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Construction Processes Paradigm and Reinforcement Alternatives for Tailings Dam Soil

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Abstract

In the last decade, Brazil was the scene of two of the world's biggest disasters related to mining tailings dams. The collapse of the Mariana and Brumadinho dams was catastrophic event that brought to light major environmental and humanitarian crises. Facts like this incite debate on the safety of dam construction methods and highlight the need for a broad discussion of dam safety legislation in the country. From the above, this paper promotes a review of various forms of construction of tailings dams and their associated problems, as well as discusses the techniques for soil reinforcement and their construction methods. The work also brings an overview of the Brazilian dams from April to July 2019, tracing the context of the Brazilian tailings dams months after the tragedy of Brumadinho. The methodology includes a robust literature review and discourse analysis. In Brazil, the number of ruptured dams is alarming, especially in the state of Minas Gerais, in which more than 7 have broken in the last two decades. Among the damages, the deaths impact society abruptly and were cataloged 455 deaths, of which 216 correspond to the rupture of the dam of the Córrego do Feijão mine in Brumadinho. To evaluate and diagnose a dam, one should consider ordinance N˚ 70,389, 2017 revoked by Resolution ANM n˚ 95, of February 7, 2022. In this context, in March 2019, we experienced several disturbing situations regarding dam instability in the state of Minas Gerais, being categorized as risky structures. To exemplify, one can cite dams classified as level 2 risk that became level 3. Due to the above facts, several studies are being conducted to improve soil aspects. For example, we highlight the increase in soil resistance that can be done using commercial and alternative materials available in the environment.

Keywords

Dams, Reinforcement, Rupture, Minas Gerais

1. Introduction

Currently, the main methodologies for tailings dam raising are downstream, centerline or upstream, which is usually the most unstable [1] [2] [3]. For example, in 2015, the rupture of the "Fundão" dam in Mariana, built with an upstream elevation, occurred in the district of Bento Rodrigues [4] [5]. This disaster released 62 million cubic meters of tailings, causing a known number of 19 deaths and affecting more than 40 cities in Minas Gerais and Espírito Santo, reaching as far as the Atlantic Ocean [6]. Another example is the "Córrego do Feijão" dam in Brumadinho/Minas Gerais [7], which also used the same construction methodology upstream. Twelve million cubic meters of tailings were dumped into the Paraopeba River Basin, reaching the São Francisco River. The disaster that occurred with the "Córrego do Feijão", was cataloged: 216 deaths and 91 missing persons [8]. When the dam burst, shortly after 12:00 pm, 11.7 million m^3 of mining tailings were released, enough to fill 5000 Olympic-sized swimming pools [9]. In 2018, 50 structures were identified in the state of Minas Gerais with no guarantees of stability and at eminent risk [10]. It is worth commenting that society has experienced problems with dams for years, and in Brazil, this rate has been increasing since 2000, totaling 10 ruptures in this period until 2019; this suggests a rupture every 2 years [11].

When a dam breaks, it brings numerous environmental problems [12] [13]. Part of this is related to the iron ore tailings, waste from the beneficiation of itabirite, and the minerals contained in this rock are found in the earth's crust in the forms of magnetite (Fe_3O_4); hematite (Fe_2O_3), goethite (FeO(OH)) and silicates. The tailings can contain heavy metals in their fine fraction [14]. For the reasons addressed, dams are classified and categorized as to their risk and damage potential [15].

The categorization of a dam must meet the risk classification established by Ordinance Resolution ANM n˚ 95, of February 7, 2022 [16]. To perform this procedure, stability reports are used as a basis that considers criteria such as the method used and its potential harm to human life [17]. Based on this ordinance, dams in 2019 that were categorized with level 2 risk moved to level 3 in the same year [18]. The number of registered structures of tailings dams is growing and this year, 769 were registered [3] [19]. Of all the dams registered by 2019, only 55% were inserted in the National Policy for Safety of Dams—PNSB [19] [20].

