Satellite Synthetic Aperture Radar for Mine and Tailings Dam Monitoring

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There is a new mining paradigm as low-grade surficial deposits replace increasingly deeper mature mines. Such shallow operations are often accessed via opencast pits with slope stability being an important safety issue. Increased tonnages also mean larger tailings dams, the failure of which can lead to human, economic and environmental catastrophes. High-resolution multipolarisation synthetic aperture radar (SAR) provides a quantitative and cost-effective tool for monitoring open pit mines and tailings dams. The example of the Fundão iron ore tailings dam is presented, the failure of which on 5 November 2015 was the worst environmental disaster in Brazilian history. The tailings dam collapsed due to a sudden catastrophic liquefaction of sand and gravels. A sudden increase in moisture content in the dam's left abutment setback (coinciding with cracks mapped over a year before the collapse) is evident in SAR imagery collected two weeks before the disaster. SAR monitoring could perhaps have prevented this catastrophe.

INTRODUCTION

The importance of monitoring tailings dams for safety, environmental protection and mining production was reinforced in March 2018 when Newcrest was forced to suspend mining operations at Cadia, one of Australia's largest gold mines, after a partial wall collapse at one of the tailings dams. Two earthquakes had recently hit the area and heavy rains in New South Wales was also cited as a factor in the failure of the northern earth-fill dam wall, which collapsed into the southern tailings dam (Sydney Morning Herald, 2018). Newcrest shares fell 5% after news of the collapse reached the market.

While the Cadia collapse was a modest economic mishap, the failure of the Fundão tailings dam on 5 November 2015 was the largest environmental disaster in Brazil's history. It unleashed 43 million m^3 of iron ore tailings, which polluted 668 km of watercourses of the Doce River to the Atlantic Ocean and killed at least 19 people (Fonseca do Carmo *et al.*, 2017) (see Figures 1 to 4). In December 2017, a Brazilian judge decided that the criminal case against 21 executives from mine owners Samarco (a joint venture between Vale and BHPBilliton) should proceed in the courts. Two years after the disaster, studies of the water quality at 16 of 18 test sites in the Doce River confirmed that it still unfit for human consumption.

The case for monitoring tailings dams and predicting failures is well made. Modern technology has a role to play as many of the tailings dams are in remote locations. Satellite synthetic aperture radar (SAR) offers a cost effective monitoring option.

Figure 1: Fundão tailings dam from Google Earth before collapse.

Figure 2: Fundão tailings dam from Google Earth immediately after collapse.

SATELLITE SYNTHETIC APERTURE RADAR

The Sentinel-1 A and B synthetic aperture radar satellites (SAR) images the Earth at 5 m spatial resolution in the C-band (5.4 GHz) every 12 days. A signal is transmitted in either horizontal (H) or vertical (V) polarisation, and the return wave received in both H and V polarisations. Data are free and the dual polarization of the system (VV and VH) may be used to estimate dielectric constants for reflectors on the surface and hence inferences of water content of surficial material may be made.

ESTIMATING DIELECTRIC CONSTANTS FROM MULTIPOLARISED SAR

The multipolarised reflection of an incident radar wave is dependent on two physical parameters: the incidence angle of the wave on the target and the dielectric constant of the material comprising the target. The dielectric constant is essentially the ability of a material to retain a charge and varies from 0 for free air to 80.10 for water at 20 °C. As soil becomes wetter, the dielectric constant increases. It is a very sensitive measure of moisture content of soils.

The dependence of incidence angles and dielectric constants for Sentinel-1 SAR images for four scenes collected over the Fundão tailings dam are shown in Figure 5. Incidence angles varied from 30.325° to 38.76° over the scenes.

Given a pair of multipolarised SAR images, we can invert the measured VH and VV reflectances for each pixel to obtain per pixel estimates of the dielectric constant and incidence angle by solving a nonlinear equation (Chilar and Ulaby, 1974).

