HAZARDOUS AREA RESULTING FROM TAILINGS DAM FAILURE

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ABSTRACT

Mining is an important economic activity for the state of Minas Gerais, Brazil. Millions of cubic meters of tailings from mining are stored in artificial retention barriers called tailings dams. However, these structures represent a significant risk, as the materials employed (mining waste, tailings, or compacted soil) raise uncertainties regarding their mechanical behavior, either due to their low shear strength or their variable permeability. In the last 20 years, at least five tailings dams collapsed in Minas Gerais, causing both death and damage. Currently, 221 tailings dams in the state could fail, and have potential to cause damage, as it is the case for the Casa de Pedra tailings dam. In the study area, numerical simulations employing depth-integrated 2-D governing equations for mudflow shows that approximately 500 houses could be affected in two adjacent neighborhoods. The simulated mud wave could reach some houses in less than 30 s. Slope monitoring, early warning systems, hazard maps, buffer zone, and retaining walls were proposed as countermeasures.

Keywords: Mudflow, tailings dam, numerical simulation, hazard map, early warning system

INTRODUCTION

According to the Brazilian Mining Association (IBRAM, 2019), the mining industry employed, by January 2019, about 195,000 direct workers. In 2018, the mineral production in the country was worth approximately US$ 34 billion, while in 2017 it brought in about US$ 32 billion. In 2017, according to the National Mining Agency (ANM, 2018), the state of Minas Gerais was responsible for almost half of the production (equivalent to 47.2%) of the metallic substances mined in Brazil.

In 2020, 433 Brazilian tailings dams have the potential to damage their surroundings: 256 with high, 142 medium, and 35 with low potential. In Minas Gerais alone, 221 tailings dams have the potential to cause damage to their surroundings: 144 with high, 56 medium, and 21 with low potential (ANM, 2020). Moreover, in Minas Gerais, 119 tailings dams have the potential to harm people living in their vicinity: 13 would impact the lives of more than 5,000 people; 21 dams could affect from 1,001 to 5,000 lives; 05 from 501 to 1,000; 24 from 101 to 500; and 56 from 1 to 100 people (ANM, 2020a).

The policy regarding tailings dams started to change effectively in 2019 after several collapses. Even with advances in law, one crucial procedure needs to be put into practice: the dewatering of tailings. As stated by the Mineral Technology Center (CETEM, 2018), the main cause of tailings dams failures is the loss of structural resistance due to excessive water in the tailings. Dewatering of tailings is clearly essential to potentially reducing both the storage volume and water seepage, and would also permit a more stable landform that, in the end, can reduce the risk of tailings dam failure.

The objective of this study is to verify, through numerical simulations, the area that would be flooded in case the Casa de Pedra tailings dam fails. Next, this paper proposes countermeasures such as slope monitoring, an early warning system, hazard maps, buffer zone, and retaining walls to protect the two adjacent neighborhoods and their residents.

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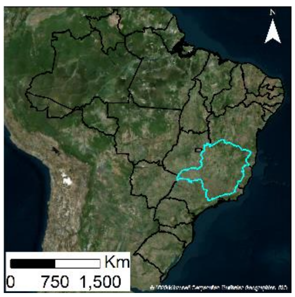
STUDY AREA

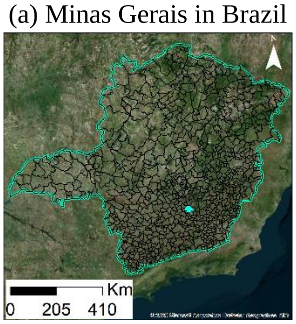
Casa de Pedra (Stone House) is the most iconic tailings dam in Brazil (Figure 1). Located in Congonhas City, Minas Gerais, it is the largest open-pit mine in an urban area in Latin America and has long been operated by Companhia Siderúrgica Nacional (CSN). The Casa de Pedra tailings dam was raised over the past years, where two nearby low-income neighborhoods already existed: Gualter Monteiro (about 382 residences and 1,479 residents) and Cristo Rei (about 325 houses and 1,248 inhabitants). Some houses in these neighborhoods are only 500 m downstream from the tailings dam, and, in the case of a collapse, the mud wave formed is estimated to reach them within 30 s, according to a Public Civil Action from the Minas Gerais State's Attorney Office (MPMG, 2019).