In this context, research is developed to better understand the construction process and dynamics of dam operation, so it is possible to propose more competent methodologies and alternatives that will ensure greater massif stability and effective monitoring [2] [21] [22] [23]. However, by to the techniques currently available, the final cost of the work and most of the problems are associated with the use of low materials quality, that is, during its construction, when the soils (clay-C) are not available in the surroundings, other materials of lower efficiency are used. Parameters such as material type, availability, material quality, and distance from the quarry to the construction site are strategic criteria to subsidize dam construction. Most soils can be used, except organic materials, silts, ground rock, and clays with a liquidity limit above 80% [24]. For this reason, research is being conducted to characterize and soil reinforcement, regardless of its engineering application. Today, a strong current of research is working to create optimal and sustainable engineering alternatives for soil reinforcement [25]-[34].

From the above, this study has an objective present constitutes a bibliographical review of an analytical nature regarding the practices of building a dam, which involves a lot of techniques of geotechnical engineering within civil construction. Thus, the contextualization of dams within a time frame, the geotechnical problems associated with construction methods, and the application of types of reinforcement with the use of alternative materials to provide greater safety to the enterprise were worked.

2. Methodology

The collection of data surveyed was comprised between April and July 2019, and the Scientific Electronic Library Online (SCIELO), Science Direct, and Scopus databases were used for the search. The inclusion criterion was defined as: articles published between the years 2012 to 2019, because initial surveys identified that in the period prior to 2012, there was little exploration of articles that described in greater detail the practices, the consequences of rupture, and the use of reinforcement in dams related to alternative commercial or natural materials.

It was not the limited language in the attempt to obtain an appropriate amount of theoretical referential. The events that occurred in 2015 with the collapse of the "Fundão" dam in Mariana/Minas Gerais and in 2019 with the collapse of the "Córrego do Feijão" dam, were events that contributed to the study in question and the delimitation of the temporal period for analysis. Thus, the time cut (2012 to April 2019) is fundamental in the methodology of the work, so that a discussion about the context of tailings dams in a contemporary moment to the main dam accidents in Brazil can be made.

Due to the tragedies that have occurred, several researches have arisen to improve dam safety, especially in their construction phase. The literature search found that studies concerning the use of reinforcement in dams are recent, because there was not so much concern about the consequences that could come to light with a rupture.

This literature review included articles presenting data surveys about the number of dams in Brazil, the percentage of them located in the state of Minas Gerais, the problems related to the consequence of disruption, and the existing reinforcement alternatives according to research directed to this subject. In the search for scientific articles, we sought to match the inclusion criteria related to this study's objective in the journal Science of the Total Environment and NATURE with the descriptors Tailings dam and Dam. In the Scientific Electronic Library Online (SCIELO) and Scopus bases with the descriptors Tailings dams and Construction methods.

As results, 18 articles were obtained in the Scientific Electronic Library Online (SCIELO), of which all were in agreement with this study. In the journal Science of The Total Environment from the 374 articles found, only 5 articles were selected. In NATURE, of the 52 articles found, 2 articles were selected. In Scopus, of the 44 articles found, 8 articles were selected. In the application with the descriptor soil reinforcement, 2913 articles were found in Scopus, and only 4 articles were used. With the descriptor soil gray, 879 articles were found, with the temporal delimiter defined in the study, 4 were found.

To support the literature review, in addition to the research mentioned above, books on dam construction were consulted, as well as renowned magazines and regulatory standards such as the safety level established by Decree Resolution ANM n˚ 95, 2022 [16] and renowned websites such as: National Water Agency (ANA), National Mining Agency (ANM) and by Resolution ANM n˚ 95, of February 7, 2022, among others.

After these steps, it was constituted a scope of study, addressing the themes: Construction methods for dams, problems related to rupture and the types of existing reinforcements for soils with the use of alternative commercial and/or natural materials.

3. Results and Discussions

3.1. Overview of Brazilian Tailings Dams until 2019

The safety of mining dams, within the time frame of this literature review, was defined by Law 12.334/2010 [20], which established dams as: "Any structure in a permanent or temporary course of water for the purpose of containment or accumulation of liquid substances or mixture of liquids and solids". For their construction, the NBR 13.028/2017 (Mining—Preparation and presentation of dam design for tailings disposal, sediment containment and water preservation—Requirements) [35] should be observed [36]. Dams are structures built vertically for the accumulation of various materials [37], however the focus of this work is on the mining tailings dam.