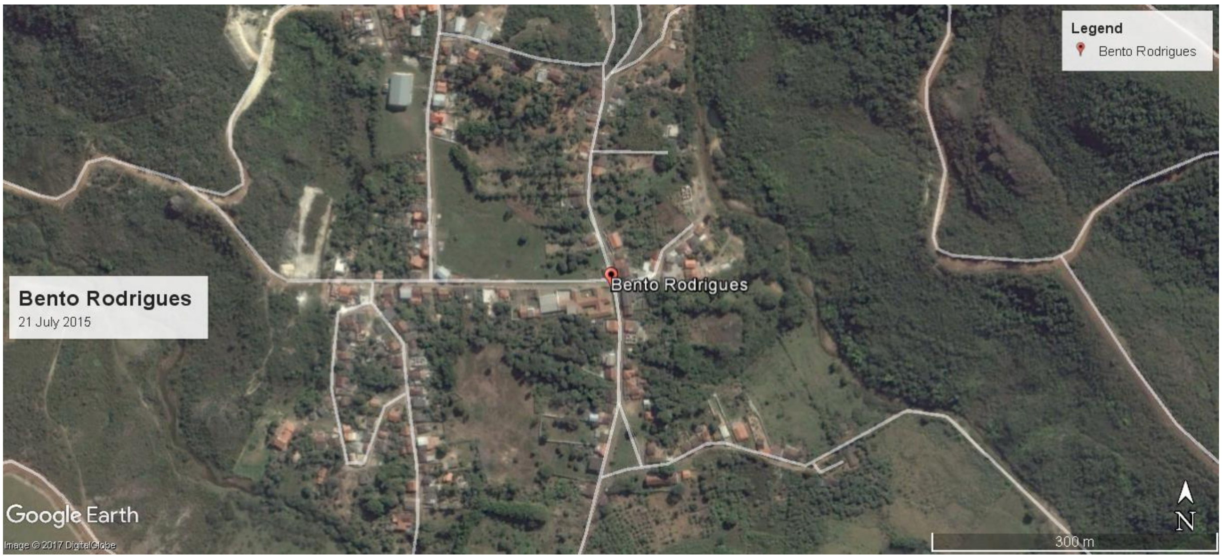

Figure 3: The village of Bento Rodrigues on 21 July 2015.

Figure 4: The village of Bento Rodrigues on 10 November 2015.

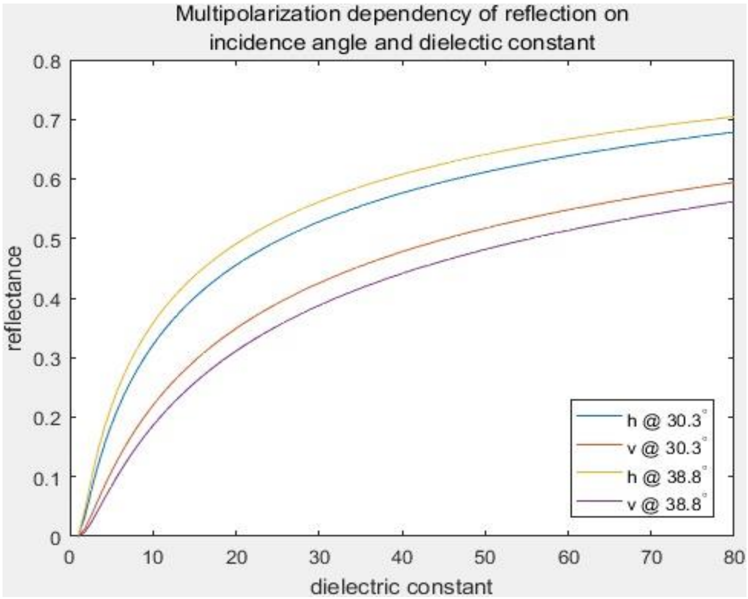

Figure 5: The nonlinear relationship between SAR reflectance and dielectric constant.

