Difficulties in building a ground model when lacking historic data archives and its impact in TSF safety assessment

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ABSTRACT

Sometimes, when working in TSF safety analysis, the historic archives with the original ground topography or details about the TSF design and construction are few or inexistent. The knowledge of the bedrock position, as the details about the embankment construction are essential to know, for instance, the tailings thickness and the construction type.

For the analysis of TSF current state stability the ground/structure model is essential, and is, in many cases, very difficult to define with few and low-quality data. The original ground topography is, often, obtained from aerophotogrammetric reconstruction, from satellite images or aerial photos, originally with low resolution and uncertainty of more than 10 m for the elevation.

In this paper is presented a case-study from a TSF where the initial data package had only the feasibility design and some very simplified reports that checked the stability of the dam before an upstream raising, i.e. it didn't exist much information and the details about the site and about the structure were very limited. To "add" difficulties to the process of defining the bedrock surface and to establish the TSF design, the embankments were built with local rocks (mainly schist and phyllite), and during the initial analysis of historical satellite images it was noticed that the original ground was excavated in different areas to increase storage area and obtain construction materials.

This paper presents the steps developed to establish the definition of the bedrock ground surface and the difficulties felt and its impacts on TSF safety assessment are discussed.

Keywords: Database; Ground model; uncertainty; TSF stability.

1. Introduction

Tailings storage facilities (TSFs) are one of the key elements of mining operations. Usually dams or embankments are used to retain tailings, which are a byproduct of the mining processes. Even though research is being developed in order to reprocess tailings to extract from it the elements that still have commercial interest, or to use it, for instance, as construction material , not all types of tailings are viable and the most part of the produced tailings still have to be stored.

During the mining operations, TSFs are usually built and raised to increase the storage capacity, often without interrupting the mining activities. Most of them were built several decades ago and about 45% have been constructed with the upstream method, which is considered the least stable among the tailings dam construction methods (Piciullo et al., 2022).

TSF failures result in environmental disasters and often also in human tragedies. The lack of knowledge on tailings behaviour and the poor performance of monitoring and management processes of the structures, can be considered as the main predisposing factors of dam failures. After the recent failures, the major mining companies are reassessing and upgrading the TSF management practices and evaluating systematically tailings dam's safety (Piciullo et al., 2022).

The TSF current state stability is one the aspects that has to be assessed in order to evaluate safety and check if any mitigation measures are needed. In order to make the stability analysis, the model of the TSF has to be prepared, and it includes both the ground as the dam's structure models. Due to the age of many of the structures and/or to poor management practices of the companies, that resulted from the low awareness to the risks at the time of the dam construction, the historic archives with the original ground topography and/or details about the TSF design are, often, few or inexistent. Building the original ground model is, in many situations, a very complex step but is fundamental to know, among others, the dam's height, tailings thickness and stored volume.

In this paper is presented the process leading to obtain the original ground model in a case study of a TSF where the initial data package had only the feasibility design and some very simplified reports that checked the stability of the dam before an upstream raising, i.e. few information existed and the details about the site and about the structure were very limited. In this case study, both the analysis of the Google Earth images as well as meeting the engineer that followed the construction of the original embankment and first upstream raise, were fundamental to conceptualize the model.

2. Case study

2.1. Site description

According with the feasibility study, the TSF under study was built in an originally trough shaped valley surrounded by steep slopes on the northern and southern sides. This valley (E-W direction), with gradient of about 2° from E to W, before construction presented a continuous flow of water.

Considering the geological maps, the main geological unit found in the area comprises low grade pelitic metasediments and is mainly characterized by tuffaceous phyllites with intercalations of feldspatic quartzite bands. In some regions sericitic schists are found and phyllites are carbonaceous. Arenaceous sediments occur as lenticles and laminae in the main phyllitic mass. Sedimentary structures are observed, and the intrusion of quartz veins is common.

Locally, the feasibility study identified the bedrock geological materials as constituted by phyllites and slates. It was also identified a massive intrusive body with considerable width and black colour, presenting quartz veins, with location unknown. The presence of faults was not observed in the area. As a geological map of the site was not produced, there is no information on the geographical distribution of the lithologies.

Nonetheless, in the northern slope, the phyllites and slates are described as thinly bedded and highly to moderately weathered. Total soil thickness is less than 1 m but presents few rock exposures. In the southern slope, rocks are well exposed and described as being highly weathered to disintegrated, especially on the western side.

2.2. TSF description

The TSF case-study (Fig. 1) here presented, is around 500x250 m and 70 m height in the highest point and started to be built around 2012, being the starter dam, mainly, the closure of the valley in the eastern and western sides of the waterline. According with the available documentation, the TSF was raised 4 times by the upstream method in 2015, 2016, 2018 and 2020/2021.