In Brazil there were 717 dams registered by the deadline date of this review, of these 88 were built with the upstream raising method, same technique used on the dams that broke in Mariana in 2015 and Brumadinho in 2019. The layout of dams in the state of Minas Gerais in 2019 can be understood by **Figure 1**.

Of the construction methods: 151 are Downstream, 88 Upstream, 37 Centerline, 381 Single stage and 61 as undefined [38]. Among the most common types of soil dams are the construction techniques by successive 1) downstream, 2) upstream and 3) centerline [2].

It is worth commenting that 43 structures were, in 2019, classified as dams with high associated potential damage. Brazil had about 200 mining dams in these conditions. This assessment is made according to their class, which is established according to the National Information System on Dam Safety [39].

As it is already known, dams suffer several problems (failure modes), which, when not treated correctly, can lead to the collapse of the massif. The downstream method is considered the safest [17]. Regarding the resistance to seismic shaking, the centerline is acceptable, downstream is considered as good and upstream at low-density segregation occurs [2].

The upstream technology loses its reliability to the downstream method among existing methods. Reported accidents are mostly associated with the upstream method (common to most mining enterprises in Brazil), thus, it becomes necessary to pay attention to technologies for geotechnical investigation, construction, operation, auscultation, and maintenance [2].

Figure 2 shows the risk classification map of tailings dams in the state of Minas