DATA PROCESSING

The dam wall that failed is shown in Figure 6, taken from Fonseca do Carmo *et al*. (2017). The Fundão tailings dam started operation in 2008 and, right from the start, saturation of sandy material was a problem. Figure 6(a) shows the state of the dam in 2011. There was a sandy tailings beach 300 m wide with the critical limit of contact between sandy tailings and sludge (labeled slime) denoted by an orange line.

Figure 6(b) shows the result of an engineering intervention: realignment of the left shoulder of the dam by moving it behind the section of a gallery filled with concrete, to allow the continuation of the landfill embankment. This retreat moved the crest of the dam closer to the water in the reservoir and the mud contained within it. The saturated mass of sandy tailings continued to grow, and by 2015, the critical limit had reached the dam crest, as is clear from Figure 6(c).

The question we pose is whether SAR may be used to monitor the saturation of sandy tailings in this situation because a technical report on the disaster (Morgenstern *et al*., 2016) concluded that the collapse was due to liquefaction of the sandy tailings, a phenomenon that occurs when solid materials lose their mechanical resistance and behave like fluids.

A dozen Sentinel SAR images over the dam prior to its collapse on 5 November 2015 were downloaded from the website of the European Space Agency (https://sentinel.esa.int/web/sentinel/sentinel-data-access). Natural logarithms were performed on calibrated and terrain corrected backscatter data. The preprocessing steps performed were:

1) update of satellite orbit parameters;
2) extraction of a geographic region of interest (ROI);
3) calibration of received data to sigma0 (backscatter) values;
4) range-Doppler terrain correction using a Space Shuttle radar derived elevation model.

