurry drainage of these tailings introduced into it.

When there is a possibility of significant groundwater flow, it is a prudent solution to isolate the reservoir from possible saturation by this negative component of the water table.

The efficiency of the reservoir drainage system is greatly influenced by the tailings deposition method.

The possible processes cited in this case are as follows:

(1) - Introduction of the integral mixture (tailings and water) deposited by flow into the gutter or pumped under pressure from the dam crest;

(2) - Release of the integral mixture (tailings and water) into the reservoir by a spigot or from the dam crest;

(3) - Deposit of the obtained large tailings (semi-dry solid phase), next to the initial platform and later raised, throwing the fine tailings separately, pumping them to the reservoir of decantation, evaporation and infiltration upstream separated by a dam from the main retention dam.

(4) - Granulometric separation of the mixture by on-site centrifugation in two plots: the large, weighted and incohesive (“underflow”) and the fine, weightless and viscous (“overflow”).

These two plots are released: (a) underflow near the retention structure, and (b) overflow at the beginning of the selective deposition beach formed by the runoff.

Dimensioning the drainage system under these conditions becomes a tricky task, as a particular solution may be oversized to the tailings underflow but undersized to the overflow, or vice versa.

However, the participation of drainage in the process that ensures stability in the case of wet tailings deposition is undeniable and very important not only from the point of view of stability, but also from the point of view of ecology.

This can be seen by examining the balance between discrete and continuous temporal net discharges and the volumes stored in the reservoir by the initial saturation of interstitial voids and the supersaturation of virtual volumes that may occur above or below natural ground level.

The following inequality is written, which is valid for the entire period T of the reservoir existence and which, in certain cases, makes the condition of preliminary execution of the reservoir drainage imperative.

$$\left[\sum_0^T q_{rej}\,\Delta t + \left(\int_0^T q_{afl}\,dt - \int_0^T q_{efl}\,dt\right)\right] > [V_{res}(1-n) + V_{res}G_{Sat}(n)]. \qquad (01)$$

By manipulating inequality, we obtain the necessary condition of the dam and tailings reservoir stability, which appears in (05), as a function:

(a) discreet deposition rate of tailings $\left(q_{rej}\right)$

(b) - continuous total water balance of the reservoir determined by drainage $\left(q_{afl} - q_{efl}\right)$,

(c) - porosity of the tailings (n), and

(d) - degree of saturation (G_{Sat}).

$$V_{res} < \frac{\left[\sum_0^T \Delta t + \left(\int_0^T q_{afl}\,dt - \int_0^T q_{efl}\,dt\right)\right]}{[(1-n) + G_{Sat}(n)]} \leq 1, \qquad (02)$$

where V_{res} is the final reservoir volume (m^3) and T is the total reservoir lifetime (years).

The portion $\left(q_{rej}\Delta t\right)$ of the numerator sum represents the solid volume of discreetly deposited tailings (Δt) over the entire period T of the reservoir life.

The difference between the two integrals in parentheses represents the balance of the tributary and total effluent flows of all water entering or leaving the reservoir, considered continuous processes (dt).

Obviously, it is the water balance parameter, which appears in the numerator of eq. (06), which defines the degree of saturation and mass balance of the tailings deposited in the reservoir.

A short period of indifferent equilibrium (metastability) is verified if $\left(\int_0^{\Delta T} q_{afl}\,dt - \int_0^{\Delta T} q_{efl}\,dt\right) = 0$, which corresponds to the saturation degree $G_{Sat} = 1$ (liquefied saturated material) and occurs during the rapid release (Δt) of the liquid tailings pulp into the reservoir with the immediate onset of drainage which increases the stability of the massif.

The procedure reduces the degree of tailings saturation to $G_{Sat} < 1$ (nearly saturated liquefied material) and increases the stability of the tailings mass, $\left(\int_0^{\Delta T} q_{afl}\,dt - \int_0^{\Delta T} q_{efl}\,dt\right) < 0$, this negative water balance remaining until the next programmed elevation.