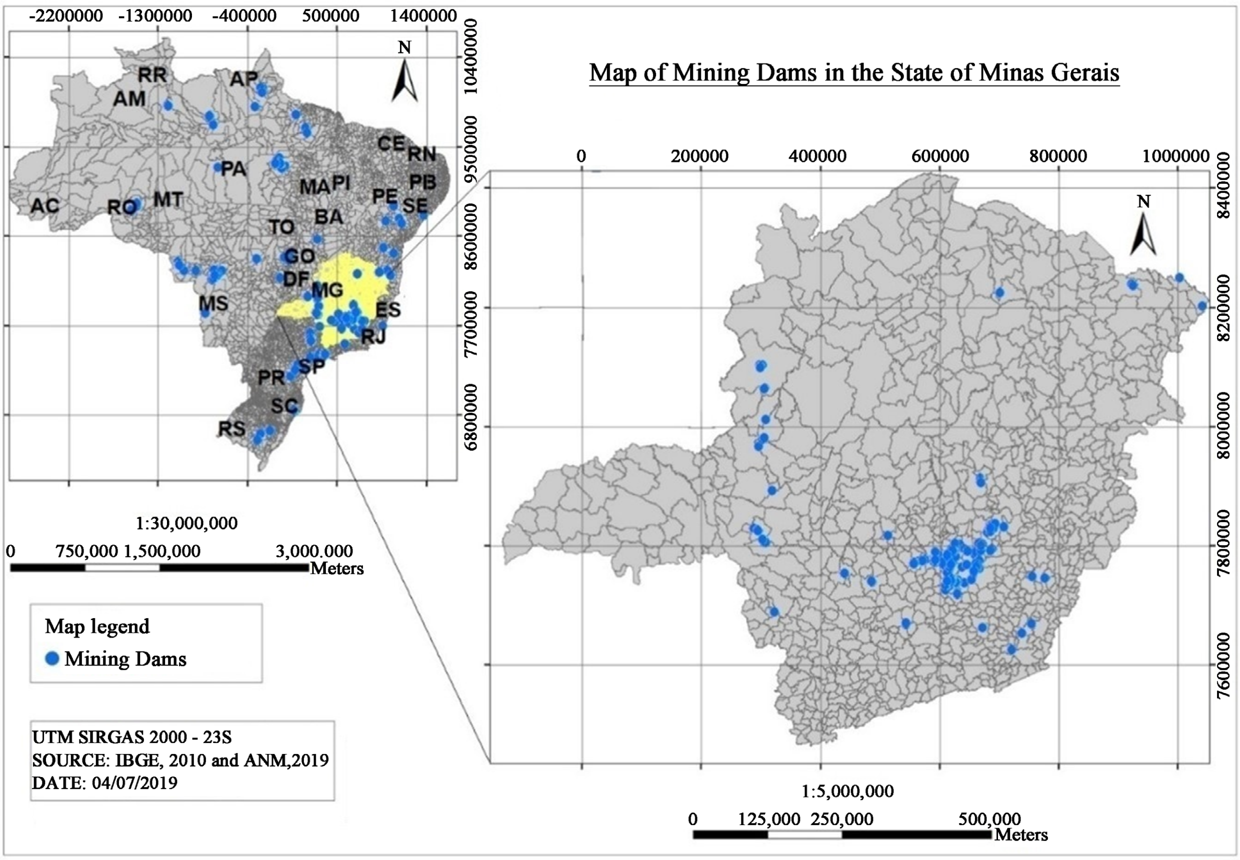

Figure 1. Mapping of Mining Dams in Minas Gerais (Source: Adapted from ANM [38]).