Table 1. Data from the study area

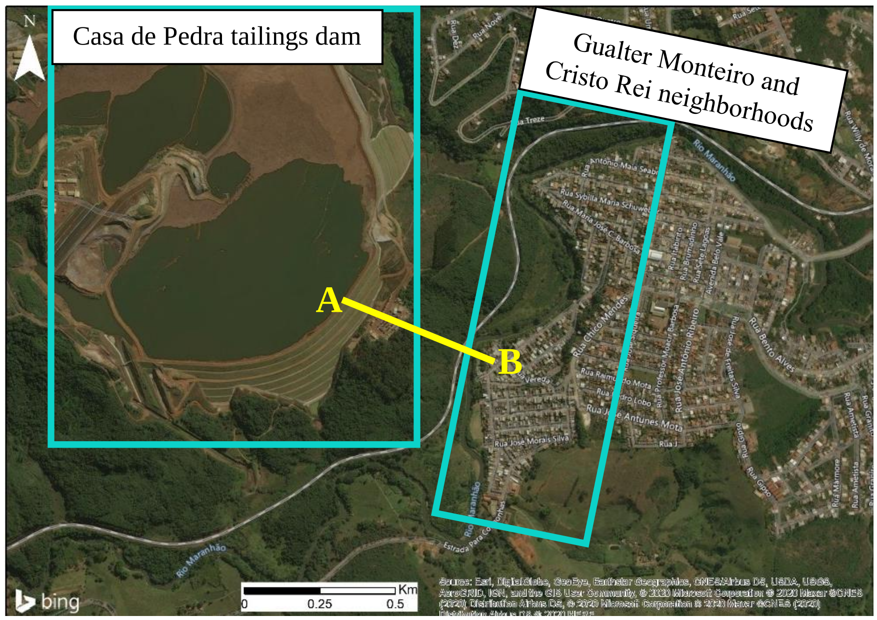
Type of data	Value	Source
Volume of tailings	21.7 million m^3	ANM (2019)
Elevation	933 m above sea level	MPMG (2019)
Mean grain size	d_{90} = 0.1 mm (very fine sediments)	Osorio (2005)
Digital Elevation Model (DEM)	1-arc-second (30 m by 30 m in resolution)	(NASA/METI/AIST/Japan Spacesystems and US/Japan)



(a) Minas Gerais in Brazil



(b) Congonhas in Minas Gerais



(c) Casa de Pedra tailings dam, Gualter Monteiro and Cristo Rei in Congonhas

Figure 1. Location of the Casa de Pedra tailings dam, Congonhas City, State of Minas Gerais, Brazil

In Casa de Pedra, from the dam crest (933 m above sea level) to the closest point in the two neighborhoods (860 m above sea level), the distance is approximately 500 m. Therefore, between these points, the longitudinal profile (73 m/500 m) is about 0.14, as shown in Figure 2.

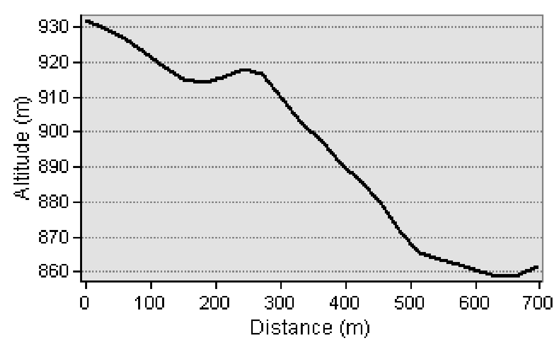


Figure 2. Longitudinal profile of the section AB from Figure 1

Events that might trigger the collapse of the Casa de Pedra occurred in the recent past: a 3.2 magnitude earthquake in November 2019, heavy rains in early 2020, and water seepage that has been detected since 2013.

Casa de Pedra has continued to receive loadings until recently, and its shape has changed over the past years. The original digital elevation model (DEM) was manually updated in ArcGIS software for the tailings dam to reach its current height of 933 m above mean sea level.

METHODOLOGY

Figure 3 illustrates the steps taken to achieve the proposed objectives. There are a few mud models that can evaluate erosion/depositional processes of mudflows. Thus, Morpho2DH, one of the solvers from iRIC (International River Interface Cooperative), was chosen for the present study. Calibration and validation were performed using data obtained, respectively, from the 2015 Mariana Dam Disaster and 2019 Brumadinho Dam Disaster, to visually compare the reported and simulated mudflows in each case. Finally, simulations were performed in the study area, and, after the results, countermeasures were proposed.

