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A Promising Approach to Mitigate Risks on the Existing Tailings Dams in Brazil

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Abstract
Mining operations lead to the production of large quantities of mineral waste, such as fluid fine tailings whose disposal is rather challenging. In Brazil, tailings disposal is facing a critical situation due to the large accidents that took place in the last couple of years. As a response to these accidents, the Brazilian Mining Agency became stricter on licensing mining complexes and issued an interruption on activities on 56 tailings dams. In this paper, the authors propose a promising approach to minimize risks on the existing tailings dams hoping that the industry succeeds at mining avoiding social harms and environmental damages. The results presented herein showed that in situ electrical dewatering is a promising technology that offers many benefits. It can significantly increase the solids content of liquefiable tailings stratum within a short time. This leads to tailings masses possessing higher shear strength. As a consequence, this technology might well lead to safe tailing dams in Brazil bringing socio-economic and environmental benefits.

Keywords Electrokinetic dewatering · Tailings · Tailings dam risks

The leakage and dam failures of tailings could cause a series of ecological and environmental risks (Ke et al. 2021; Xue et al. 2022). Therefore, safe disposal of tailings is necessary. Tailing's disposal has been based on minimizing short-term capital and operating costs. As suggested by Williams (2014), this approach has led to the widespread adoption of surface storage facilities to dispose of tailings delivered by centrifugal pumps and pipelines. Tailings are normally pumped from the mill to the impoundment as a slurry that consists of approximately 25%–30% solids. At the impoundment, tailings are dispersed through cycloning or spigotting at several discharge points around the impoundment that are used sequentially to achieve size differentiation of the material. According to Kossoff et al. (2014), size-differentiated dispersal not only helps preserve the integrity of the dam by placing the coarser more porous material, a mixture of sand-sized and finer silt particles, in the structure itself but also results in the finer fraction, a clay-like particle, forming an impermeable barrier that aids to minimize piping and seepage across the dam structure. The authors also pointed out that this practice may lead to the possibility of a sub-horizontal water table forming.

A perched water table on the impoundment could cause the loose coarse tailings to become saturated. These coarse and saturated tailings when subjected to rapid shear loading, experience a rapid pore pressure increase and temporary loss of strength, which may lead to liquefaction. Such a stage, as Thevanayagam and Martin (2002) suggest, leads to slope instability. As a consequence, like Rico et al. (2008) pointed out, mine tailings dams fail each year.

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In Brazil, tailings disposal is facing a critical situation. On November 5th, 2015 Fundão Dam failed to generate serious environmental and socioeconomic problems. According to Aires et al. (2018), 34 million m^3 of iron ore tailings were released reaching Bento Rodrigues, a small sub-district of Mariana in the State of Minas Gerais, destroying more than 80% of its buildings and leaving a death toll of 19 people. Tailings also flowed to the Rivers Gualaxo do Norte (*circa* 55 km), Carmo (*circa* 22 km) and Doce (*circa* 600 km) and then reached the Atlantic Ocean on November 22nd 2015 causing enormous environmental damage as reported by several authors, including Quadra et al. (2019) and Cordeiro et al. (2019). In accordance to Segura et al. (2016), during tailings flow cities such as Barra Longa and Governador Valadares, on the State of Minas Gerais, and Colatina, on the State of Espírito Santo, had their water supply compromised. Some authors, including Carmo et al. (2017) and Burritt and Christ (2018), consider the collapse of Fundão Dam as the largest environmental disaster of the world mining industry.

On January 25th, 2019 another tailings dam accident took place in the State of Minas Gerais. Brumadinho Dam, in the metropolitan region of its Capital, failed to leave a death toll of 251 people and 19 are still missing. The failure is considered the largest labor accident in Brazil since the great majority of the fatalities were working on the mining premises at the time of failure (Souza and Fellet 2019).