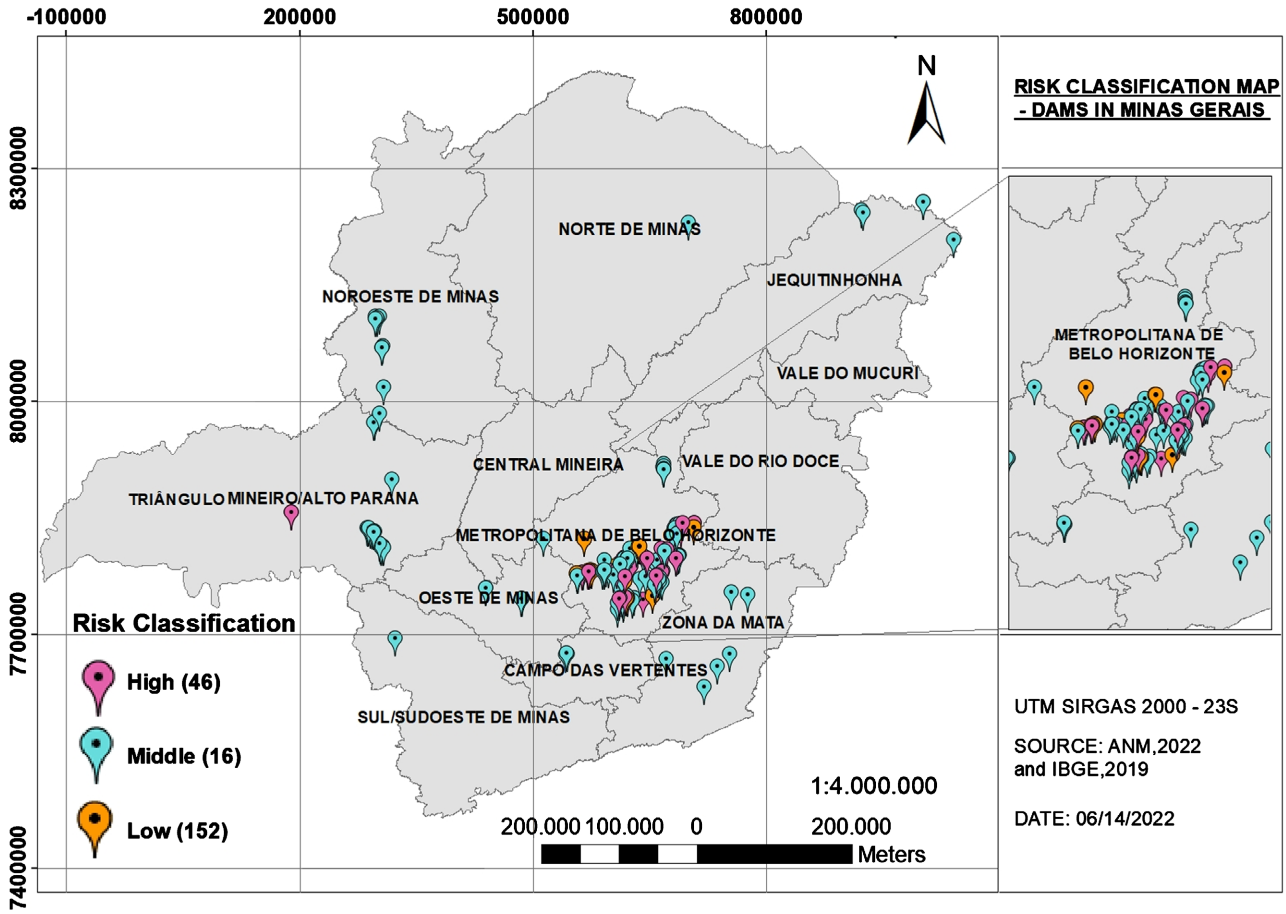

Figure 2. Mapping of the Risk Categories of Mining Dams in the state of Minas Gerais (Source: Adapted from ANM [38]).

Gerais in 2019. It is notorious that the sites are evidenced according to some parameters: 1) state of conservation of the structure, 2) technical characteristic, and 3) adequate standards with the plan of safety of dams, parameters once defined by Law 12.334/2010 [20]. Therefore, they are classified according to the aforementioned criteria and divided into high, medium and low risk, which considers the risk category and associated potential damage in Annex 1 of ANA Resolution n˚ 91 [40].

With the analysis of 147 dams, the most prevalent causes of rupture are [41]: poor maintenance of drainage structures; lack of continuous monitoring and control during construction and operation; growth of dams without adequate safety procedures; the overload from mining tailings. In addition to tremors, pipping, cracks, fissures, overflow, and pore pressure that cause problems in the structure of dams.

The ANM, due to the foregoing, according to its new motion for resolution 04/2019 made on an emergency basis in February 2019 [42] [43], informs the prohibition of the upstream construction method definitively. However, this resolution was replaced by 13/2019 [44] where the mischaracterization of the dams was extended, and there was the inclusion of dams that must have automatic monitoring in real-time and integral by the mining companies. As a measure to lessen impacts and ensure safety, the removal of all the use and occupancy facilities that exist in the High Salvage Zones (HAZ) was considered, thus reducing the associated potential damage. Likewise, the prohibition of dams "responsible for the dam" inserted in the PNSB (National Policy on Dam Safety), regardless of the construction technique is prohibited to maintain/ build in areas of ZAS. Another relevant aspect to mention is that, with resolution 13/2019 [44], the entrepreneur will have new deadlines and gradually in the mischaracterization of dams, with the following deadlines: until 15 September 2022 for upstream dams with volume 12 million m^3, by 15 September 2025 for volume between 12 million and 30 million m^3 and last until 15 September 2027 for volume 30 million m^3 [3] [43] [44] [45].

The review made here highlights the panorama of tailings dams up to months after the Brumadinho tragedy. Tracing this historical perspective generated a academic reference information for comparison with the changes in dam legislation that are constantly evolving. As discussed here, recent mining dam failures in Brazil have fostered changes in the way dam safety is legislated. Today, modifications to the PNSB via ANM Law 14.066 of 2020 [46], as well as a series of ANM resolutions (e.g. ANM 13/2019; 32/2020; 40/2020 and 56/2021) [44] [47] [48] [49] are urgently required to modernize and improve the various issues related to legislation, management, auscultation, monitoring and decharacterization of dams. It is understood that these proposed measures, from the scope of the PNSB to the restructuring of the Emergency Action Plans for Mining Dams (PAEBM), will require some time for companies and their employees to adapt. With this new scenario, a restructuring of the mining sector is expected, ensuring a more sustainable enterprise, aware of the importance of the correct management of its tailings storage facilities.