Besides the feasibility report, the initial existing documentation about this TSF were: the raising stability analysis reports (Fig. 2), made previously to the raises construction (from 2014, 2015, 2017 and 2020); two site investigation campaigns, from 2014, with two boreholes and a crosshole test, made on the crest of the starter dam, and another from 2019, with two boreholes, with limited depth and only crossing tailings; and the current topography. At current stage this TSF is not receiving tailings anymore and is under closure process.

Even though in the existing documentation the raises present benches (Fig. 2), when looking at the topography (Fig. 1), it is clear that no benches were materialised during the raise's construction, and it is only visible a trace of one of the benches in the western and eastern extremes of the southern slope.

2.3. Challenges in building the TSF model

A good documentation and reporting system is essential for tailings management (ICMM, 2021; MAC, 2021). When it is missing, the companies working in TSF safety assessment face a huge challenge. Without it there is no good data to work with, sometimes no data at all, and big difficulties arise as the TSF history cannot be established.

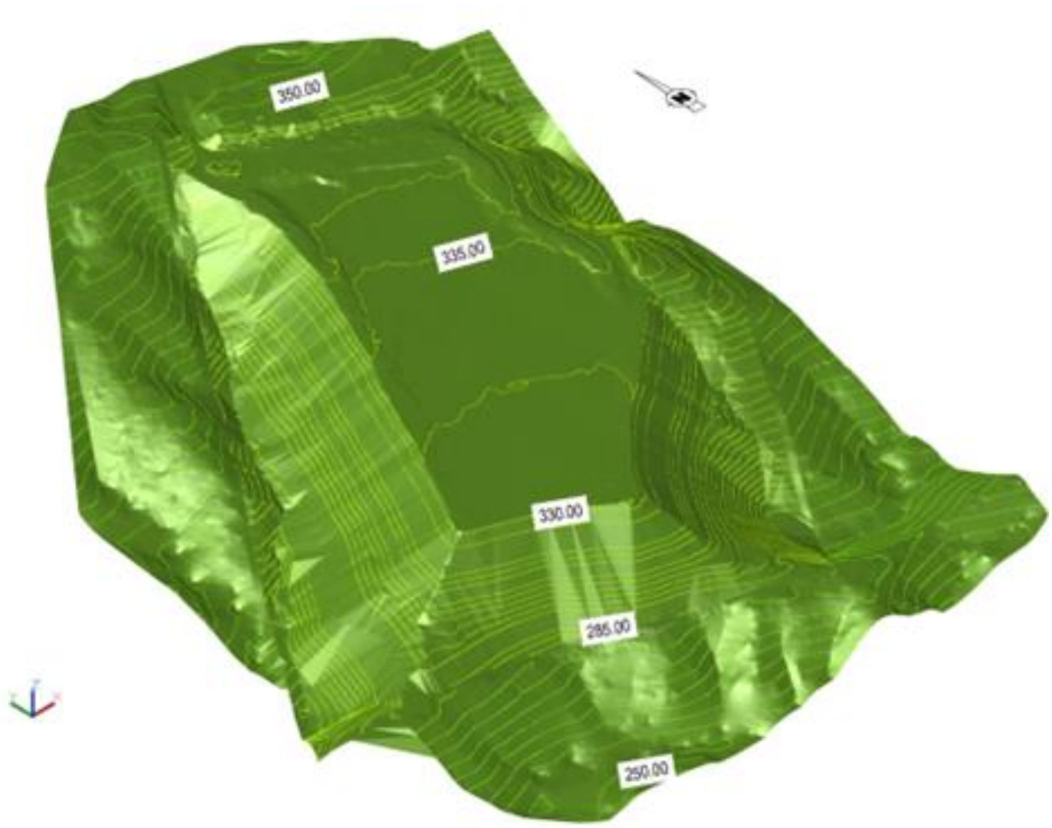

Figure 1. Current 3D topographic surface of the case-study TSF

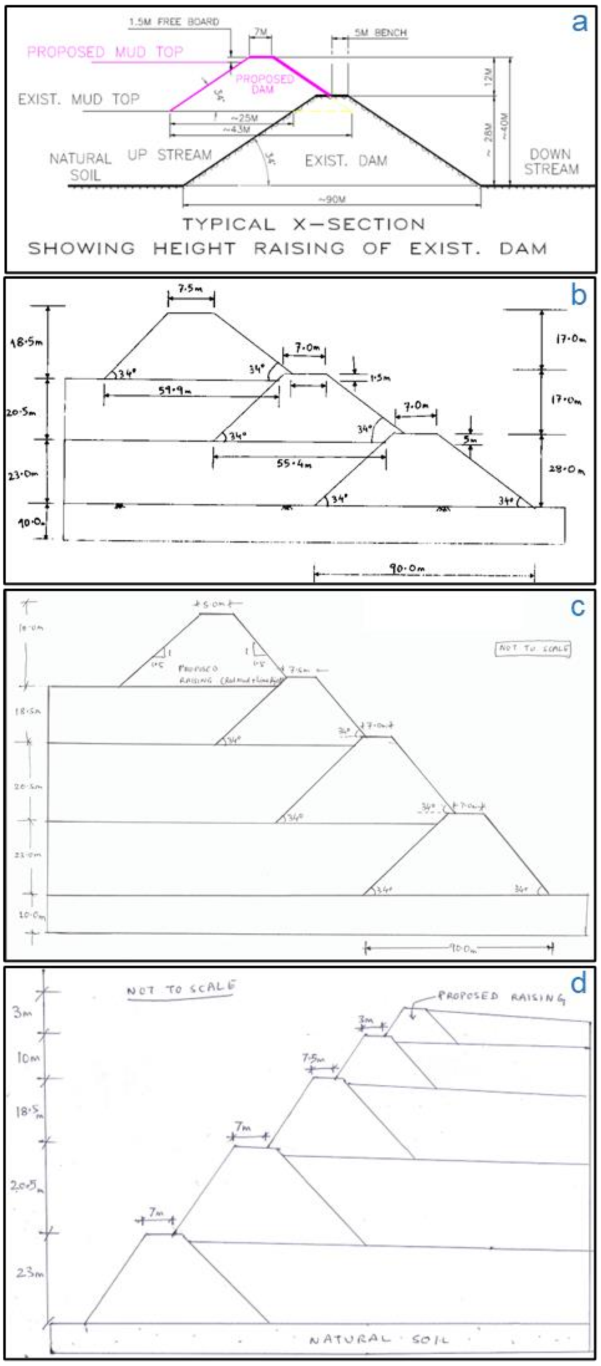

Figure 2. Proposed cross-section for (extracted from the stability reports): a. raising nº 1 - 2014; b. raising nº 2 - 2015; c. raising nº 3 - 2017; d. raising nº 4 -2020.

Besides the parametrization of the tailings, foundation and embankment materials, to evaluate the current state stability, it is necessary to have a model for the TSF.

In this paper, and without focussing on the difficulties that exist in characterizing tailings, the objective is to focus on the other model characteristics, that are as important as the tailings and sometimes as challenging. In this case study, due to the lack of reliable information about the site, conceptualising the TSF structure model posed as a huge challenge, both for the bedrock ground surface as for drawing the dam itself.

The first mismatch found was, as already discussed, the lack of correspondence between the existing simplified drawings of the raises prior to construction and the current topography, that didn't allow even to confirm the heights of existing embankments. Still regarding the embankments, another mismatch is related with the construction materials defined in the documents, as they are not the ones observed on site.