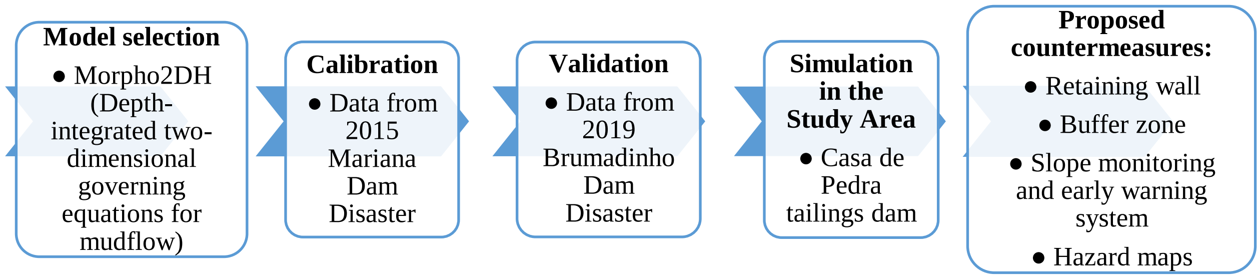


Figure 3. Methodology flowchart

The Morpho2DH model employs mass and momentum conservation equations of mudflow in depth-integrated 2-D form and a mass conservation equation of bed sediment. The mass conservation equation for the flow body is described with an erosion term:

$$\frac{\partial h}{\partial t} + \frac{\partial hu}{\partial x} + \frac{\partial hv}{\partial y} = \frac{E}{c_*} \quad (1)$$

where t is the time, h is the flow depth, and u and v are the depth-averaged velocities in the x and y directions, respectively. Takebayashi and Fujita (2020), explained the equations developed in 2004 by Egashira and Itoh, stating that the term on the right-hand side indicates the sink and source of the mass and expresses the development and decrescence of a mudflow by an exchange of the mixture of water and sediment between bed surface and mudflow. In this equation, c_* is the concentration of sediment in the static deposition layer (bed layer), and E is the erosion rate of the bed.

The momentum conservation equations are as follows (Egashira & Itoh, 2004):

$$\frac{\partial hu}{\partial t} + \frac{\partial huu}{\partial x} + \frac{\partial huv}{\partial y} = -gh\frac{\partial z_b}{\partial x} - \frac{1}{\rho_m}\frac{\partial P}{\partial x} - \frac{\tau_{bx}}{\rho_m} \quad (2)$$

$$\frac{\partial hv}{\partial t} + \frac{\partial huv}{\partial x} + \frac{\partial hvv}{\partial y} = -gh\frac{\partial z_b}{\partial y} - \frac{1}{\rho_m}\frac{\partial P}{\partial y} - \frac{\tau_{by}}{\rho_m} \quad (3)$$

where g is the gravity acceleration and Z_b is the bed elevation. The pressure P is assumed to be static pressure, ρ_m is the density of the mudflow, τ_{bx} and τ_{by} are the shear stresses in the x and y directions.

These equations are part of the numerical analysis model installed in Morpho2DH, one of the solvers present in the free public software iRIC, developed by a research group in Japan. Morpho2DH was developed in 2014 by Professor Hiroshi Takebayashi at the Disaster Prevention Research Institute of Kyoto University. The model can reproduce the transport and erosion/deposition processes of debris flow and mudflow due to landslides.

RESULTS AND DISCUSSION

Figure 4 shows the results of the simulation in the study area considering the release of 20 million m^3 of tailings, which is approximately the total volume announced to the authorities. The calculated elevation change interval is from negative 30 m to 30 m. Negative values mean that erosion occurred, whereas positive values indicate the deposition of tailings. The mudflow spreads out to cover an area of 1.42 km^2 and stops after 300 s (5 min).

For the simulations, the total collapse of the dam wall was assumed, as was the case of the 2015 Mariana Dam Disaster and 2019 Brumadinho Dam Disaster. Additionally, since most of the houses located in the

Gualter Monteiro and Cristo Rei neighborhoods were not built to the standard building codes, their resistance was not considered in the simulations. Even if these houses had followed the building code, they could not withstand the force of the mudflow and would not be substantial obstacles.

Countermeasures to protect the people living close to Casa de Pedra tailings dam were proposed from the results obtained from the simulations.