3.2. Dam Failure Events in Brazil and Worldwide

Among the failures with dams, the damages are irreparable to life and impact the environment. For example, the rupture of the Vajont dam in Italy in 1963 caused 2,600 deaths. It was broken by overtopping with the landslide of a total volume between 270 and 300 million m^3 [50]. On another occasion, in the United States of America, in 1976, the Teton dam broke through victimizing 100 people and generating economic losses close to $1 billion. Another example is the failure of the Gouhou Dam in China in 1993, which presented 300 deaths [51]. In the Austin dam, in the USA, the dam's construction on porous sedimentary rocks with a low shear resistance zone in its foundation caused its rupture [50].

Other cases of dam accident are reported below: Only in Chile there were several ruptures: Barahona (1928), El Cobre (1965) and Cerro Negro (1985) [52]. According to studies, the causes are associated with earthquakes close to massifs associated with sandy materials. Subsequently, on February 27, 2010, the Malue earthquake occurred being this considered the sixth largest in the world and had its impact and movement between the Nazca plate with South America [53] [54]. It is estimated that this earthquake directly affected the dams of Las Palmas, Vetadel water, Chancón, and Bellavista [52].

The Chilean experience shows that even in large-magnitude earthquakes, all failures occurred in the upstream dams, except for the damage suffered by the Alhué dam, a downstream dam [52]. Another example can be cited, like as dam failure in the structure of Aitik, which suffered means impacts, caused by wind erosion, potentiated in periods of drought and transporting large amounts of particulate material, negatively altering the quality of the air. In this way, engineering techniques are used to minimize the impact of the wind as such as the installation of windbreaks that propose a significant reduction of particulates. However, to validate the modeling result, further studies and tests for model calibration are needed [55].

Referring to Brazil, between the years 2015 to 2019, dam ruptures occurred with the use of the dowstream technique, the same construction technology, being these in Minas Gerais: Fundão dam in Mariana (2015) and Córrego do Feijão dam in Brumadinho (2019) [9] [56]. The event that happened at the Fundão dam on November 5, 2015, when approximately 62 million cubic meters of tailings hit the Gualaxo do Norte River in Mariana and then the Doce River [6]. Along this route, the tailings caused the death of 19 people and impacts where it passed. Thirty-nine municipalities from Minas Gerais to Espírito Santo were affected, along 670 kilometers [9] [57]. The rupture of dam I (B1) of the Córrego do Feijão mine in Brumadinho-MG occurred on January 25, 2019.

According to the company's former chief executive, Fábio Schvartsman, the dam contained 11.7 million m^3 of tailings being less in volume than the Mariana tragedy [58].

It is understood from the above that problems related to dam safety are not a Brazilian exclusivity. This perspective shows the need to look for alternatives to increase the security of enterprises of this magnitude. Characterizing Brazilian soils, as well as developing techniques for monitoring and strengthening construction materials for dams can be effective ways to assess greater stability and safety to mining complexes.

3.3. Use of Soil Reinforcement Materials and Techniques for Busbars

The soil is the product of the interaction of 5 independent factors: material of origin, time, climate, relief, organisms and originates from the decomposition of the rocks that constitute the earth's crust [59]. The decomposition is related to physical and chemical agents, and this process is called weathering [60] [61]. It is worth commenting that Brazil presents a varied soil typology in its territory and classifies them as: Argissolos, cambissolos, chernossolos, espodossolos, gleissolos, latossolos, luvissolos, neossolos, nitossolos, organosolos, planossolos, plintossolos, vertissolos [62]. Due to the tropical climate (high temperatures and water availability), it is common to find thick layers of mature soils in Brazil (such as latosols and cambisols). It is important to emphasize that latosol is composed mainly of kaolinite type clays, iron oxides and hydroxides (hematite and goethite) and aluminum hydroxide (gibbsite). They are found mostly associated with smooth-rounded relief with a slope of less than 7%, being deep and porous, well-drained and permeable (even when more clayey), and being very common in Brazil [63]. Soils like these, end up, for much, being the constructive raw material of the mining dams.