As a response to these accidents, the Brazilian Mining Agency (ANM) became stricter on licensing mining complexes and issued an interruption on activities on 56 tailings dams, out of the existing 790 in the country, in the beginning of April 2019 as Ventura (2019) reported. According to the author, these dams had their activities impaired since ANM did not approve their Stability Control Declaration or their owners did not present adequate reports attesting their stability. The fact is that the geotechnical community in Brazil is afraid of issuing stability reports on tailings dams since the arrest of geotechnical engineers responsible for the Brumadinho Declaration of Stability Condition.

Tailings dam reservoirs are extremely heterogeneous since tailings are dispersed through cycloning or spigotting at several discharge points around the impoundment that are used sequentially to achieve size differentiation of the material. Hence, to mitigate risks on such structures it is necessary to employ a screening technique to map zones prone to liquefaction within the dam reservoir.

A screening method for the evaluation of the liquefaction strength of coarse materials was first introduced by Seed and Idriss (1971). The procedure use blow counts from the standard penetration test (SPT) correlated with a parameter that represents the cyclic loading on the soil called cyclic stress ratio. During the 1980s, Robertson and Campanella (1985) developed a similar screening method based on the results of the cone penetration method. Since then, both methods have been revised, updated and are extensively used by the geotechnical community. According to Andrus and Stokoe II (2000), an alternative screening technique is provided by in situ measurements of shear wave velocity Vs, since Vs and liquefaction strength are similarly influenced by many of the same factors (e.g., void ratio, state of stress, stress history, and geologic age). There are some concerns when applying Vs as an indicator of liquefaction strength in tailings since most seismic methods have not adequate resolution to detect very thin liquefiable strata.

An interesting approach to overcome this limitation is measuring Vs in situ employing the multichannel analysis of surface waves method (MASW). The MASW method, proposed by Park et al. (1999), is based on dispersive characteristics of surface waves. In layered media, as suggested by Bitri et al. (2013), the velocity propagation of surface waves depends on their wavelength since waves of different wavelengths sample different parts of the layered medium (e.g., short-wavelength waves propagate only in near-surface layers whereas high wavelength waves propagate not only through the near-surface layers but also deeper layers). So, as the authors suggested, by using surface waves over a wide range of frequencies, one can effectively sample different portions of the material profile.

Once a liquefiable tailings stratum is identified one could apply in situ electrokinetic dewatering to reduce its moisture content and increase its shearing strength. Electrodes could be pushed in the strata using a conventional geotechnical drilling rig to the desired depth and the process could be rapidly started by using a conventional direct current power generator. To extract the tailings leachates out the liquefiable tailings stratum it is necessary to install automatic double diaphragm pumping systems fitted with a fluid level sensor in each cathode since changes in pore water pressure must be kept as little as possible outside the liquefiable tailings stratum.

In this paper, the authors propose a promising approach to minimize risks on the existing tailings dams in Brazil hoping that the industry succeeds at mining avoiding social harm and environmental damages. It is generally believed that liquefaction potential could be mitigated by densification, drainage, and reinforcement. However, as Thevanayagam et al. (2016) pointed out, low hydraulic conductivity and coefficient of vertical consolidation for silty soils appear to adversely affect the soil densification process during dynamic compaction (DC) and stone column (SC) installation. The authors indicated that pre-installation of closely spaced wick drains might expedite the dissipation of excess pore pressures during DC and SC installation and enhance soil densification. On the other hand, some authors like Thevanayagam and Martin (2002) also suggest that liquefaction could be avoided by cementation/solidification by grouting. Herein, the proposed approach consists of minimizing risks associated with liquefaction through in situ electrokinetic dewatering.

Materials and Methods

Tailings were collected from Germano Mining Complex, where Fundão Dam collapsed in 2015. A semi-quantitative energy-dispersive x-ray fluorescence chemical analysis indicates that the aforementioned tailings are composed of oxygen (76.113%), iron (16.336%), silica (5.607%), and aluminum (1.814%), and manganese (0.131%). The typical properties of the tailings are summarized in Table 1. A picture of the Germano Iron Mining Complex tailings obtained from a scanning electron microscope is shown in Fig. 1.