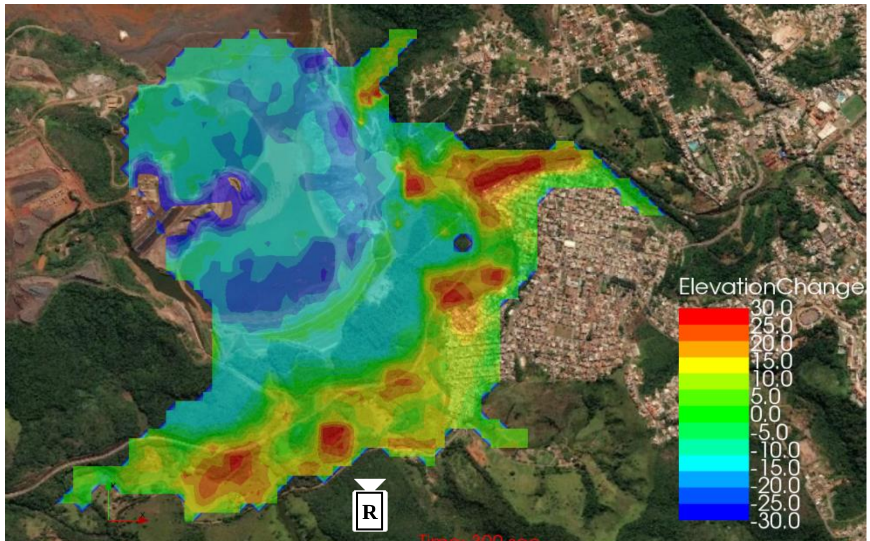


Figure 4. Elevation change (in meters) for a released volume of 20 million m^3

A. Slope monitoring and Early Warning System

Based on Karunathilake et al. (2019), a ground-based radar, as indicated by the white icon marked with an 'R' letter in the central lower part of Figure 4, could be used for slope monitoring. Depending on the rate of displacement of the slope or dam wall, according to the diagram proposed in Figure 5, warning messages could be sent before the collapse takes place.

B. Proposal of Hazard Maps

Two different hazard maps were created after the simulations. Figure 6 shows a map that displays the potential change in elevation after the release of 20 million m^3 of tailings from the collapse of Casa de Pedra. This hazard map gives an idea of the depth the mudflow could reach in some points of the two neighborhoods.

Figure 7 is a map showing the mudflow times of arrival, reaching different sections of the Gualter Monteiro and Cristo Rei after the release of 20 million m^3 of tailings from the collapse of Casa de Pedra. According to the simulations, it takes less than 30 s for the mud wave to affect some houses of the two neighborhoods, which corresponds to the estimates in the Public Civil Action filed by the MPMG (2019).

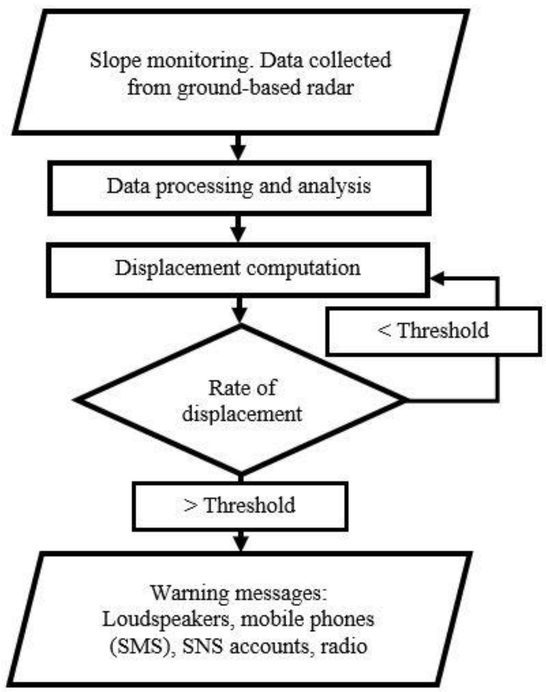


Figure 5. Proposed diagram for the slope monitoring integrated into the early warning system

C. Proposal of a Buffer Zone

For the buffer zone in Figure 8, not only 20 million m^3 (about the current total volume), but also three different amounts of tailings, (5, 10 and 30 million m^3) were used in the simulations. A comparison of the three shows that the affected area, even with the increase of the released mud, is not much different in either of the three cases. For this reason, a released volume of 20 million m^3 was selected to establish a buffer zone.

