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Performance analysis for filtered iron ore tailings disposal

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Abstract

The generation of tailings is an inevitable concern of mining operations, since they are generated in large quantities and affect the environment both qualitatively and quantitatively. Rarely are minerals found pure in nature; generally they are found in small concentrations in raw ore, which requires processing to extract the metal of interest.

Among the various methods of tailings disposal, the most common at Brazilian mines is superficial disposal of tailings in the form of slurry, using tailings dams. These facilities must be designed and constructed to manage large quantities of water as well.

Regarding the mining of iron ore in Brazil, there is a trend of increased production of tailings, which has generated growing concern among companies wanting to minimise the environmental impacts and costs associated with the disposal and containment of such material. Thus, ways to manage tailings is a topic of great interest to mining companies, which have been looking for alternative disposal methods that are cost-effective and environmentally safe. Dewatering of tailings has become an attractive alternative that mitigates the environmental and social impacts of mining.

Beyond that, the new resolutions under the National Dam Safety Policy in Brazil, associated with lower filtering equipment costs and other advantages, make tailing filtration an attractive alternative to the current methods of surface tailings deposition, particularly when applied in other countries in areas where the availability of space and water is limited.

The objective of this paper is to show the result of a conceptual analysis of tailings disposal in the Iron Quadrangle region of the state of Minas Gerais, through a case study of the technique of filtered tailings disposal. The methodology of this work consisted of developing conceptual and hypothetical scenarios for modelling tailings disposal alternatives. These scenarios involved the use of the tailings filtration technique and the conventional technique used for tailings disposal in Brazil. The data used in this study incorporated the studies of process engineering conducted by Guimarães (2011) for evaluating dewatered tailings from the Iron Quadrangle. In this context, this paper also contributes to understanding of the geotechnical conditions for filtered tailings disposal and to prediction of the performance of this technique.

1 Introduction

According to Instituto Brasileiro de Mineração (IBRAM, 2011), iron ore currently ranks first on the list of products that generate Brazilian export income in the mining industry. Moreover, iron ore also ranks first in providing new investments in the mining sector for projects during the period from 2011 to 2015.

> *"Given the increasing socio-environmental demands at the Brazilian and global scenarios, investments are being promoted in technological improvement, seeking better quality products, lower costs and reduced negative effects to the environment. The facts here reported denote the need for increasing levels of production and quality of iron ore, concurrently with the complex supply of ore treatment plants and lower iron content, given the need for better use of the reserves. In this antagonistic situation, investments in research and technology are being made to ensure the maintenance of competitiveness and even survival of companies engaged in the exploration and processing of iron ore, in a scenario of global competition". (Mapa, 2006)*

A clear trend of increased production of iron ore tailings faces difficulties based on environmental agencies' imposition of licensing requirements for new tailings disposal areas. These difficulties are the result of official concern over the mining activity with regard to operational aspects, safety, and possible damage associated with dams that hold the tailings disposal reservoirs.

In September 2010, the Brazilian government established the National Dam Safety Policy, based on Law 12.334, applicable to the accumulation of water, tailings, and industrial waste, and created the National Information System on Dam Safety. In this law, a dam is defined as "any structure along a permanent or temporary water course for containment or accumulation of liquids or mixtures of liquids and solids, comprising the dam itself and its associated structures". The law defines the responsibilities and determines that the dam owner is legally liable for the safety of the facility. The dams are now inspected regularly and there must be a safety plan and an emergency action plan.

Based on these observations, it is necessary to study and adopt alternative methods of tailings disposal. In this context, the ideal arrangement would be one that uses the smallest area possible, reducing environmental hazards and offering better conditions for geotechnical structures used for tailings disposal, whether stacks or dams. This latter aspect is directly associated with reduced risk to the environment and society. As mentioned by Gomes (2009b), the ideal solution would be dewatering of tailings, a process still poorly understood and applied by Brazilian mining companies.

Tailings can be generated in different physical states – slurry, thickened, or filtered tailings – and each state results in different geotechnical behaviour. The technique of thickened tailings disposal, which consists of removing water from slurry, has been presented as a viable alternative for disposal, in view of the potential risks associated with slurry held behind dams and/or lack of control during the construction of these structures. However, although this practice is internationally recognised, it is not yet commonly used by Brazilian mining companies.

Davies (2011) mentions that the technique of filtering tailings is becoming increasingly common in many mines in the world. According to this author, there are more filtered tailings than surface paste disposed. Figure 1 shows the evolution of the number of thickened tailings facilities in the world up to 2010.

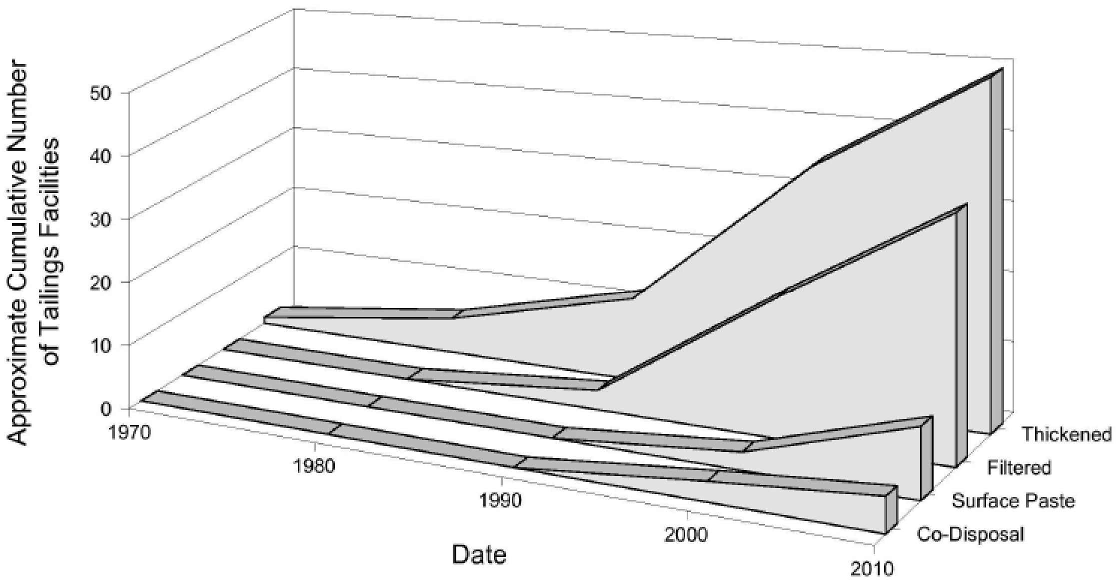

Figure 1 Trends in dewatering of tailings (Davies, 2011)