In the absence of drainage, the water balance becomes positive $\left(\int_0^{\Delta T} q_{afl}\,dt - \int_0^{\Delta T} q_{efl}\,dt\right) > 0$, which takes the degree of saturation of the tailings. to G_{Sat} >1, (supersaturated liquefied material) and brings the tailings mass closer to a structural collapse or rupture.

When there is an equality between the inflow and the effluent of the percolation flows, this time period represents a uniform and constant flow regime and corresponds to a stabilization and zero variation of the groundwater level.

When the inequality between the inflow and effluent flow occurs, these periods represent the transient percolation flow regimes, with the preponderance of the inflow over effluent or vice versa.

The rise (↑) of the water table corresponds to the increase in saturation level G_{Sat} >1, and the decrease (↓) of the safety factor Fs, which are both negative factors in relation to the stability of the massif.

If effluence predominates, a depletion of the water table occurs (↓) and the variation of the above parameters is in the opposite direction and represents an increase in stability (positive factors).

Given the above it is noted the positive influence of maintaining the predominance of effluent flows over the tributaries, where the mass of tailings is unsaturated $G_{Insat} < 1$, with the maximum moisture content near the viscosity limit $LV < (LL = 1)$, according to the previously mentioned suggestion by Komamura and Huang [*1974*].

During successive elevations of the dam, both the volume of the reservoir and its height increases over time.

If at the release of the "underflow" the deposited sandy material is fluffy, when decanted and sedimented it usually becomes thickened under the additional weight of the following heights, and over time it becomes thickened material.

The sandy material becomes more compact and approaches the state line corresponding to zero volumetric variation.

Following are various elements related to the ruptures of the dams and reservoirs of Mariana and Brumadinho dams, which have certain similarities, but also present some important differences.

The relationship between the height of the reservoir at rupture and the starting dam height presents an intriguing similarity, despite the differences in geographical locations, dams final heights, and employed heightening processes.

Obviously, this is an indication of the existence of a critical height ratio, and it indicates the necessity of restricting the heights of the dams constructed by the upstream progressive elevation method, as used in both Mariana and Brumadinho dams.

Sequentially raised tailings dams can be classified as upstream, downstream or centerline, according to the placement of the sequential raisings relative to the initial dam. Central and downstream raised dams are typically seen in traditional dams, designed for hydroelectric power plants or the like.

Dams raised by these processes can withstand the combined action of hydrostatic and ground pushes due to their robustness and the larger volume of material employed in their execution.

On the other hand, upstream raised dams that are constructed by hydraulic landfill processes rely on previously laid tailings as a foundation for the subsequent raisings.

In this method, the waste is drained and ideally its mass, initially metastable, becomes progressively more stable with the dissociation of the liquid phase.

In this case, where the dams have a higher height, say (± 100 meters), the construction of a drainage system before the reservoirs become operational is recommended.

Break of the Fundão dam (Mariana) and reservoir

The site chosen for the Fundão dam and reservoir form of a large amphitheater with an appreciable longitudinal slope along its inland waterways.

The drainage basin of the Fundão Stream and its four small tributaries develops parallel to the Germano Stream basin where a larger reservoir was built, described in the publication Tailings Dams in Brazil published by the Brazilian Committee of Dams and Pimenta de Ávila Consultoria Ltda. in 2012.

The Germano Stream reservoir was successfully constructed using the so-called drained stacking process of coarse sandy material placed in a semi-dry or semi-dry reservoir.

The silto-argylous fine material is pumped like a slurry and is discharged into the fines material reservoir where water is mainly eliminated by evaporation to atmosphere.

The process originally referred to as "dry stacking" has been successfully employed in bauxite mining, in tropical regions of the country and in smaller dams.

Apparently, in the case of iron mining, the fine material deposited at the Germano Dam would require a smaller volumetric concentration for pumping and launching in the reservoir, which is cited as 30 to 35% by volume, which would constitute dry stacking variant, but applied to iron ore and in this case is known as the evaporative drying disposal process.

The construction of the Germano dam and reservoir were the initial model of the Fundão stream dam and reservoir, but received downstream a drained stacking as a structural reinforcement suggested by Pimenta de Ávila Consultora Ltda.