The Minas Gerais Government enacted State Law 23,291 on February 25th, 2019, to establish, within the state territory, a buffer zone for the construction of new tailings dams. Hence, existing settlements inside hazardous areas do not benefit. In the study area, if a buffer zone were to be established in Casa de Pedra, reallocation of about 500 houses inside the hazard area would be necessary.

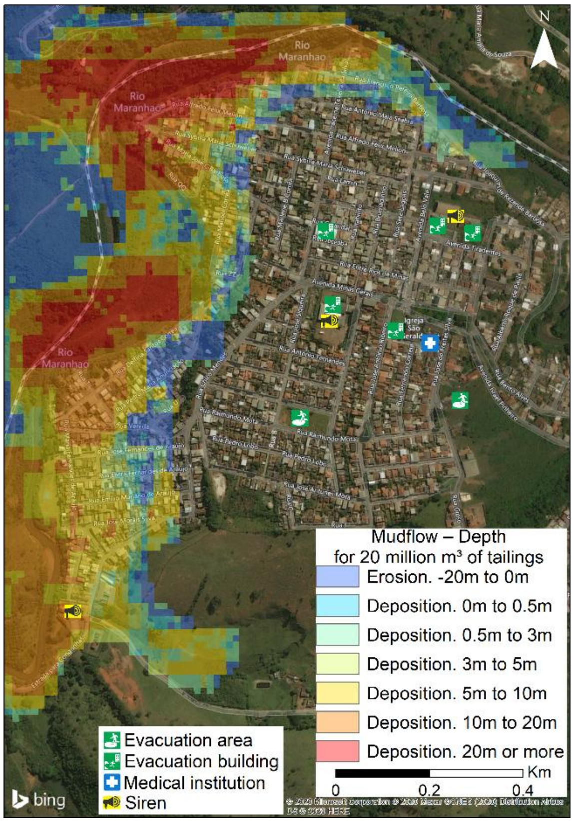


Figure 6. Hazard Map with mudflow depth

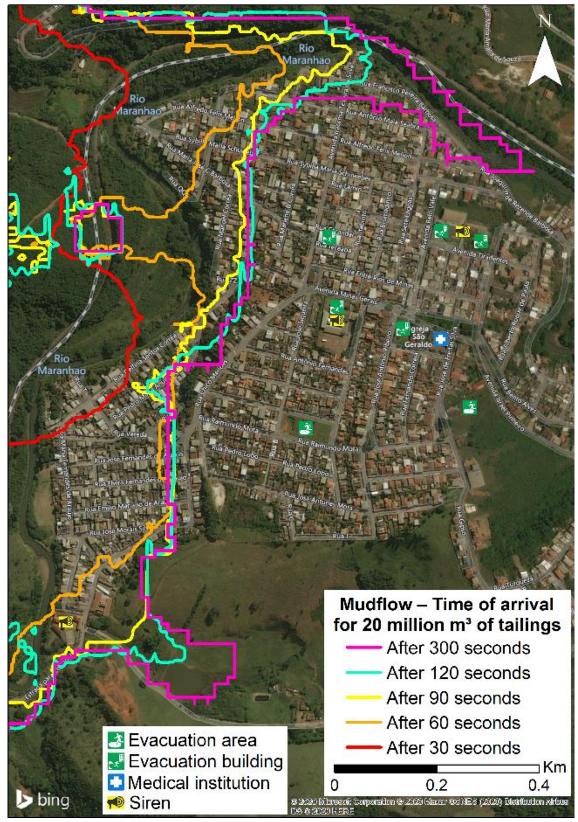


Figure 7. Hazard Map with mudflow time of arrival

D. Proposal of a Retaining Wall

A retaining wall (Figure 9) was considered for placement between the tailings dam and a railway, to protect the two neighborhoods. According to the simulations, even with some breaches, a retaining wall would be able to protect the Gualter Monteiro and Cristo Rei neighborhoods, after the release of 20 million m^3 of tailings. However, the simulation showed that the mud wave reached more than 50 m in height in some spots, making the construction of such a wall not feasible.

CONCLUSION AND RECOMMENDATIONS

The numerical simulations indicate that, in case of a failure of the Casa de Pedra tailings dam, the mudflow would reach some houses in the two neighborhoods in less than 30 s, and, ultimately, about 500 houses would be affected by the mud wave. Countermeasures were considered in this study to protect the residents. The best solution for the residents of these two neighborhoods is the establishment of a buffer zone. Until this measure is put into practice, the slope monitoring and early warning system, as well as hazard maps, can provide some means for the protection of the residents. The retaining wall, as demonstrated in the simulation, would not be a feasible measure.