According to Araújo (2006), filtered tailings can be deposited in a stable structure, using the following process:

- Thicken soil to a concentration of 60%.
- Dewater with filters to reach the final moisture content.

- Transport the resulting cake by conveyors or trucks and distribute it with tractors.
- Compact with sheepsfoot roller in layers until it reaches a minimum degree of compaction, about 85% on the Proctor Compaction Test.

Percolation in a mass of filtered tailings is governed primarily by the unsaturated permeability characteristics of the mass; this reduces the saturation of this type of structure. Davies (2011) suggests that, in general, filtered tailings exhibit a 70–85% degree of saturation, enabling optimal compaction of the material.

Filtered tailings disposal is basically an earthmoving operation, known in the literature as dry stack. In this operation it is not necessary to compact all the tailings. It is possible to create a compact structural zone only in the region where potential surface rupture is critical in order to increase the shear strength of the material, as shown in Figure 2. This method also reduces operating costs.

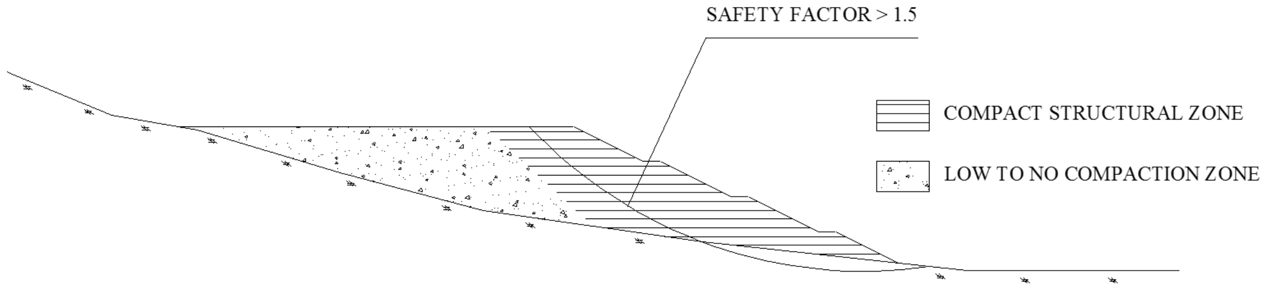

Figure 2 Dry stack cross-section (Lupo and Hall, 2010)

The constructive considerations for dry stacks differ from those for disposing tailings in the form of pulp, as generally practiced by miners in Brazil. According to Davies and Rice (2001), the main considerations are as follows:

- Site preparation: This involves implementing a surface water and groundwater collection and redirection system in order to avoid water contact with the tailings, minimising erosion and generation of acid mine drainage, if applicable. This 'clean' water can also be reused in the ore processing plant and pumped to a treatment station.
- Transportation and tailings disposal: This is performed with the use of conveyor belts or trucks. Due to issues of load-bearing foundation for trafficability, and considering that the moisture content of the filtered tailings can be just above the optimum moisture for compaction, it may be necessary to adopt an operational plan for tailings disposal.
- Reuse and water supply: A major reason for adopting the technique of filtered tailings disposal is the ability to reclaim water for the beneficiation plant. This advantage is very important in arid environments where water is a valuable resource. This involves the temporary storage of water behind dams.
- Reclamation and closure: This is the main advantage of filtered tailings disposal. The ease of progressive reclamation and closure of the facility is guaranteed because of the possibility of starting reclamation very early in the project life cycle. This can have many advantages in the control of fugitive dust, in the use of reclamation materials as they become available, and in the short- and long-term environmental impacts of the project.

According to Davies and Rice (2001), the La Coipa gold and silver mine in Chile has one of the largest filtered tailings facilities in the world (Figure 3). The site is located in a seismically active area and its structural integrity has been confirmed over the years.

Figure 3 Dry stack at the La Coipa mine, Chile (Davies and Rice, 2001)

Although the adoption of the filtering technique is more widely adopted worldwide compared with the technique of paste tailings disposal, there are very few technical papers published about filtered tailings, unlike the case of paste tailings disposal. Davies (2011) corroborates this statement and reports that the reasons for this are unknown. He also states that the absence of studies often leads to wrong decisions.

2 Methodology

For purposes of comparative analysis, we designed a conceptual and hypothetical case study for modelling tailings disposal alternatives, allowing the evaluation of scenarios for the disposal of pulp and filtered tailings and their impacts on the reservoirs. The tailing production data and input parameters for engineering the processes were obtained from Guimarães (2011). The author did technical and economic analyses of the various filtering technologies available for disposal of iron ore tailings generated in some processing plants in the Iron Quadrangle. Guimarães (2011) worked with three alternative process routes. We only used two alternatives of Guimarães (2011) because they involve filtered tailings. The third alternative was not adopted because it was designed to generate tailings in paste form as a product of sludge thickening, which is not the objective of this paper. The following is a summary of the results found by Guimarães (2011) and the assumptions made for the design of his three scenarios for tailings disposal:

- Dry stack (filtered tailings).
- Disposal of tailings in pulp form, using a dam built with compacted soil.
- Disposal of tailings in pulp form, using a cycloned tailings dam.