Electrokinetics dewatering tests were carried out employing the system illustrated in Fig. 2. The system consists of a plastic water tank with a capacity of 100 L that houses electrodes and tailings sample, a 0–340 V DC power source to apply the voltage potential, an ammeter to measure the generated electric current throughout the tailings mass, graduated burettes to measure dewatering and a metallic ruler to measure settlement.

Additionally, a fall cone apparatus was assembled in the plastic tank to assess the change in the undrained shear strength of the tailing during the process of electrokinetic dewatering. Hansbo (1957) proposed to determine the undrained shear strength, s_u, from the cone penetration amount d (mm) of soil by the fall cone, as follows:

$$s_u = K\frac{W}{d^2} = K\frac{mg}{d^2}(\text{kPa}) \quad (1)$$

where W is the cone weight (N), m is the cone mass (g), g is the gravitational acceleration (9.8 m/s^2) and K is the cone factor. According to the BS standard BS 1377-2 (1990), the conical tip has a standardized weight and size (30° and 80 g) and the sinking time is 5 s. In these conditions, the cone factor (K) is equal to 1.0.

Plastic electrodes were used to mitigate corrosion generated by electrolysis (Fourie et al. 2007; Bourgès-Gastaud et al. 2017). Electrodes consist of anode rods with a height of 540 mm and a diameter of 17 mm and cathode rods with a height of 540 mm and a diameter of 28 mm. Cathodes have circular 10 mm diameter perforations lined with Whatman filter paper grade 1 to discharge effluent water with minimum turbidity. The elemental contents of the effluent were measured by an inductively plasma mass spectrometer.

To prepare the test, tailings were air-dried, smashed, and mixed with distilled water with an electrical conductivity of 13.52 μS/cm using an industrial blender to obtain a remolded sample with a moisture content of 63% (i.e., 1.3 times the tailings liquid limit). Then, the remolded sample was filled into the plastic tank with three cathodes and positioned, layer by layer, to minimize the occurrence of air bubbles. After filling the tank, three anodes were inserted in the tailings mass and the wire connections were fixed on the top of each electrode. The fall cone apparatus was then inserted

Table 1 Summary of tailings properties

Specific gravity	3.9
Gravel (%)	0.0
Sand (%)	12.3
Silt (%)	86.7
Clay (%)	0.9
Liquid limit (%)	25.1
Plastic limit (%)	18.7
Plasticity index (%)	6.4

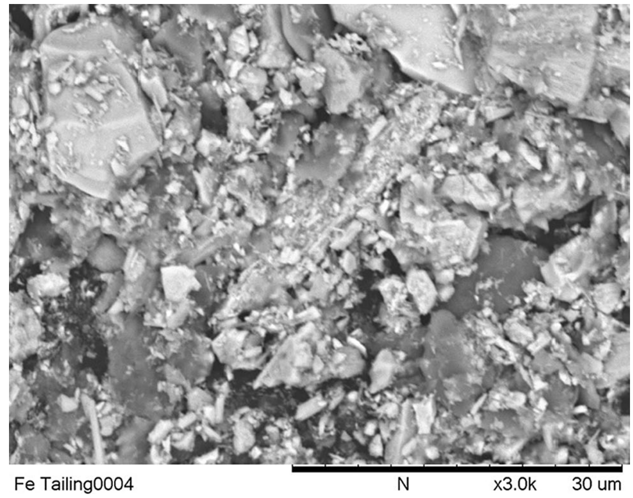

Fig. 1 Tailings from Germano Mining Complex

Fig. 2 Electrokinetic dewatering test setup

into the tailings mass. Experiments started by turning the power source on and ended when drainage has finished by switching the power off. During the test, the volume of the discharged water and the electrical current was monitored every 6 h. Additionally, a fall cone test was carried out at 24 h intervals. An elemental measurement was carried out to assess effluent quality parameters.

Results and Discussion

The efficiency of electrokinetic dewatering of iron tailings was analyzed and the effluent quality is compared from the perspective of the Brazilian resolution on effluent discharge on water bodies (CONAMA 2005). Specific items include water drainage, moisture and solids contents, undrained shear strength of iron tailings and settlement of the tailings mass during dewatering. Detailed descriptions of the results are presented as follows.