When trying to establish the case-study TSF model, the starting difficulty was the lack of good quality information on the original ground topography. To add extra bit of uncertainty, when looking to the few available historical satellite images available on Google Earth it was possible to check that along with the TSF raises, there were zones that were excavated to increase the storage capacity, first in the south zone, followed by a narrower strip the northwest zone, and the last excavation, and the biggest, in the northeastern zone. These excavations were not documented.

During the TSF operation time, the engineers responsible for it changed over time so, when this work started, the owner engineer that was responsible for the site, hadn't followed the construction. The excavations were confirmed during the site visit, when talking to the site engineer that followed the initial works. Also, he told the team that the excavated material was used to make the embankments, and that in the construction of the raises, the benches were not kept, as the material for the new raise was always dropped from the top.

In this case, it was missing the documentation, not only from the construction phases, as from any maintenance actions done during the TSF operation. Also, only in 2019, some monitoring actions started, with some regular drone flights and reports.

As the TSF is recent, the construction site engineer still works in the company, even if in a different area, and was possible to meet with him, but in many other TSFs, this is not possible anymore. His memories and insights about the construction added valuable information to the TSF model building reinforcing the need to keep record reports of all construction phases.

The focus of this paper will be on the strategies followed to obtain a what is found to be a reliable definition of the bedrock ground surface to work with.

3. Original ground topography

3.1. Topographic data

Even though the feasibility study is from 2009, the original topographic map was not stored in the owner database. The only information about the original ground was the image presented in Fig. 3. As it can be seen, this image has very low detail (contour lines at every 3 m) and it is not coordinated, being very difficult to use it as being the bedrock ground surface.