The methodology also included a literature review for geotechnical conditions of iron ore tailings to predict the expected performance of a dry stack.

2.1 Filtering tailings in the Iron Quadrangle

This subsection summarises the most relevant geotechnical aspects of filtering the tailings generated in the beneficiation plants of mines located in the Iron Quadrangle, as presented by Guimarães (2011).

He analysed samples from the main iron ore processing plants of the mining giant Vale S.A., as listed in Table 1. For each point in the process flow diagram, where there is tailings output, samples were collected and submitted to physical, chemical, and filtering tests at bench scale. The author's aim was to obtain the best alternatives for dewatering tailings (paste or filtered tailings), in terms of technical and cost benefits.

Table 1 Mining plants where Guimarães (2011) collected samples

Mining plants	Cities (State of Minas Gerais)
Alegria IB2/IB3	Mariana
Brucutu	São Gonçalo do Rio Abaixo
Cauê	Itabira
Conceição	Itabira
Fábrica Nova/Timbopeba (FN/TO)	Mariana
Pico – ITM A/B	Itabirito
Vargem Grande (VGR)	Nova Lima

Based on the results of the physical, chemical, and bench filtering testing obtained and his experience, Guimarães (2011) defined three alternative process routes for Iron Quadrangle tailings. He presented these alternatives in a case study, particularly focused on the Instalação de Tratamento de Minérios de Vargem Grande Project, ITMI VGR, scheduled to start operating in 2013, with generation of 1,025 t/h of flotation tailings and 546 t/h of slurry. The alternatives proposed by Guimarães (2011) are presented.

- Alternative 1 consists of separate thickening of flotation tailings and slurry. In this alternative, the flotation and slurry tailings are thickened and pumped to the filtration plant. The best technical and economical alternative for filtering the flotation tailings is the use of conventional disc filters, with moisture content of 12.0% for the cake. In the case of sludge, the use of horizontal filter presses is technically feasible, with a final moisture content of 20.9% for the cake.
- Alternative 2 consists of separate thickening of flotation tailings and slurry. After thickening, flotation tailings and slurry are blended and pumped to the filtration plant. Through a technical-economic analysis it was concluded that the best alternative for filtering the mixture of flotation tailings and slurry is the use of horizontal filter presses, with cake moisture of approximately 14%.
- Finally, Alternative 3 is the same as Alternative 1, except for the moisture content of the slurry. In this alternative, the slurry is initially thickened and then thickened again until it reaches a water content of 56%.

Guimarães (2011) states that, for the filtering to occur, it is necessary to apply a force incident on the particles; this can be achieved by gravity, vacuum, pressure, or centrifugation. In iron ore plants it is usual to use vacuum, which can be applied through conventional disc filters and horizontal filter presses, and positive pressure, which can be applied through pressure filters. Guimarães (2011) also notes that one of the main benefits of filtering using positive pressure is the production of cakes with lower moisture content compared with other filtering techniques.

2.2 Hypothetical scenarios for tailings disposal in the Iron Quadrangle

The data obtained by Guimarães (2011) were important in this study, as they made it possible to develop arrangements for disposal of filtered tailings.

For comparative purposes we developed three scenarios, as follows:

- Scenario 1: Dry stack, according to Alternatives 1 and 2 of Guimarães (2011).
- Scenario 2: Conventional dam, according to what is practiced in the segment for the disposal of pulp.
- Scenario 3: Cycloned tailings dam, also according to what is practiced in the segment for the disposal of pulp, segmented in grain and fine size.

For Scenarios 2 and 3, we developed an alternative called ‘conventional disposal’, related to non-dewatered tailings, where the tailings are disposed in the form of pulp. The process route alternatives considered are summarised in Table 2.

Table 2 Alternative process routes studied for tailings disposal in the Iron Quadrangle

	Alternative 1	Alternative 2	Conventional disposal*
Flotation tailings	Conventional disc filter Final moisture content: 12%	Horizontal filter press Final moisture content: 14%	Tailings disposed in the form of pulp Final moisture content: 100%
Slurry	Horizontal filter press Final moisture content: 20%		

*Final moisture content was calculated for 50% of solids content by weight.

2.3 Geotechnical conditions of iron ore tailings

Iron ore tailings are divided into fine and granular tailings. Despite the existence of the fine fraction in the tailings generated in the process of beneficiation of iron ore, the literature, such as Mendes (2008), Gomes (2009b), Milonas (2006) and Machado (2007), indicates that the fraction that controls the geotechnical characteristics of the iron ore tailings is the granular fraction. However, iron ore tailings do not behave like a sand, based solely on the particle size. The geotechnical parameters are also affected, for example, by the amount of iron present in the material, as indicated by Espósito (1995, 2000), Lopes (2000), Presotti (2002) and Russo (2007), among others.

Fine tailings are usually obtained after desliming iron ore during the concentration phase; these tailings are constituted of fractions of silts and clays. Lima (2006) notes that these tailings behave like thin plastics in general and are highly compressible. They can be carried through pipes in the form of slurry containing large amounts of water.

Espósito (2000) states that iron ore tailings are composed of hematite (10–15% solids content), with a density of solid particles (ρ_s) of around 5.25 g/cm^3, and quartz, with ρ_s between 2.65 and 2.70 g/cm^3. When performing a mineralogical characterisation of tailings from the Córrego do Feijão Mine, located in the state of Minas Gerais, Gomes (2009a) found that almost all the iron present was derived from quartz and that hematite was responsible for virtually all existing silica in the samples studied, although other minerals were also present at low levels.

Many studies have been conducted to learn iron ore tailings’ geotechnical properties. For example, it is known that the geotechnical properties of iron ore tailings vary as a function of iron content. This influence is widely discussed in the technical literature with respect to geotechnical characteristics. The following is an overview of some important data of iron ore tailings that have been published in the technical literature.