According to the studies surveyed, it was concluded that in Minas Gerais it has a high probability for kaolinitic clay formation (**Figure 3**), because in its territoriais extension it presents clayey altered sediments, mainly in the central and southwestern portion [3]. The mapping carried out in the state of Minas Gerais shows 7 municipalities and areas close to these with high concentration of kaolinitic clay substances (**Figure 3**). It is worth mentioning that the most promising municipalities for the formation of these substances are: Lavras, Belmiro Braga, Brás Pires, Santa Maria de Itabira and Medina, these municipalities have concentrations of stems in these places, and also have kaolinite clay in Uberaba and kaolinite in Ijaci. It is important to note that, although the state of Minas Gerais contains few points identified with kaolinitic clay and kaolinite, the kaolin substance is easily found throughout its territory. In this context, the state shows potential for deposits of these substances, so it is necessary that more detailed geological mapping occurs within the state of Minas Gerais.

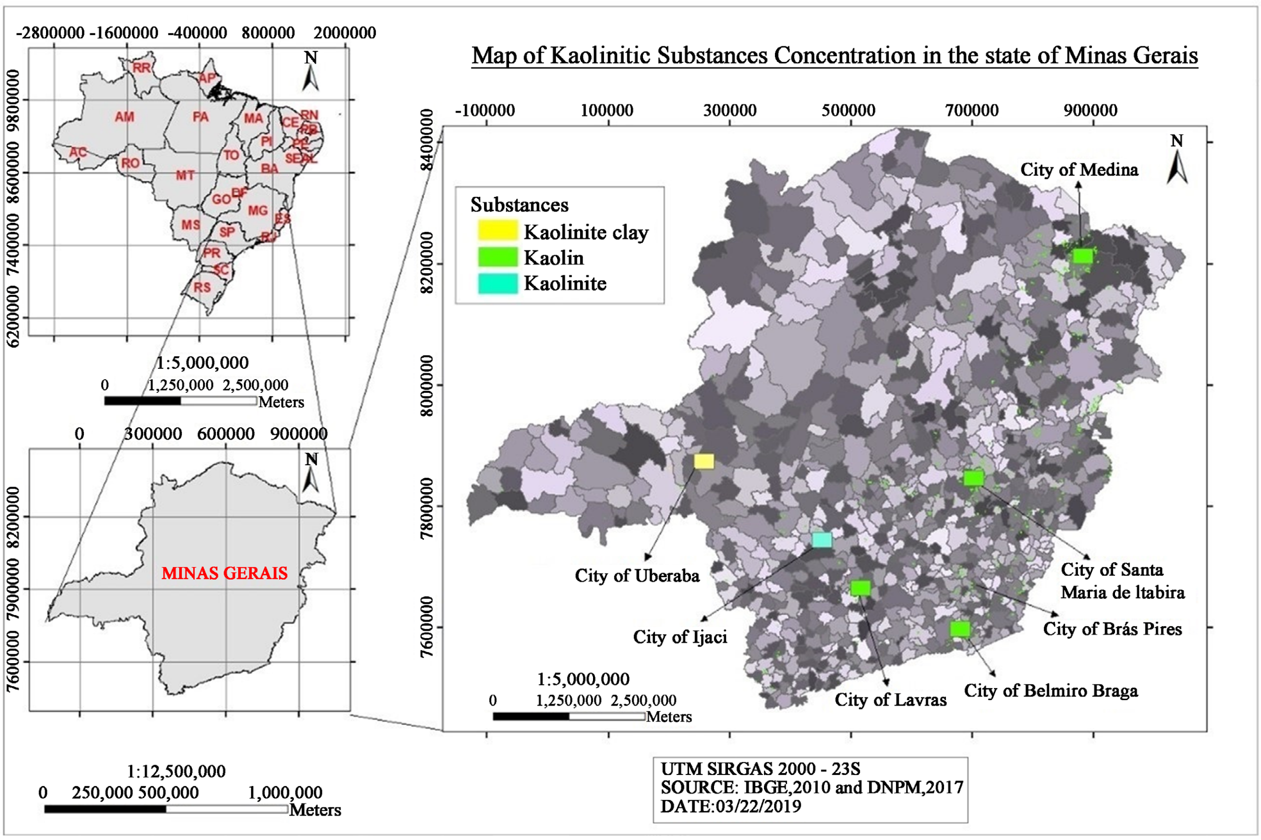

Figure 3. Map of Kaolinitic Substances Concentration in the state of Minas Gerais (Source: Adapted from ANM [38]).