To overcome the lack of topographic information, in 2021 the owner subcontracted the preparation of a topographic contour plan based on old satellite images (Fig. 4). The aerophotogrammetric reconstruction was obtained from available free images from NASA satellites from 2000-2001. The maximum resolution obtained by the company was contours at every 0.5 m. The uncertainty in the obtained altimetry by this method depends on the base data and on the methodologies used but is often high. The DEM model obtained was checked using DGPS points, which are fixed points without topography changes in the time lapse between 2000 to 2021, that were used to correct the altimetry obtained and to adjust to the ground realities.

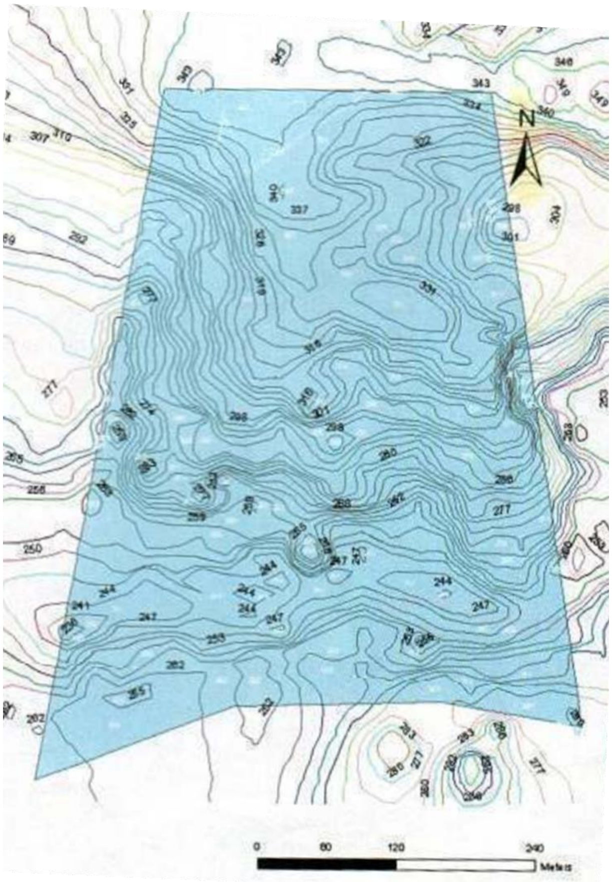

Figure 3. Contour plan of the site (extracted from the feasibility study) from 2009 (?)

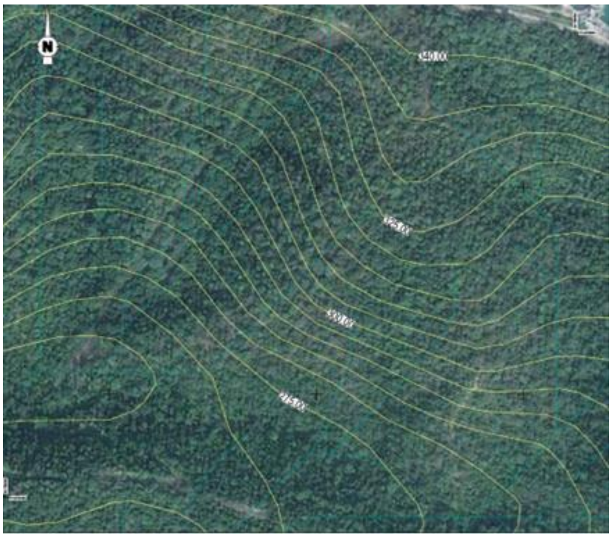

Figure 4. Contour plan obtained from satellite images (2000-2001), above the 2009 Google Earth image.

The reconstructed topographic data provided has also some limitations, not only in the topography detail as in the obtained morphology of the original ground. For instance, the surface presents a smooth surface and the E-W valley in the southern part of the TSF area (see Fig. 3) was not captured. Also, the overlap between the satellite obtained topography and the current topography in the areas where the bedrock outcrops show altimetry variations, sometimes of more than 10 m.

3.2. Additional data

3.2.1. Site investigation

To characterize and parametrize the materials at this site, an extensive site investigation campaing was designed. It comprised mainly boreholes, as information about the bedrock position and about the embankments extension was needed. Other tests, as CPTu and downhole tests, were also made to complement the site information but were mainly directed to characterize the tailings.

The boreholes were distributed along the TSF area and defined to stop only when crossing the bedrock in 3 m. As no benches exist, it was only possible to work from the top of the TSF. The main difficulty observed from the site investigation campaing was to separate, in some positions, the weathered bedrock from the embakments, as the embakments were made from excavated bedrock material. Due to that, to the original foreseen 28 boreholes had to complemented by 3 extra boreholes in specific sites to clarify that doubts. In the end of the campaing, 2 extra boreholes were needed because CPTu tests were unable to cross the full tailings thickness.