- There is a tendency for the friction angle value to stabilise as the iron content increases (Hernandez, 2002; Espósito, 2000).
- There is a tendency for increased friction angle with decreasing porosity or voids.
- For higher porosity, there is no greater variation in the peak friction angle with variation of the iron content (Fe). For denser materials, there is a trend of stabilisation (Hernandez, 2002), as shown in Figure 4.
- The effect of iron content on shear resistance and permeability tends to decrease as the void ratio decreases.
- The behaviour of loose to dense tailings is clearly distinguished, especially for low values of void ratio or porosity (Presotti, 2002; Hernandez, 2002; Russo, 2007).

- There is no significant difference in the friction angle obtained via direct shear test or triaxial consolidated drained (CD) (Russo, 2007; Espósito, 2000).
- For high densities, tailings will tend to behave in terms of residual strength (Russo, 2007).
- Compaction has a much stronger influence than iron content on tailings behaviour in terms of resistance (Presotti, 2002; Hernandez, 2002; Russo, 2007).
- The hydraulic conductivity of tailings tends to stabilise for high iron content, regardless of initial density (Espósito, 1995; Santos, 2004), as shown in Figure 5.

With regard to the parameters of shear resistance and characterisation of compacted iron ore tailings, there is little information available in the literature. Perhaps the reason is the absence of compacted structures with compaction control. The available data come from studies evaluating the applicability of this material for paving, which generally involves blending it with other materials such as waste rock. The following are some findings obtained from the literature (Fernandes et al., 2004; Abbade et al., 2010; Silva et al., 2010):

- For the Proctor and intermediate compaction tests, optimum moisture levels between 9.2 and 15.6% were obtained. The application of one or another energy level does not appear to significantly impact the behaviour of the compaction curve in terms of optimum moisture contents.
- With respect to the maximum dry density, values ranging between 1.88 and 2.84 g/cm^3 were obtained. This very broad range is probably because of variations in iron content.

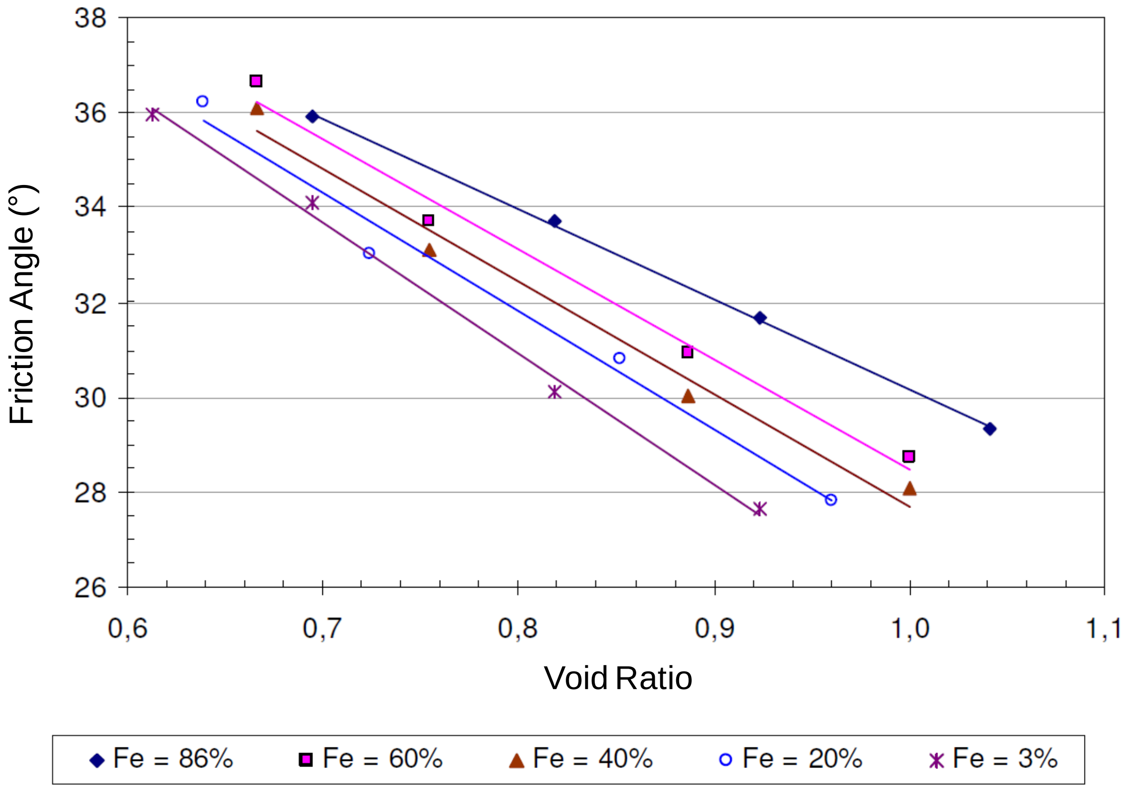

Figure 4 Variation of peak effective friction angle with iron content (Hernandez, 2002)