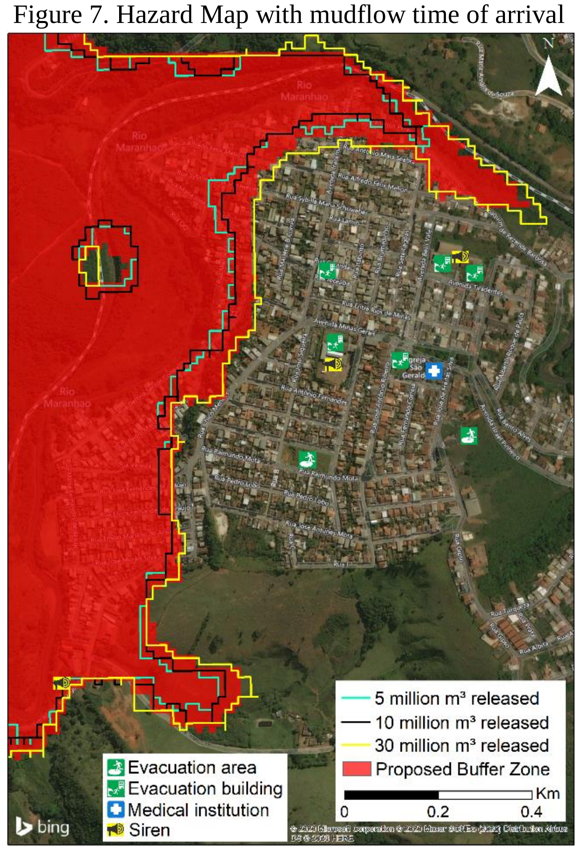


Figure 8. Buffer Zone and affected areas depending on different volume of tailings released

Dam break numerical simulations in Brazil are usually performed through a hydrodynamic approach, whose focus is to understand the potential effects of flooding through software such as HEC-RAS. However, this method is not the most suitable for tailings dams because of the difference in physical properties compared to water reservoirs. Therefore, it is necessary to understand the behavior of the tailings using a more realistic assessment, an approach to the perspective of the mechanics of sediment transportation. Morpho2DH proved to be a useful alternative software that can be used along with others to obtain different perspectives of tailings dams.

Morpho2DH can be used as an auxiliary tool for rescue teams as it is capable of simulating with some accuracy the depth of mud of the area that is affected by a mudflow, as observed in calibration and validation. The estimation of the depth gives rescue teams information on how much they have to excavate to find people or property submerged by a mud wave.

Finally, it is crucial to monitor the current tailings dams to maintain updated data that can be employed in the models to obtain more reliable results.

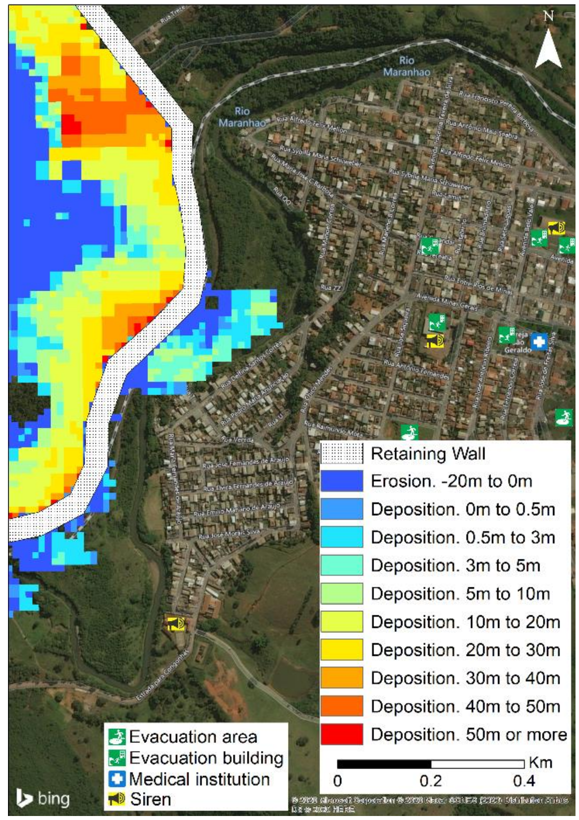


Figure 9. Proposed Retaining Wall

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