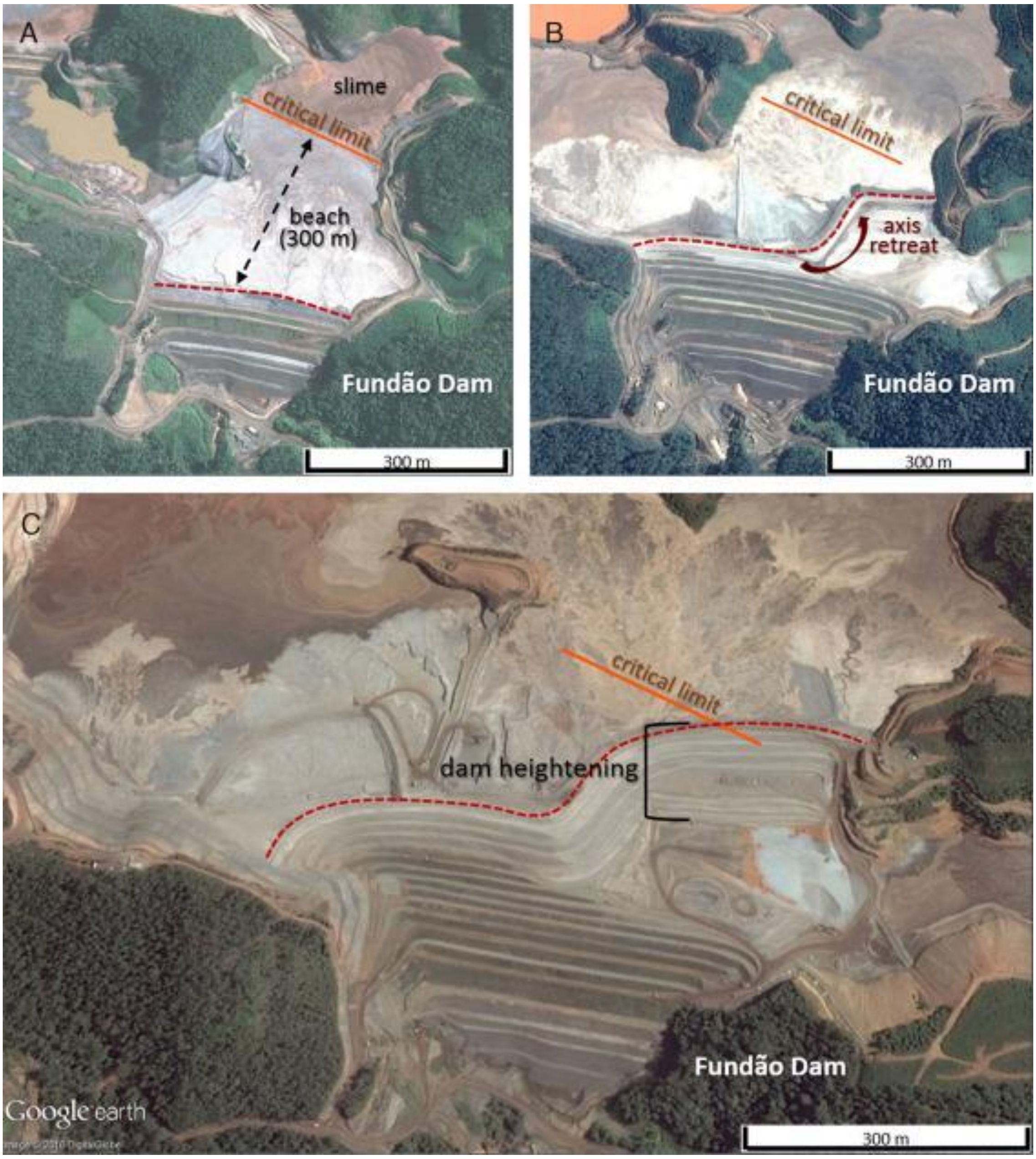

Figure 6: Detail of the Fundão tailings dam.

Dielectric constants were then estimated for each scene from the VH and VV polarized images. The largest 1% dielectric constants were coloured on the images in Figure 7, with red being the largest dielectric constants, corresponding to the wettest tailings dam slurry.

The report into the collapse of the dam commissioned by owner Samarco (Morgenstern *et al.*, 2016), released in August 2016, notes that cracks appeared in the left abutment setback of the dam wall in 2014 (Figure 8). These cracks were repaired. The report is available on a dedicated website (http://fundaoinvestigation.com) and registration is required to access it. Eye-witness accounts confirm that the dam failed at the left abutment setback. Dielectric constant estimates confirm moisture build-up in the vicinity of the repaired cracks prior to the catastrophic collapse (Figure 9).

In this case, the Figure 10 is clearly worth a thousand words. Arguments for monitoring moisture are quite persuasive, although work still needs to be done to convince the technical community. We contacted the lead author of the Morgenstern report with a preliminary version of our study and were told that, “any inquiry about the Fundão report should be addressed to the legal firm that commissioned it (Cleary, Gotlieb et al. in New York). I think that their details are presented somewhere on the website containing the report.”