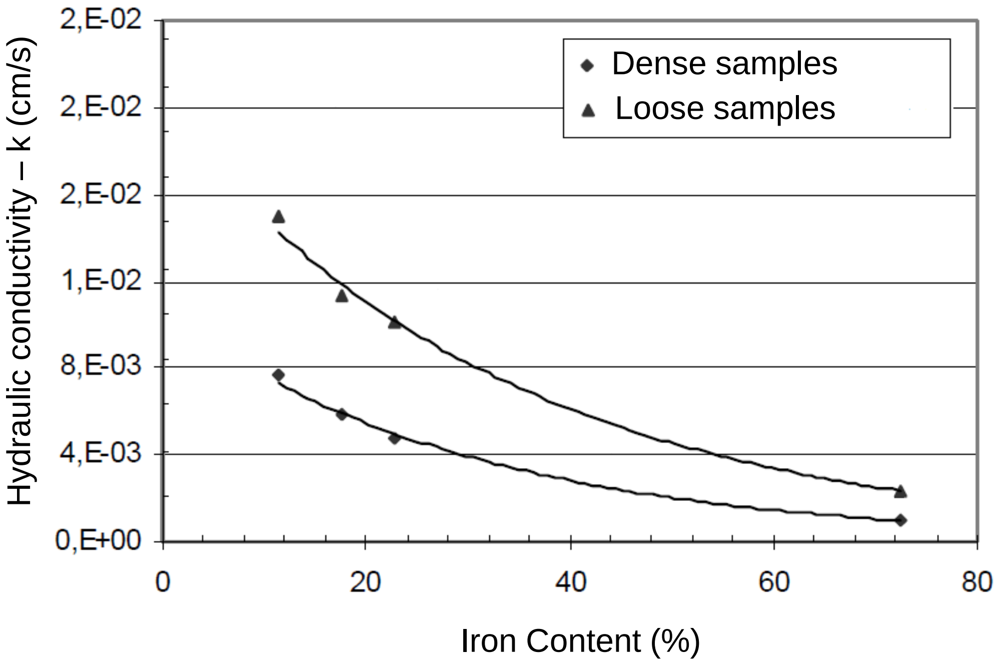

Figure 5 Influence of iron content on saturated hydraulic conductivity of iron ore tailings (Santos, 2004)

This subsection shows that it is possible to obtain safer structures compared to the current methods of surface tailings deposition common at Brazilian mines, reducing geotechnical risks. This is possible due to the reduced void ratios achieved.

3 Data

For preparation of tailings disposal scenarios, we adopted a hypothetical topography and a useful life of 20 years. Based on the data generated by Guimarães (2011), volumes of tailings to be disposed were calculated for each alternative. Therefore, it was necessary to adopt the void ratio for all alternatives and the solids content by weight for tailings in pulp form. The ITMI VGR project reported by Guimarães (2011) will generate 1,025 t/h of flotation tailings and 546 t/h of mud.

Given the uncertainty of the void ratio for tailings deposited in pulp form, a value between 0.7 and 1.1 is commonly adopted, according to current Brazilian practice in the design of pulp tailings dams (Welch, 2000; Mafra et al., 2011). According to these authors, the unit value can be used at basic level studies for tailings disposal in reservoirs. In this work, for the disposal method in pulp form, we adopted a void ratio of one, while for filtered tailings, we assumed a value of less than one.

For the density of solid particles, we applied the theoretical equation of Espósito (2000), shown below:

$$\rho_s = 0.026\ Fe + 2.65 \quad (1)$$

Where:

ρ_s = density of solid particles.

Fe = iron ore content.

According to Guimarães (2011), the iron content in the samples of sludge generated in a pilot plant with the future ore feed of ITMI VGR is 37.3%. Thus it was possible to obtain a density of solid particles of 3.62 g/cm^3.

We also assumed the solids content for tailings in pulp form. Mafra et al. (2011) states that mining waste is usually transported in pulp form with a solids content of between 30 and 50%. In this work, we adopted a solids content of 50%.

Table 3 presents production data, geotechnical characteristics, and the total volume obtained for each tailings disposal alternative, assuming a useful life of 20 years. These data are needed for the geometric scenarios for tailings disposal.

Table 3 Data from each studied alternative

Parameter	Unit	Alternative 1		Alternative 2	Conventional disposal
		Flotation tailing	Mud tailings	Blend (flotation and mud tailings)	Blend (flotation and mud tailings)
Moisture content at the filtered tailings plant output	%	12.0	20.0	14.0	100.0*
Moisture content of disposed tailings	%	12.0	20.0	12.0	100.0*
Nominal tailings production	t/h	1,025	546	1,571	1,571
Total tailings production	t	179,580,000	95,659,200	275,239,200	275,239,200
Specific gravity – Gs		3.62	3.62	3.62	3.62
Void ratio (e) of disposed tailings		0.6	0.75	0.7	1
Dry density (ρd) of disposed tailings	t/m^3	2.26	2.07	2.13	1.81
Volume of disposed tailings	m^3	79,372,376	46,244,088	129,255,978	152,065,856
Moisture content for saturated disposed tailings	%	16.6	20.7	19.3	27.6
Volume of water in disposed tailings	m^3	21,549,600	19,131,840	33,028,704	275,239,200
Volume of water retained in the tailings (100% saturation)	m^3	29,764,641	19,818,895	53,223,050	76,032,928
Volume of water that creates the tailings pond	m^3	-8,215,041	-687,055	-20,194,346	199,206,272

*for 50% of solids content by weight.

According to data shown in Table 3, the values found for maximum dry density lie within the range obtained from the technical literature (between 1.88 and 2.84 g/cm^3) for compacted tailings. The moisture content adopted for the filtered tailings refers to the moisture when the tailings leave the filtration plant. Although we chose arbitrary values for void ratio of disposed tailings, the values for maximum dry density are consistent with the data obtained from the literature for filtered tailings, which will be compacted in the field.

The following figure summarises the flotation tailings, mud, and water volumes that were obtained for each alternative. It is important to note the contrast of the lake formation when comparing the filtered tailings alternatives (Alternatives 1 and 2) with conventional disposal.