3.2.2. Other data

For the conceptualization of the model, the historical satellite images played a very important role, allowing to understand a bit better the TSF history. Even though the image distortion, caused by the satellite positioning at the moment that the image was obtained, does not allow to consider the image horizontal coordinates as fixed, they allow to obtain information about the relative positioning of some events during the construction steps.

The main available images for the site are from:

- 2012, during the beginning of the works and excavation of the centre line and southern area;
- 2013, showing the starter dam and the excavations on the narrow strip in the NW side;
- 2015, after the construction of the first raise and during the excavation of the NE area;
- 2018, during the works of the 3rd raise;
- 2020, during the works of the 4th raise.

4. Generating a ground surface

Generate a reliable bedrock ground surface was a dificult task, considering that each piece of information has strong limitations. To gain confidence in the final result, the following steps were followed:

1. The current topography (Fig. 1) was used and the E-W direction of the valley was marked with an approximate direction as existing in the satellite image from 2009;
2. The image of the original ground presented in Fig. 3 was drawn and the altimetry was attributed to each line. The horizontal positioning was adjusted using the E-W line direction and other

points that were possible to correlate with the current topography. The final surface was generated (Fig. 5);
3. The satellite image original ground surface was generated (Fig. 6);
4. The ground surface obtained from the boreholes was generated (Fig. 7).

After completing all the surfaces, they were all overlapped, including the current topography, and were produced a set of sections in the two main directions, aligned with the TSF main axis. The main information used to generate the final bedrock ground surface was the areas where there is natural ground in the current topography and the bedrock borehole obtained surface. The surface obtained from the borehole data points is considerably smaller, as being an upstream raised TSF, the dimension of the top available area is much smaller than the dam base area. The sections were used to draw the bedrock position between those two surfaces.

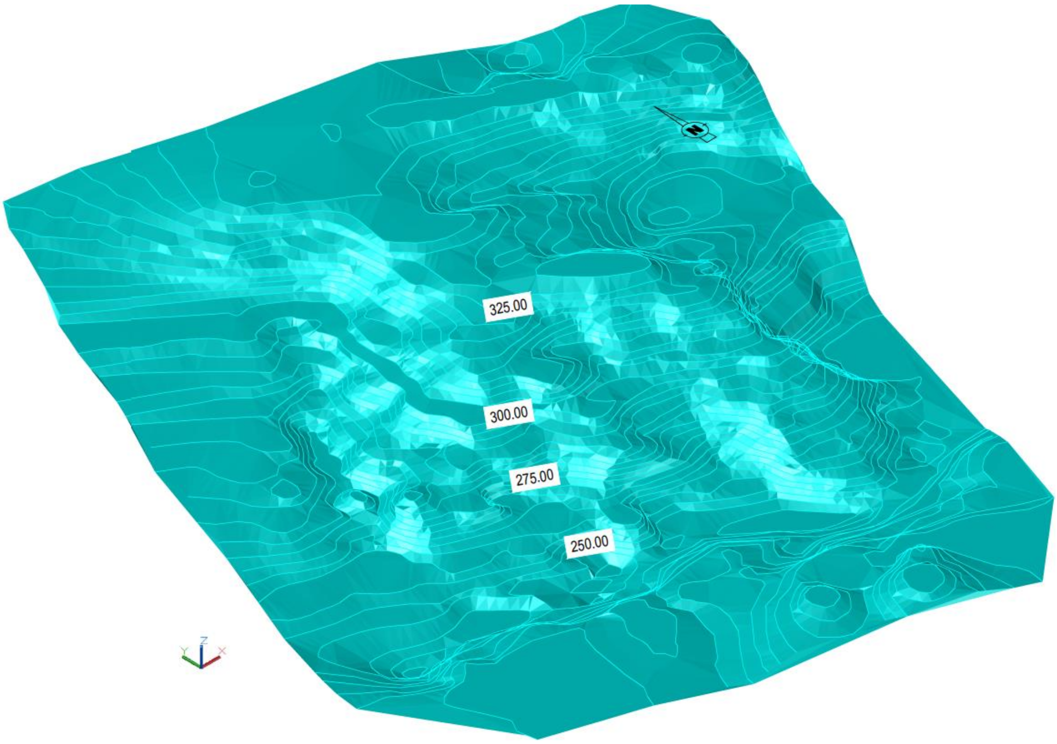

Figure 5. 3D topographic surface of the original ground obtained from processing the feasibility study contour topographic plan