Table 1. Similarities and differences between Mariana and Brumadinho dam failures

Mariana Dam	Brumadinho Dam
Total dam failure and complete reservoir emptying. Break time: 15:45	Total dam failure and complete reservoir emptying. Break time: 12:30 hours..
Heightening of the dam at a fast pace.	Heightening completed. Dam and reservoir in process of decommissioning.
Dam construction performed by draining coarse piles of tailings and by the dry stacking variant of the fines or drying method.	Dam construction performed by simultaneously releasing coarse weighted underflow mud and fine weightless overflow mud.
Drainage built from five watercourses by two outlying galleries, but proved ineffective.	Drainage diverted from the three small watercourses to the Dam VI reservoir but was interrupted after beginning of decommissioning.
Instrumentation: Not described in the publication; CPT and Piezometers Stand pipes (?).	Instrumentation: Inclinometers, Standby Piezometers and Surface Markers.
Seismic shocks from rock excavation blasts followed by natural seismic shocks of almost the same intensity	Rock excavation blasts, but no natural earthquake
Relationship between reservoir height and initial dam height: (110⁄24) = 4,58	Relationship between reservoir height and initial dam height: (81⁄17) = 4,76
Very large environmental damage from the inclusion of water from the Santarém reservoir downstream of the Fundão dam and its mixture with the mud. The Doce River was reached to its full extent.	Minor environmental damage that struck the Paraopeba River to its confluence with the Três Marias Reservoir (São Francisco River).
Animals and fish perished in large quantities	Animals and fish perished in smaller quantities
19 fatalities, most of them occurred at the dam's work site.	256 confirmed fatalities. 14 still missing and presumed dead.

The CBDB publication does not describe the dam and reservoir of Fundão Stream that had the participation of other consultants in its project.

The rupture of the Fundão dam and reservoir was the subject of a detailed analysis by the collegiate of consultants chaired by Professor. N. Morgenstern [*2016*], and composed by S. G. Vick, C. B. Viotti and B. D. Watts, with the collaboration of G. Atkinson [*2016*] in the seismology sector.

This report confines itself to pointing only to the probable causes of the rupture and determining to them the trigger(s) that initiated the process, without going into any other details except the purely technical ones.

The report considered the proposal by Pimenta de Ávila Consultoria Ltda. for the creation of a separate reservoir for the containment of the slender clay-like slime intended for stocking of the drained stacking of coarse sandy weighted deposits deposited in the semi-dry or semi-wet state, as valid and robust proposal.

But the following points should be noted:

(a) the process of concurrent release of coarse semi-dry / semi-dry material and fines slurry; (b) the process of phasic dissociation or water withdrawal only by evaporation which is a natural, inexpensive and uncontrollable process;

(c) previous experience with fine bauxite and non-hematite tailings;

(d) the positive previous experience was obtained with structures of height approximately three times lower than the Fundão dam.

The report is extremely parsimonious in information about the construction of the two peripheral drainage galleries that were apparently designed to drain the flows of the three small natural watercourses on the right bank and two, somewhat larger and located on the left bank of the Fundão reservoir.

No information is provided and obtained on the geometry, construction joints, extent, flow and discharge of these two drainage devices.

Its frustrated operation is the first cause of the other failures of this project, as it compromised the control and management of both the liquid phase of the mud and the natural flow of the basin streams.

Thus, due to lack of drainage, the deepest part of the reservoir was initially saturated.

The embankment of the starting dam was deformed but was restrained by the rockfill against the embankment.

Drainage of the massif is now carried out at a higher level by means of a draining mat and the kananets-type horizontal plastic drain, which seems not to have been a very suitable solution except for better judgment.

From this situation, the industrial water demand increased and a process of loss of control of the dam and reservoir elevation that was not interrupted but accelerated began.

At this time, the opportunity to build a two-stage retention dam (liquid and solid) of the tailings has been missed as the proposed initial drainage of the massif proved to be inoperative.