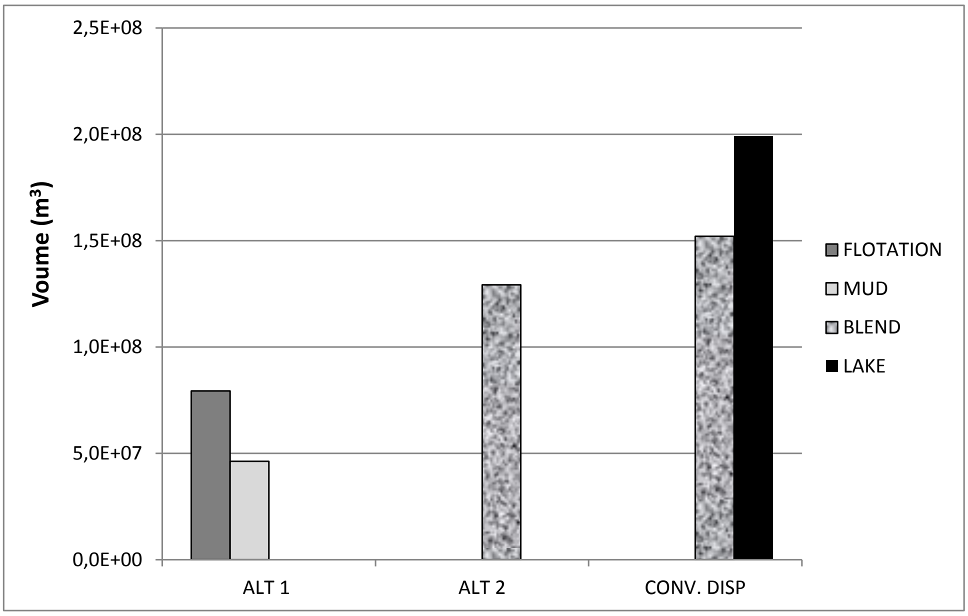

Figure 6 Alternatives and volumes

The tailings disposal scenarios were formulated after establishing the volumes and conditioning process. Filtered tailings (Alternatives 1 and 2) involve disposal in dry stacks. For these two alternatives, the volumes obtained were close to each other, so we combined them as a single disposal scenario. For conventional disposal, we created two different scenarios with tailings dams. The difference between these scenarios is in the construction method: one scenario uses a compacted soil dam and the other uses flotation tailings as construction material (cycloned tailings dam). Table 4 presents a summary of the volume for each disposal scenario.

Table 4 Volume obtained for each disposal scenario

Scenario	Filtered tailings (Alternative 1) Mm^3	Filtered tailings (Alternative 2) Mm^3	Conventional disposal Mm^3
1 – Dry stack	125.6	129.3	–
2 – Conventional dam	–	–	152.1
3 – Cycloned tailings dam	–	–	152.1

4 Results

The figures below show the obtained arrangements for each tailings disposal scenario. Table 5 summarises the geometry characteristics of each scenario. There are great advantages in the filtered tailing disposal, due to significant reduction to the area in the plan.

Table 5 Geometric characteristics for each disposal scenario

Scenario	Area (10^4m^2)	Height (m)
1 – Dry stack	168.8	276
2 – Conventional dam	288.7	216
3 – Cycloned tailings dam	237.2	211