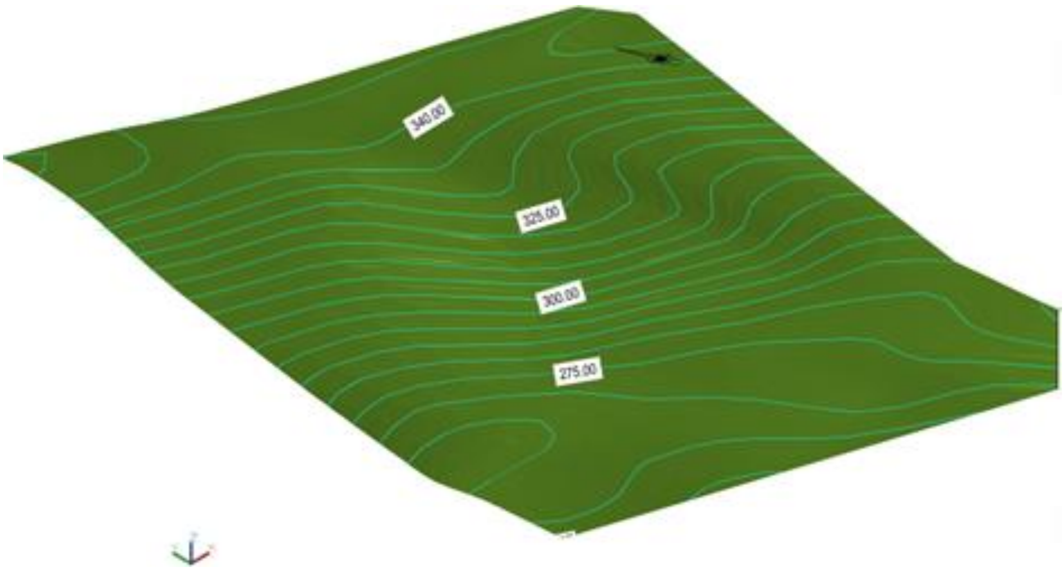

Figure 6. 3D topographic surface of the original ground obtained from satellite images