An indentation level was created for the deposition of the drained piling to perform the unsuccessful gallery restoration works in the left bank that resulted in its injection-molded filling.

Drainage of the deposited massif worsened and the level of saturation increased, which led to the use of spot drainage solutions where there was evidence of instability.

Even so, the monthly rate of rise of the drained stacking deposit continued to increase, as did the area flooded by mud, which favored the emergence of supersaturation by the rise of the water table.

In this critical phase an interpenetration of the two phases of the tailings, which should not happen, occurred.

The left bank massif in the reservoir became heterogeneous with layers of saturated plastic mud interspersed with the wet sandy layers, all of which were subjected to a rising geostatic gradient with the slope unconfined by the downstream side recess. Morgenstern's report points to the collapse trigger as either a side mud extrusion or a "squezzing effect" of the "slimes" material.

But the rupture of the Fundão reservoir dam also has the presence of a factor that cannot be ignored and which is presented in the same report and transcribed here.

These are the seismic aftershocks that occurred on November 5, 2015, due to the excavation blasts carried out at the Vale mine in the left bank (13:02) and followed shortly after (14:12) by natural seismic disturbances.

Both of these events occurred shortly before the dam rupture started on his left abutment.

The big question surrounding the rupture of the Fundão dam, which probably will never be answered, is: Was it the drainage stack overload and the mud-shearbands, or the natural seismic shocks what ultimately triggered the initial rupture?

Obviously, the lack of natural drainage of from the streams forming the basin, the negative effect of the mixture of saturated fine clay with squezzing effect, the very rapid raising and resulting saturation, all these conditions contributed to the eventual collapse of the dam. Nonetheless, the emergence of the latent instabilities ("shearbands") also contributed, as pointed out by Nova [*2002*].

Critical combinations of load and deformation were created, which even for infinitesimal load variation generate infinitely large displacements, that is, the collapse that occurs even in the region considered stable by applying the Mohr-Coulomb criteria.

Table 2. Natural Seismic Shakes and Digging Blasts prior to the Fundão Dam rupture. Apud Atkinson [*2006*] in Morgenstern et. al. report [*2016*]

Local time	**Shake Magnitude (Mw)**	**Distance from the Reservoir (km)**	**Nature**
13:01:49	2,1	2,6	Digging Blast
13:06: 06	2,3	2,6	Digging Blast
14:12:15	2,2	< 2	Seismic (pre-shake)
14:13:51	2,6	< 2	Seismic (main)
14:16:03	1,8	< 2	Seismic (after-shake)
15: 45			Beginning of dam rupture

The stockpile rupture occurred in two stages: at the left bank and at the abutment near Vale's exploration pit, and at the dam where the initial rupture gradually spread throughout the supersaturated reservoir.

The consequent damage to the rupture was a destruction of much of Bento Rodrigues village and other nearby sites that were hit by the tailings wave diluted in the water of the Santarém reservoir, unfortunately deployed in an inappropriate location downstream of the Fundão reservoir. upstream of urban agglomeration.

A large amount of the diluted mud filled the reservoir of the Risoleta Neves Hydroelectric Power Plant and then merged into the Rio Gualaxo, a tributary of the Rio Doce where it traveled all the way to the ocean.

Breaking dams and catastrophic runoff from reservoirs are events of disastrous consequences and great damage.

Human lives and the lives of other living beings are obviously not recoverable. However, these tragic events are not completely irreversible, but they take a long time to recover almost fully.

The toxicity of tailings is very relative, since the natural components of the earth's crust where everyone lives, such elements are not toxic at first. Its high concentration may even be toxic, but being diluted in large volume of liquid, it is no longer. The river system at the mud's path is the most affected, of course.

But its tributaries are hardly affected by the catastrophe that hits the mainstream and promote a slow recovery process that can take decades, according to the proper pace set by the natural environmental system. So, talking about the destruction and death of the entire Rio Doce river is a very pessimistic and dramatically exaggerated attitude.

Failure of the Brumadinho dam and reservoir

The Brumadinho dam and reservoir are described in detail in the previously mentioned publication of the Brazilian Dam Committee. The construction and elevation of this dam and reservoir was completed approximately 4 years ago.