In parallel, there are several materials that can be used to compose a dam, such as: compacted soil, residual mine soil and sand, among others. Among the techniques used, tailings sand dams are seen as relatively vulnerable structures that do not offer the same safety as conventional dams (built for water impoundment or power generation) [52]. In this context, clays emerge as promising construction matrices because they have good cohesion and low permeability.

For the construction of a dam, a series of aspects must be taken into account, among them Location, available data: planimetric and altimetric survey, study of the area near the catchment area, stream flow, precipitation, data on evaporation, physical-mechanical analysis of the local soil, organic matter contents at various depths, data on infiltration, destination and accumulation of water [64]. In addition to the correct choice of dam construction materials, most dam stability problems can be circumvented with a good geological and geotechnical characterization of the site to be built. For this purpose, the detailed geological mapping, right in the prospecting phase, for the choice of the place where the structure of the tailings dam will be built is central to the success of the undertaking.

One of the tools that can be employed is computational modeling in 3D Algorithms [65] [66]. Research based on surface discontinuity surveys, hole drilling, *in situ* and laboratory tests are also of great value [67].

It is common to apply treatments and methodologies to reinforce soils and substrates to ensure the stability of tailings dams. Soil reinforcement is understood as some structural containment techniques that consist of combining soil with other materials to increase its strength, aiming to make the soil more resistant and less deformable. For example, the application of lime can improve the geotechnical properties of soils by acting as a stabilizing agent [68]. A research that has been standing out is the DCP technique (acronym for Dynamic Compaction Penetrometer), which can be used during construction for the compaction control of an iron ore tailings dam, raised by the upstream method [69].

Another technique for soil stabilization is bioengineering. Krabel documented in 1936 the first use of soil bioengineering for stabilization in the United States [70]. Root reinforcement is a key factor contributing to steep (downstream face) slope stability [71]. Most studies quantify root reinforcement from a rooted soil shear strength standpoint, where it is often implemented within an infinite slope stability analysis [72]. The use of plants is the most widely used model due to its great conceptual simplicity. The model depends only on obtaining two variables, the rate of roots per soil area and the tensile strength [73]. The type and size of the vegetation applied are also crucial to ensure good slope stability.

Another technique employed is the use of foundation slabs combined with piles (pilote system plate) for soft soils [74] [75]. Structural engineering techniques are employed for soil reinforcement, such as using pile slabs developed mainly in firm and over-compacted clays [76].

When dealing with the issue of expansive soils, adding lime is recommended, as it is an aerial binder, resulting from the calcination of limestone or dolomites through thermal decomposition, and subsequent hydration forming calcium hydroxide ($Ca(OH)_2$). Furthermore, when added to the soil, calcium hydroxide immediately modifies the pH [77].

The application of materials in the soil provides changes in geotechnical characteristics and has become promising in solving problems in engineering works. In this context, it is necessary to understand the soil and its characteristics better in order to propose geotechnical engineering techniques that contribute significantly to its improvement. The environmental and economic issues related to environmental impacts have fostered an interest in developing alternative materials that can meet the specifications of geotechnical projects [78].

4. Conclusion

The main objective of this study was to present engineering research in the field of civil construction with the premise of soil reinforcement. It was possible to outline the context of Brazilian dams in 2019, discussing sensitive points concerning construction methods and their potential failure modes. A discussion going through several cases of dam ruptures/failures worldwide showed similar points between the events, emphasizing that the debate on dam safety is fundamental from a historical and global perspective. A discussion about soil types showed the potential of the Minas Gerais substrate to subsidize dam construction with quality material. In addition, possibilities and different techniques for soil reinforcement were presented as alternatives to increase dam safety. Finally, we must understand that the events that occurred in Mariana and Brumadinho are inadmissible, being evident, therefore, are needs to evolve in regulatories, environmental, and engineering aspects so that crimes such as the mentioned do not repeat themselves.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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