Figure 3 presents images of electrokinetic dewatering of Germano tailings with time under the voltage gradient of 7.5 V/cm. According to Bourgès-Gastaud et al. (2015), electrically assisted dewatering is sufficient to remove a significant portion of the interstitial and vicinal water that cannot be removed by mechanical dewatering that takes place under self-weight and under the weight of the overlaying layers of the tailings mass. The electrokinetic phenomena involved include the well-known phenomena of electrophoresis, electro-osmosis, and electromigration as indicated by Mahmoud et al. (2016). Under an applied electric field, cations from the external diffusive layer are attracted toward the cathode. As these cations move, they drag along bound water and the surrounding free water by viscous forces, thus creating a net flow of pore water towards the cathode. At the cathode, water could be removed from the tailings mass through drainage. In the case of Germano tailings, dewatering is improved by the presence of sand particles that could limit liquefaction during mining blasting operations by dissipating excess of porewater.

As Fig. 4 shows, dewatering increased with a declining rate and it is associated with the reduction of electric current in the tailings mass (Bourgès-Gastaud et al. 2015). It is observed that dewatering finishes when the amount of electric current passing through the tailings mass is very low (Bourgès-Gastaud et al. 2017). As the electrokinetic process takes place hydraulic fracturing occurs, as shown in Fig. 3, electric current is reduced (Hu et al. 2016).

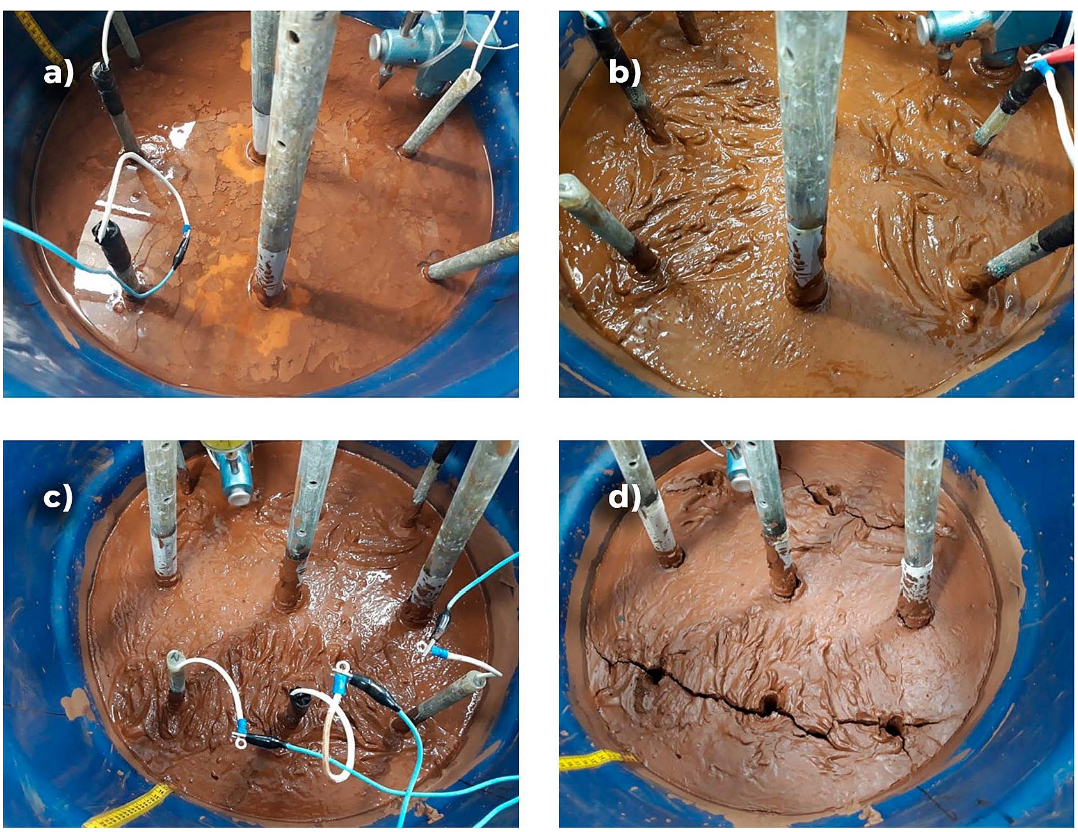

Fig. 3 Electrokinetic drainage of tailings with time: **a** 0 h; **b** 48 h; **c** 96 h and **d** 288 h