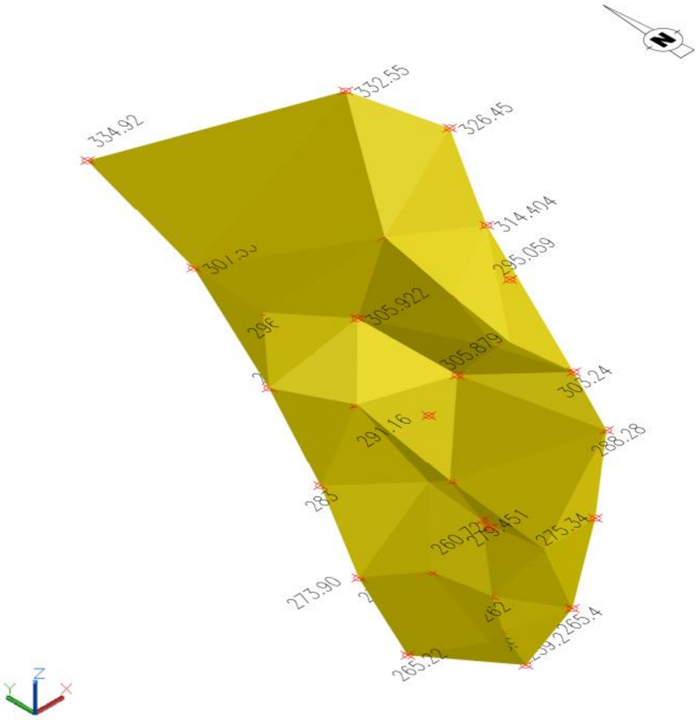

Figure 7. 3D ground surface generated from the borehole point data

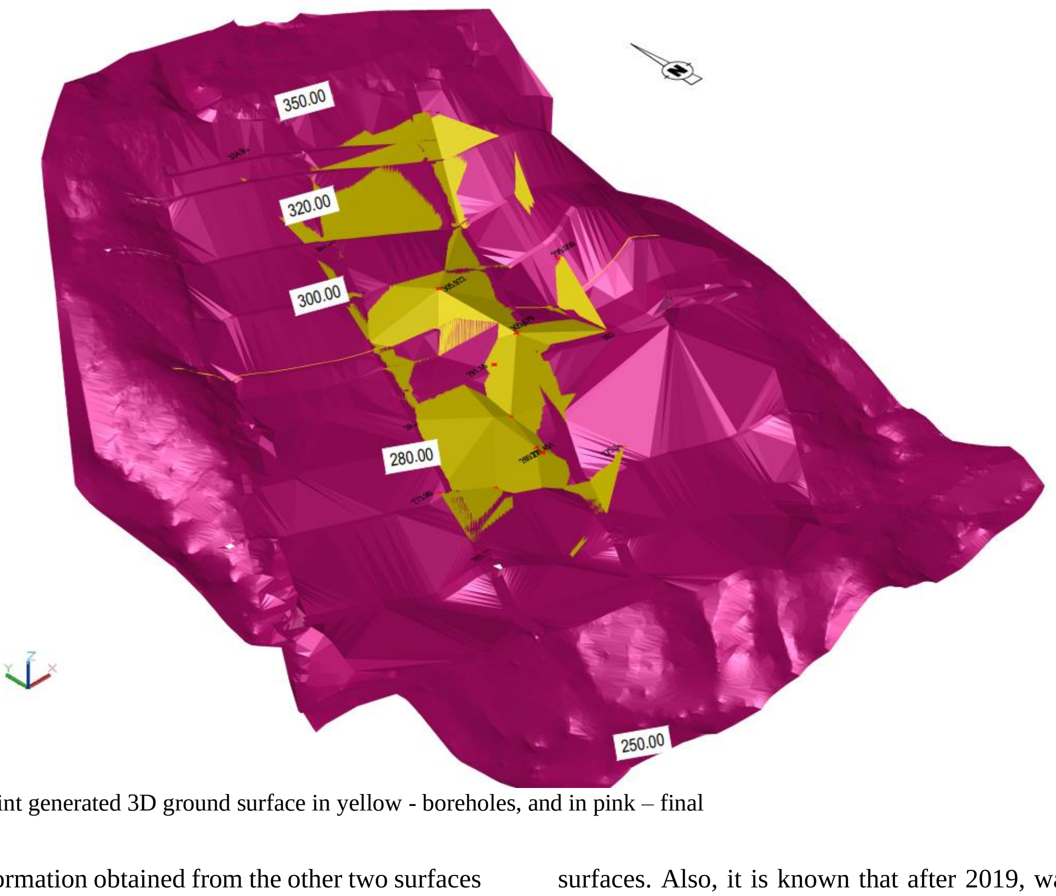

Figure 8. Joint generated 3D ground surface in yellow - boreholes, and in pink – final

The information obtained from the other two surfaces was limited. As stated before, the satellite images original ground wasn't able to catch the original topographic variations, as for instance the altitude and development of the E-W waterline. The uncertainty regarding the positioning of the feasibility topographic surface also limited a lot its use, nonetheless it was possible in some points to analyse the trend of the original ground and approximately replicate it while connecting the other two surfaces. Also, it is known that after 2019, was made a correction in the altimetric datum in the study area, and as there is no information about the coordinate system used or about the altimetric data in 2009, so a difference may exist also in the altimetric positioning. Adding to that, due to the excavations the current state of the bedrock does not correspond to the original ground. After drawing the joint ground in the 2D sections, a new surface was generated. Finally, this surface was corrected, in order to include the information obtained from the historical satellite images. In some areas the triangulation between the boreholes averages the altitude between the points and does not capture the more vertical altitude difference produced by excavated rock. The relative positions from the excavation were introduced in a new set of 2D sections and the excavation form was drawn into it. After the final joint ground surface was created always having as fixed points the ground position in the boreholes and the TSF external area from the current topography (Fig. 8). As a consequence of the corrections made to consider the excavations, as can be seen in Fig. 8, in some positions the final bedrock surface is below the borehole originated surface.

5. Difficulties and uncertainty

Along this paper were discussed several existing difficulties when trying to create a ground surface in the absence of data. The steps to solve the difficulties depend on the existing set of data and on the TSF itself.

In this case-study, the inexistence of benches limited the positions available to perform the site investigation, reducing a lot the area available to obtain fixed bedrock positions. Nonetheless, it was possible to generate a reliable bedrock ground surface.

When overlapping the final surface to the original ground topographies (Fig. 9) it is seen that they do not match, even though the one from the feasibility study can has the same forms than the exterior area of the TSF.

Assuming as true the satellite generated original ground surface, it would have resulted in lower tailing thickness, smaller embankments height and lower storage volume, which would not be consistent with the other more reliable pieces of information. Gathering the evidences from available data is essential to conceptualize a well-reasoned idea during modelling.

The use of the term reliable has the objective to alert to the fact that there is uncertainty associated with the result. There are fixed known points, as the boreholes as the external areas, but, as presented, a set of assumptions were needed to connect the fixed points that, nonetheless, aimed to approximate the final result to the “reality”.