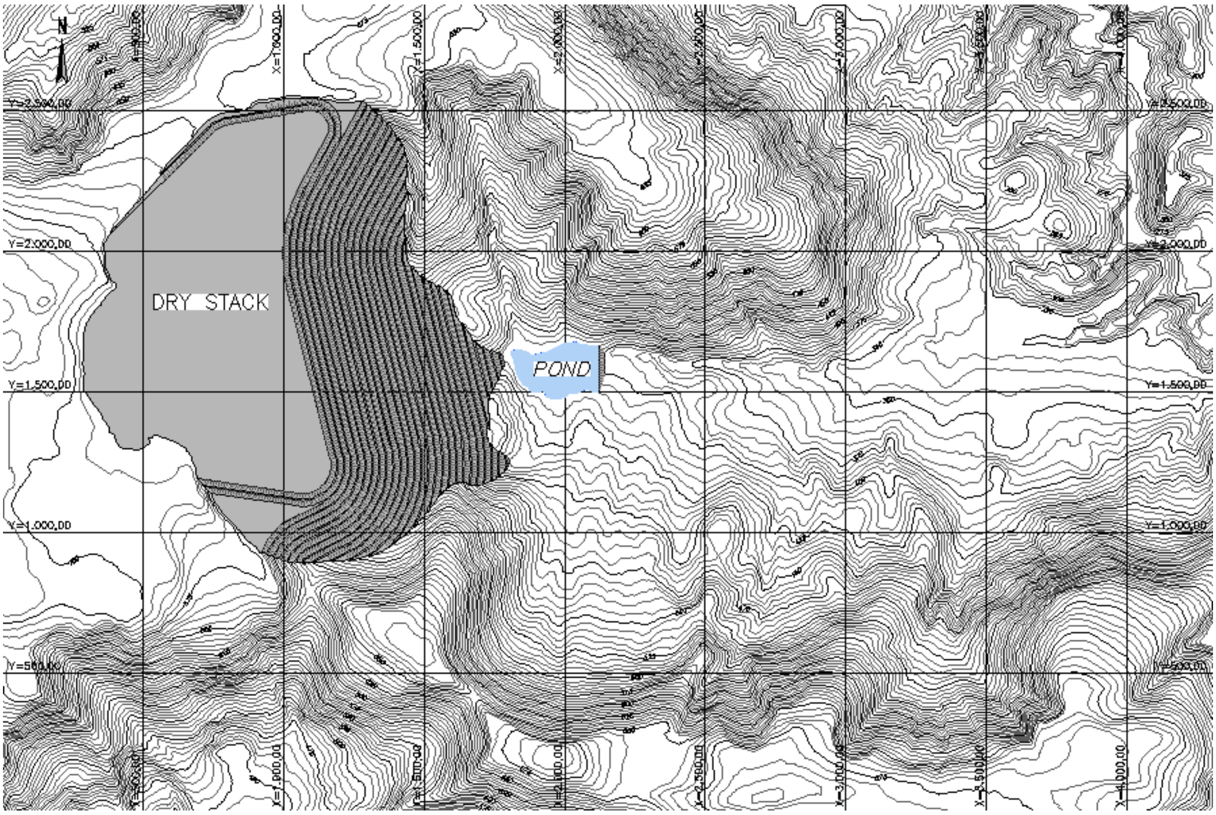

Figure 7 Scenario 1: dry stack

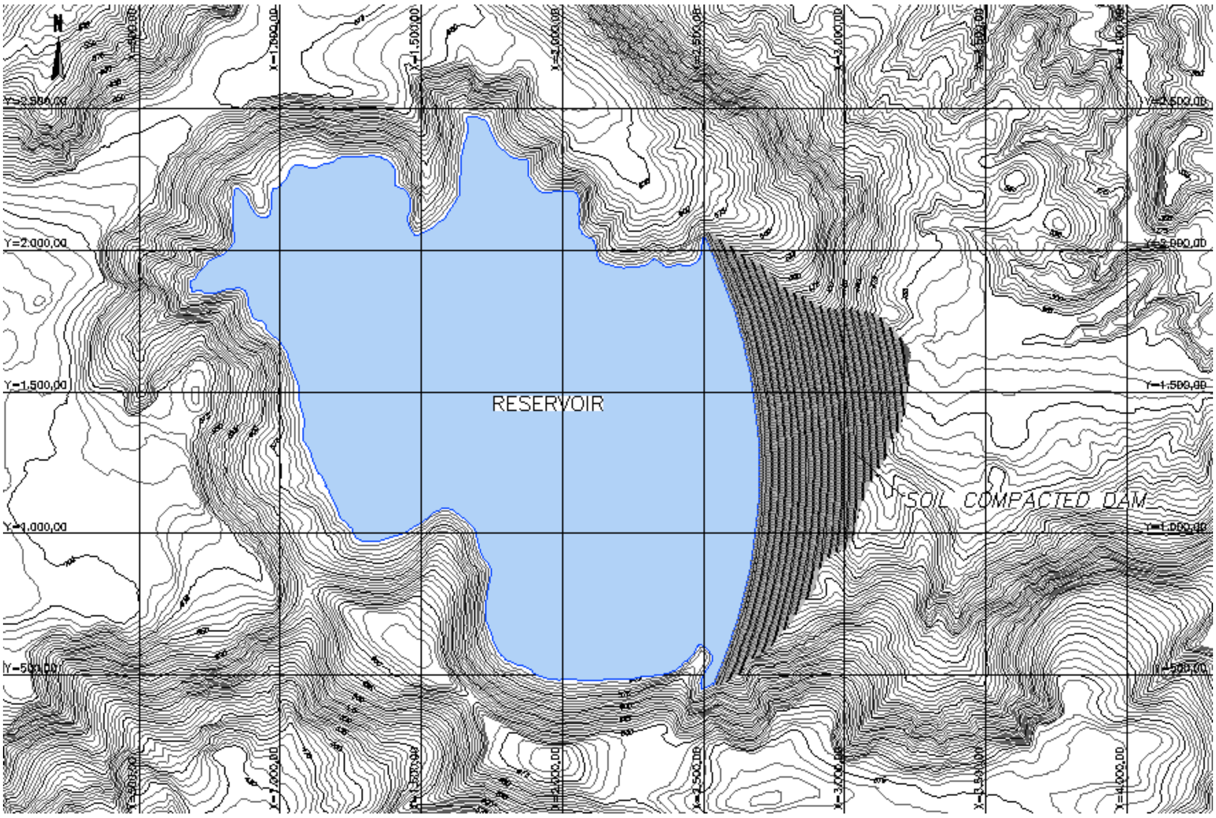

Figure 8 Scenario 2: conventional dam

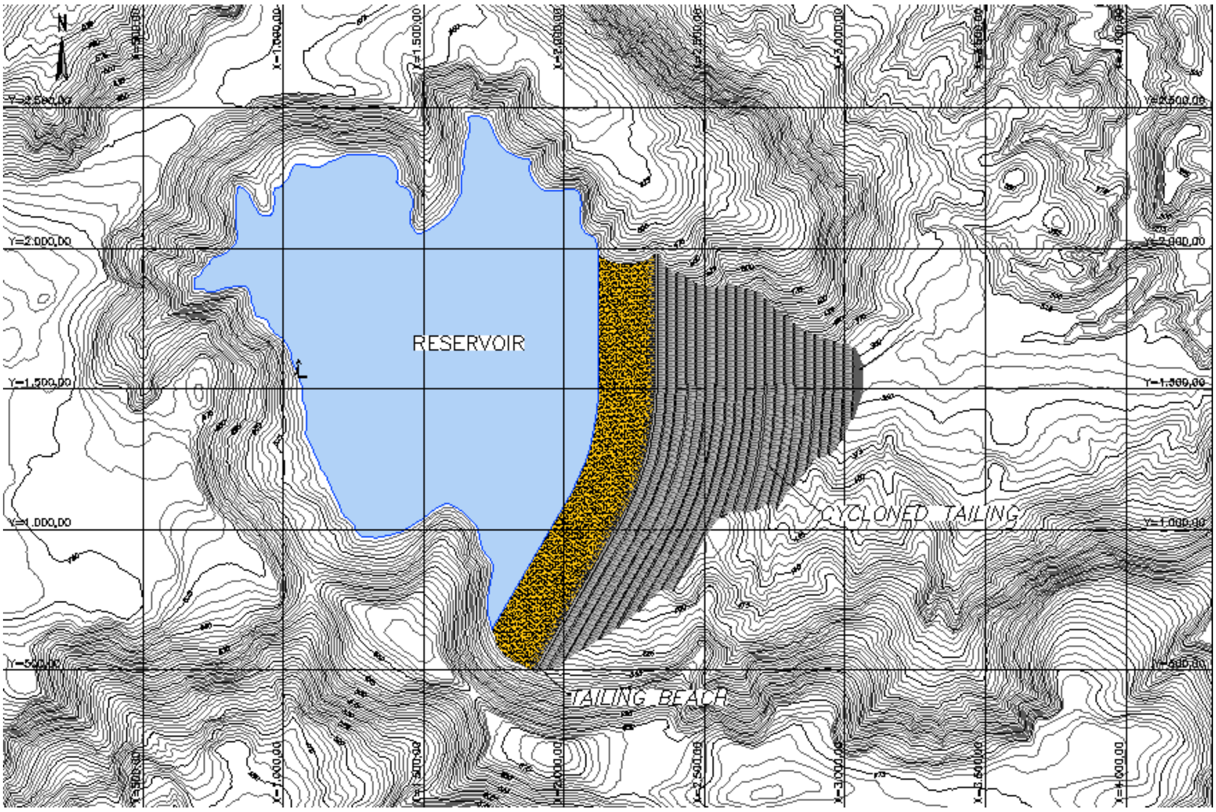

Figure 9 Scenario 3: cycloned tailings dam

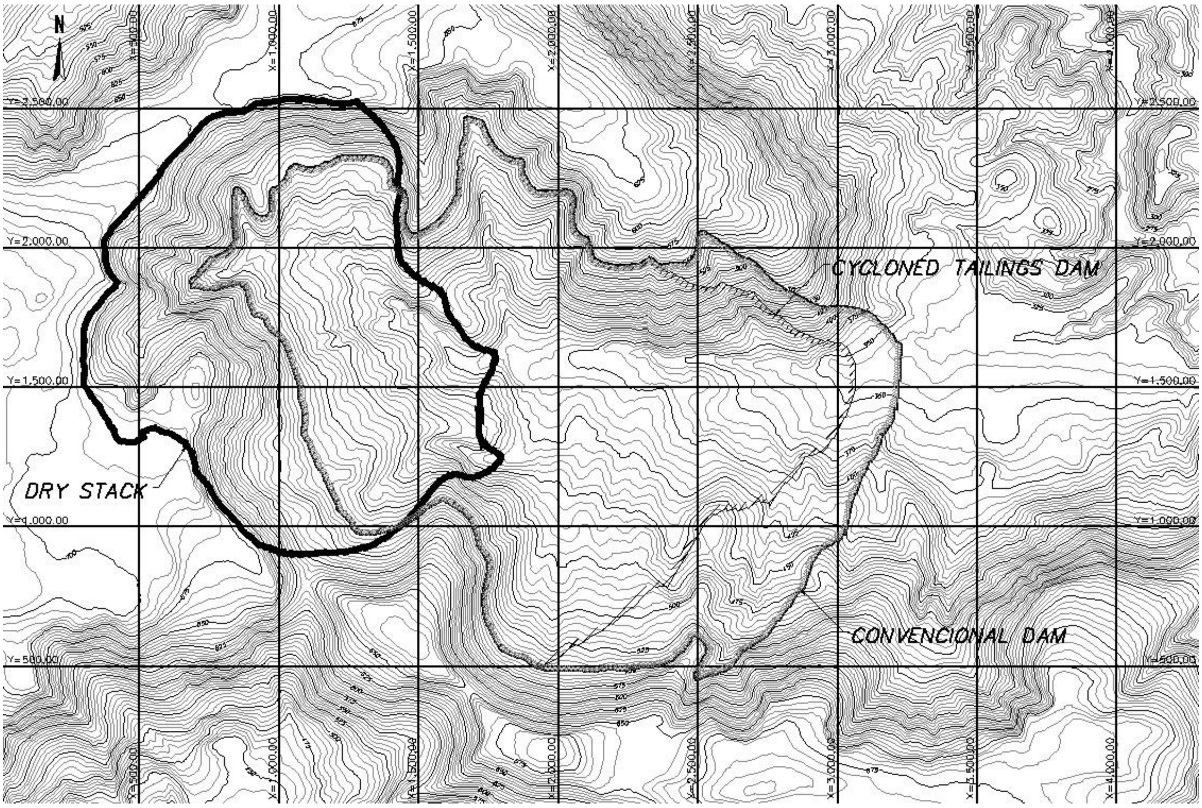

Figure 10 Scenarios 1: dry stack, 2: conventional dam and 3: cycloned tailings dam

5 Conclusions

This article shows it is technically possible to filter and dispose iron ore tailings from the Iron Quadrangle in dry stacks of filtered tailings. The studies presented here were based on the literature, so it was possible to predict, in general, the technical feasibility of dry stacking of iron ore tailings and its expected performance. Furthermore, the results show that compacted tailings provide better conditions for geotechnical stability compared to the construction of tailings dams.

The field compaction must be in accordance with the local water balance and can be performed as shown in Figure 2. In dry periods, it will be possible to execute the 'compact structural zone', which will serve to contain tailings to be compacted without control, forming a 'low to no compaction zone' during rainy periods.

Considering the parameters of shear strength and permeability that can be obtained for iron ore tailings with lower void ratio, it is possible to obtain safe structures for disposal of filtered tailings. It is important to note that projects must be preceded by field and laboratory tests in order to accurately predict the best technical and economic feasibility. In Brazil, research should be conducted regarding the following:

- Compacted iron ore tailings erodability.
- Unsaturated soil behaviour, for better understanding of the strength properties and percolation in a mass of compacted tailings, including wetting and drying curves and suction curves.

With regard to economic feasibility, each project must be studied separately. This study should also take into account reclamation and closure, which is not commonly done in Brazil. Still, more than economic feasibility must be considered in choosing the best alternative for tailings disposal. Other aspects that should be studied are listed below:

- Area available for tailings disposal.
- Potential environmental liabilities.
- Reduction of associated risks with tailings disposal in geotechnical structures.
- Reduced risk to the environment and society.

The addition of polymers for thickening tailings influences the geotechnical behaviour during disposal. Therefore, it is important to be careful when comparing the results presented in this paper against the real behaviour of the filtered tailings, given the chemical process to which this type of tailings is susceptible during the thickening process.

Acknowledgements

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