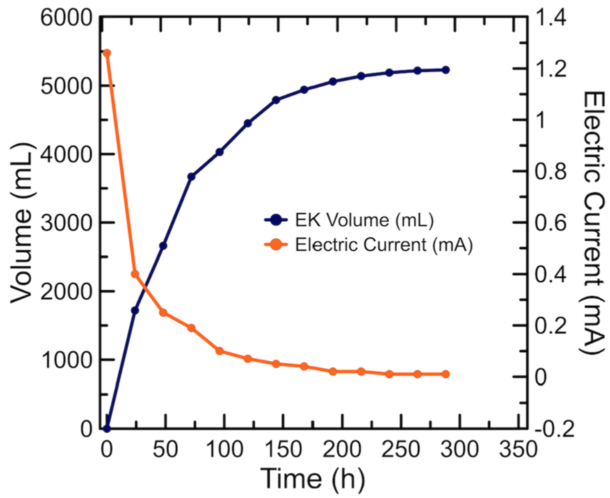

Fig. 4 Electrokinetic drainage of tailings: variation in drainage and electric current with time

According to Mahmoud et al. (2010), the initial reduction of the electric current is due to the chemical polarization of the electrode. The authors also pointed out that the long-term reduction could be associated with the tailings dewatering which causes the zone around the anode to become less and less conductive. The low voltage gradient tends to dry out the tailings around the anode, as seen in Fig. 3, but is much more energy-efficient as suggested by Lockhart (1983). It is also perceived that during the dewatering process tailings moisture content decreases with time, increasing the solids content to levels around 50% as shown in Fig. 5. The tailings mass near the cathodes shows a greater increase in soil solids compared to the soil mass close to the anode since the water molecules from the double layer move toward the anode (Vocciante et al. 2016; Menon et al. 2019; Martin et al. 2019; Mahalleh et al. 2021).

The relative volumes of water loss by evaporation were not as significant as the consequence of the electrokinetic drainage since tests were performed in a temperature-controlled environment.

On the other hand, the increase in solids content leads to a sharp increase in the undrained shear strength of the iron tailings mass as Fig. 6 shows. Final shear strength reached 25 kPa, which is well above the 10 kPa requirement of Directive 074 to be reached within 5 years after active deposition has stopped (ERCB 2009). This requirement for tailings performance criteria and requirements for oil sands mining schemes was issued by the Province of Alberta (Canada).

Test results indicate that changes in undrained shear strength occur due to the free water dehydration process induced by electro-osmosis, and to the adsorbed water dehydration process induced by electromigration. It was also observed that values of the undrained shear strength remained stable at the final stages of the electrokinetic process indicating a permanent tailings improvement. This phenomenon had already been described in the literature by several authors, including (Casagrande 1948, 1952, 1983; Bjerrum et al. 1967; Gray and Mitchell 1967, 1969; Gray 1970; Lo and Ho 2008; Lo et al. 2008; Micic et al. 2011).

To investigate the removal process of ions presented in the iron tailings by the electrokinetic dewatering process, the contents of Al, Fe, and Mn, as well as pH, were determined