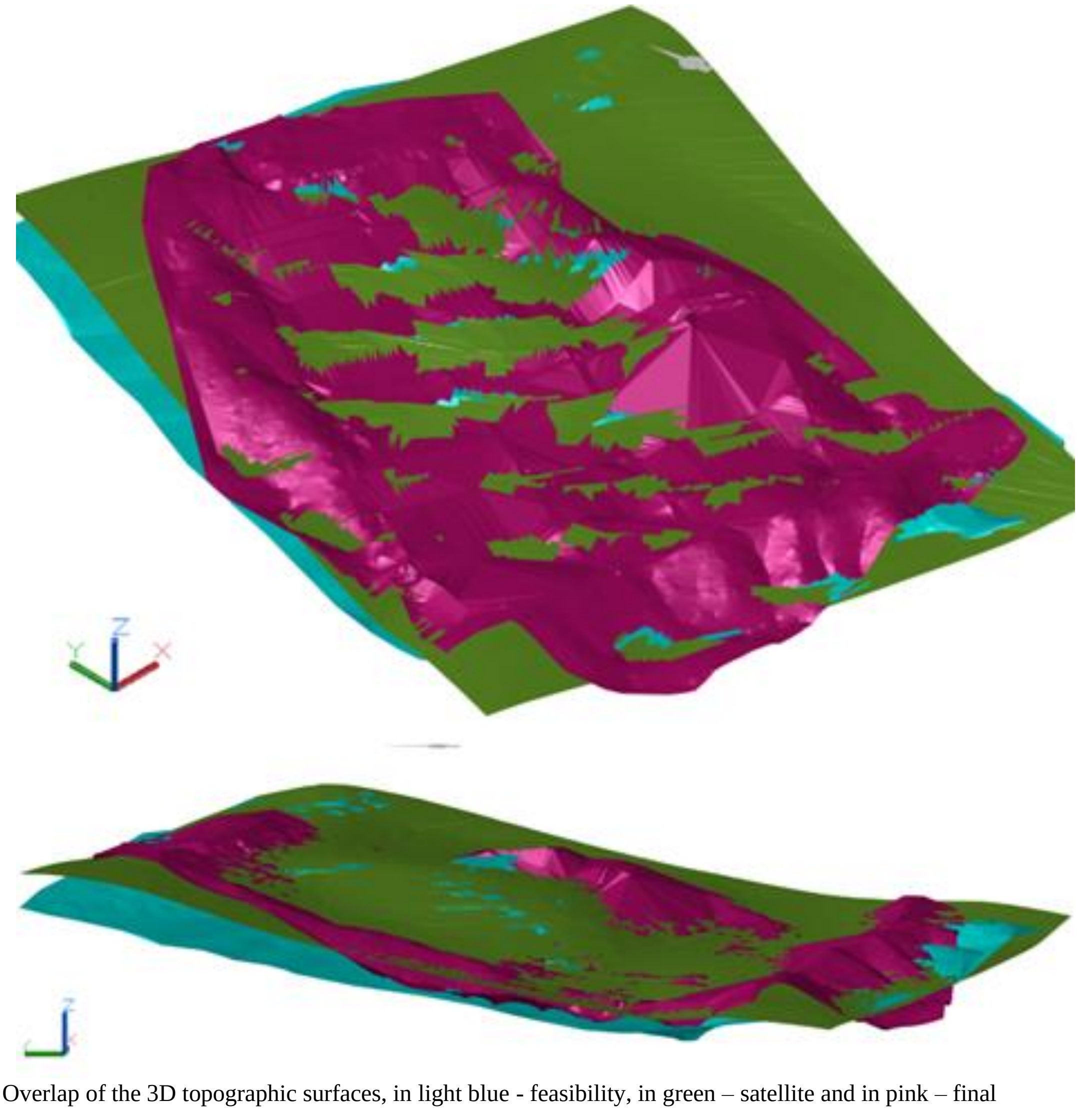

Figure 9. Overlap of the 3D topographic surfaces, in light blue - feasibility, in green – satellite and in pink – final

6. Conclusions

When lacking the documents and the information that supports building the TSF model, strategies have to be created to allow to verify the current state stability analysis. The main difficulty is the lack of reliable data and, unfortunately, there is not always a magic solution to solve the needs.

In a TSF model, the bedrock position plays a very important role, as from it is obtained the definition of the embankments base, and of the tailings thickness.

In some situations, creativity and engineering judgement end up being the best solution to create the most reliable bedrock ground surface, but it is very important to keep in mind that this surface has some uncertainty associated. Here, again, judgment takes an important part and the decisions must be made considering the risk associated.

With this paper it is also highlighted the importance of an integrated knowledge base, throughout the entire TSF lifecycle, as define in GISTM (ICMM, 2020). As stated in Principle 2 of GISTM the owner should "*Develop and maintain an interdisciplinary knowledge base to support safe tailings management throughout the tailings facility lifecycle, including closure*", where are included data on climate, geomorphology, geology, geochemistry, hydrology and hydrogeology (surface and groundwater flow and quality), geotechnical, and seismicity (Requirement 2.2).

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