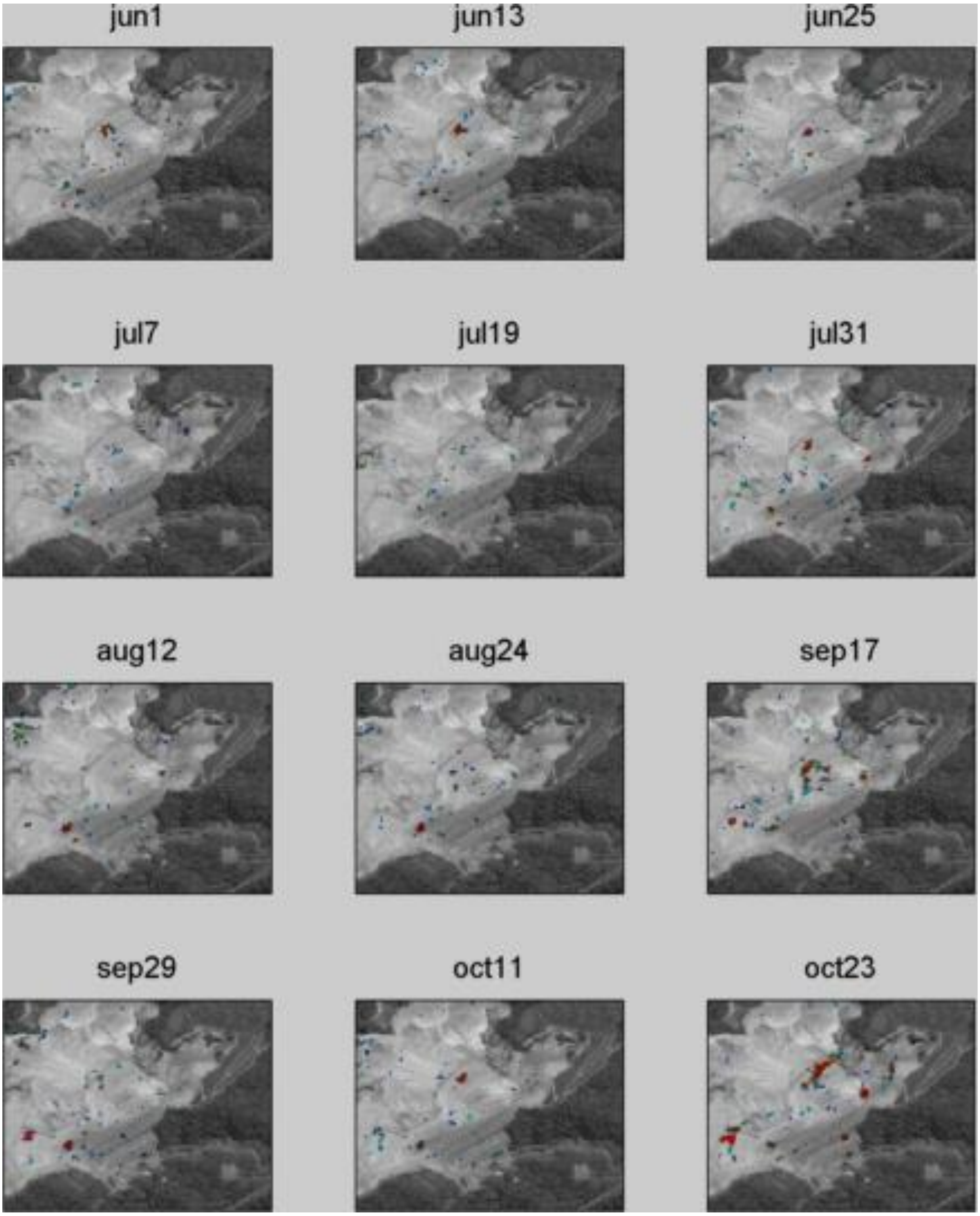

Figure 7: Moisture estimates for 12 SAR scenes before the dam broke.

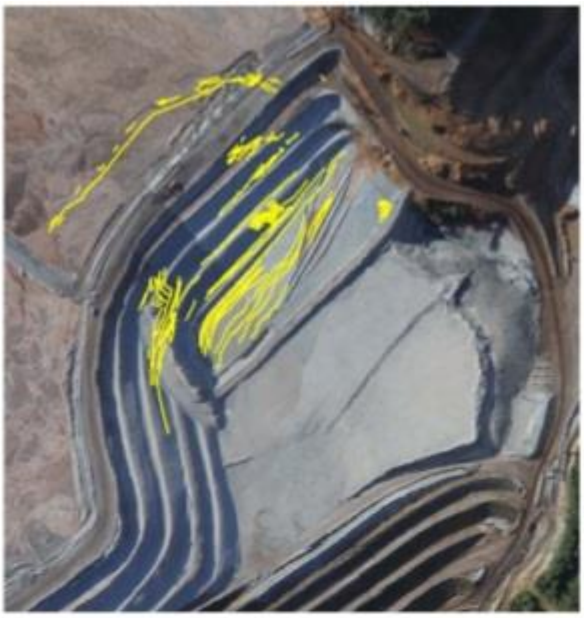

Figure 2-14 August 27, 2014 cracking at left abutment setback

Figure 8: Cracks mapped at the left abutment setback over a year before collapse.

Figure 9: Moisture starts to build up in the vicinity of the 2014 cracks.