The construction and elevation process used was the upstream raising method with the release of tailings mud from the crest of the starting dam and the subsequent raisings.

The natural flow of the Feijão creek was diverted and used in industrial flotation processes and in the transport and release of pulp into the reservoir by hydraulic means.

Dissociated water from the mixture was discharged as sludge that was apparently collected and drained into the auxiliary reservoir, conveniently located on the right bank, where it was stored by dam VI and used to concentrate and transport the pulp or pour downstream. This structure remained intact after the ruptured main dam.

Main dam I was instrumented and monitored as described in the above publication. The site chosen for the implementation of dam I and its reservoir structures is an area shaped like a small geological amphitheater of approximately triangular configuration, set on a slope and located in very hilly terrain crossed by the Feijão creek and its small tributaries.

a b

Fig. 1. Fundão Dam and Reservoir; (a) during construction and before rupture, and (b) after rupture and upon emptying of the reservoir

The length indicated in the dam crest project was 610 meters and the reservoir area 0.24 km^2. By roughly assessing the extent of the reservoir perimeter in contact with the natural slope terrain, we obtain approximately 1600 meters of indirect runoff contribution, eventually concentrated in three gutters and an undetermined contribution from the groundwater to approximately this same extent.

The surface affluent flow during the construction and elevation period was compensated by the effluent drainage of the slopes (construction) and mainly by the deviation of the main effluent flow to dam dam VI (industrial operational and water transport use).

Thus, during the elevation of dam I and its reservoir, the water balance was negative, which favored the effluent flows mentioned, maintaining the saturation degree $G_{Sat} < 1$ and maintaining the unsaturated and non-liquefied massif.

At the end of the construction of the dam, all the affluent flow was either sent to the dam VI reservoir and transferred downstream, or in the event that this transfer does not start to be absorbed by reservoir I, which reversed the water balance making it positive, which can be verified in photographs by the presence of the stagnant pools of water on the surface of the reservoir.

But in this scenario during all time the transient influence of the new water table affluent or effluent flow was not considered in the construction of the unsaturated reservoir I.
As the dam is raised, new groundwater percolated after each raise in reservoir level I, but with the completion of construction of this reservoir the new groundwater stabilized and became a static water table without percolation.

After a reasonable period of time (say three years), its flow reversed and it ceased being effluent, and became affluent relative to dam reservoir I.

At this moment, a growing process of dam I reservoir saturation began, which shortly before the rupture, reached a $G_{Ssat} > 1$ supersaturation level.

Evidently all these conjectures, although logical, need to be confirmed by observations of the percolation regime of the new groundwater and its interaction with the created groundwater of the reservoir I.

The Rain, Fluvial and Lysimetric Observation Protocols as well as their conjunction, take years to define the regime and hydrodynamic nature of groundwater percolation and are very costly. This kind of analysis was not done in this case, in our knowledge.

The artificial debris flow runout that resulted from the rupture was the flow of a non-Newtonian fluid with some natural or apparent viscosity.

Photographs that record the dam rupture clearly indicate that the breach occurred in two stages involving:
(1) a less viscous and more mobile material that searched the Feijão creek stream bed, and

(2) a more viscous and less mobile material contained by the starter dam and which has ruptured last.

This differential of rheological behavior is explained by the greater presence of water in rupture (1) and its lower presence in rupture (2).

In fact, the mobility coefficient (m) is the inverse of the viscosity coefficient (η), that is, the fluid that initiated the flow was less viscous, more mobile and therefore richer in water content.

It was concluded that:

(1) the non-Newtonian fluid was supersaturated and with the supersaturation degree $G_{Ssat} > 1$ and in

(2) the liquified fluid with the saturation degree $G_{Sat} = 1$.

Therefore, the rupture occurred due to the supersaturation ($G_{Ssat} > 1$) of the tailings due to the lack of adequate drainage of the stocked mass, which apparently failed to be done.

Fig. 2. Brumadinho Dam and Reservoir before rupture with the undrained water puddles on its surface

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