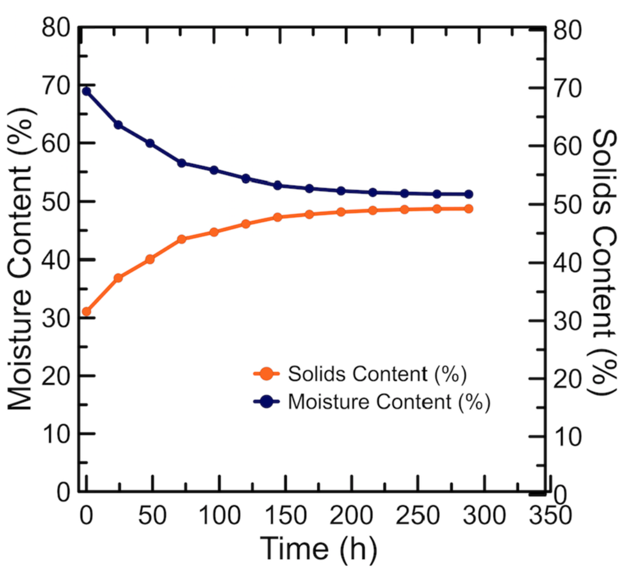

Fig. 5 Electrokinetic drainage of tailings: variation in moisture content and solids content with time

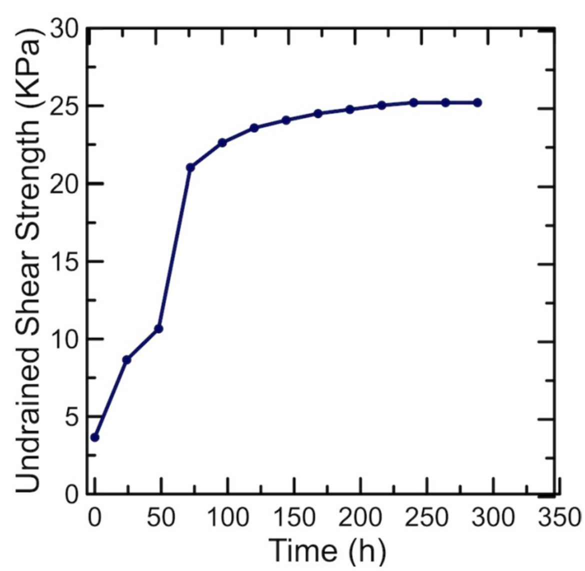

Fig. 6 Electrokinetic drainage of iron tailings: variation in undrained shear strength with time

Table 2 Effluent discharge parameters

Parameter	Effluent	Brazilian discharge standards
pH	7.9	n/a
Al (mg/L)	8.4×10^{-2}	n/a
Fe (mg/L)	1.4	15.0
Mn (mg/L)	4.2×10^{-2}	1.0

n/a not available

and compared to the effluent discharge standards set by the resolution #357 issued by the Brazilian Environmental Council (CONAMA 2005). Table 2 shows the results.

The results presented in Table 2 indicate that the effluent could well be discharged into a water body with no further treatment since the concentration of iron and manganese were well below the effluent discharge standards set by the resolution #357. It was also perceived that the application of a lower voltage gradient resulted in a lower pH rise of the drainage water at the cathode as suggested by Veal et al. (2000).

The results presented herein showed that it was possible to dewater iron tailings from an initial solids content of 31% to a final solids content of 49% with an energy use of between 0.37 and 0.85 kW h/dry ton. Veal et al. (2000) reported similar results (i.e., 0.6 kW h/dry ton) dewatering tailings from a sand mine from an initial solids content of 45%–67%. More recently, Fourie et al. (2007) and Bourgès-Gastaud et al. (2015) reported energy consumption of 1 kW h and 3.5 kW h per dry ton of material dewatered for fluid fine tailings employing electrokinetic geocomposites. When metallic alloys were used as electrodes, Wilmans and van Deventer (1987) reported energy consumption varying from 144 to 880 kW h per dry ton for dewatering ultra-fine kimberlite tailings. One should notice that dewatering could be achieved at lower costs by employing plastic electrodes since they induce lower current when compared to metallic alloys electrodes despite the magnitude of the applied voltage gradient (Sánchez 2018).

In conclusion, the decision to adopt a given technology to mitigate risks on existing tailings dams is often a compromise between many factors, including capital and operating costs, reliability, and environmental performance. Electrical dewatering as a promising technology offers many benefits. It can significantly increase the solids' content of liquefiable tailings stratum within a short period leading to tailings masses possessing higher shear strength. As a consequence, this technology might well lead to increasing in safety on the existing tailing dams in Brazil, bringing socio-economic and environmental benefits.

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