CONCLUSIONS

Free satellite SAR imagery may be used to estimate moisture content images for slimes dams and open pit mines at 5 m spatial resolution using nonlinear estimation of dielectric constants in the scene. The revisit time of the Sentinel SAR satellite is 12 days, allowing for a cost-effective bi-monthly moisture monitoring program to be implemented for tailings dams and opencast mines.

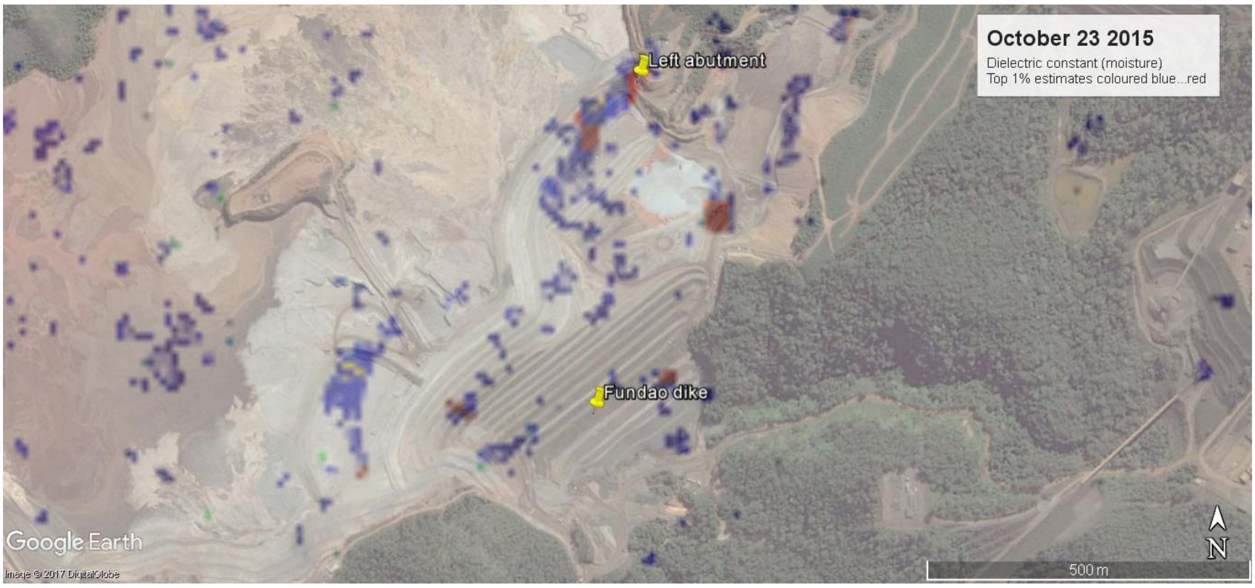

Figure 10: Two weeks before the left abutment failed, moisture is clearly an issue.

REFERENCES

Chilar, J., Ulaby, F.T. (1974). Dielectric properties of soils as a function of moisture content. https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19750018483.pdf

Fonseca do Carmo, F., Hiromi, L., Kaminoa, Y., Junior, R.T., de Campos, C.L., Silvino, G., Junio da Silva, K., de Castro, X., Mauro, M.L., Uchoa, N., Rodrigues, A., de Souza Miranda, M.P., Pinto, C.E.F. (2017). Fundão tailings dam failures: the environment tragedy of the largest technological disaster of Brazilian mining in global context. *Perspectives in Ecology and Conservation,* 15, 145–151.

Morgenstern, N.R., Vick, S.G., Viotti C.B., Watts B.D. (2016) Report on the immediate causes of the failure of the Fundão dam. http://fundaoinvestigation.com/wp-content/uploads/general/PR/en/FinalReport.pdfNorbert R.

Sydney Morning Herald (2018). Work suspended after dam collapses at Australia's largest gold mines (10 March). https://www.smh.com.au/national/nsw/work-suspended-after-dam-collapses-at-australia-s-largest-gold-mines-20180310-p4z3s7.html.