Minimally invasive XRF-CPT for in situ mineralogical and geotechnical investigations of tailings

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ABSTRACT: Throughout the world, tailings have accumulated as processing residues from the mining industry that still contain significant amounts of base, rare earth and precious metals. Rising demands from high-tech industries bring tailings into the focus as a source of raw materials. Fugro has developed a new tool for fast, minimally-invasive and in situ screening of tailings. A standard cone penetration test (CPT) combined with a built-in, highly sensitive X-ray fluorescence (XRF) detector measures element-specific X-ray fluorescence radiation in the screened soils. The system simultaneously detects metal content and distribution, and geotechnical parameters, such as lithology and density, within tailings bodies — in real-time and with high resolution. In this contribution, we present insights from copper tailings exploration in Chile comprising field investigations and 3D modelling of the element distribution for the studied tailings bodies. The XRF-CPT can investigate tailings to a depth of several tens of meters, making it a faster and more cost-effective tool to assess and quantity metals contents compared to conventional approaches based on drilling, sampling and assaying. Our studies demonstrate the relevance and capability of XRF-CPT investigations as a promising tool for commercial environmental assessments and feasibility studies for the re-mining of tailings.

1 INTRODUCTION

Mine tailings, the accumulation of processing residues from the mining industry, are widely distributed across the world. In China, about 10 billion tons (bt) of tailings existed in 2009, and 1 bt of tailings material being added each year (Xiong et al., 2009). Tailings in regions with a long mining history can contain considerable amounts of metals and unextracted by-products. Especially in older (and deeper) tailings, metal contents tend to increase due to the lower metal recovery in the past (e.g. Pan et al. 2014).

On the one hand, recent interest in historic mine waste is linked to the increasing demands in rare metals for the high-tech industry and the associated rise in metal prices. It makes tailings a potentially valuable source for re-mining (Ussath et al. 2017). The Pan-European Reserves & Resources Reporting Committee (PERC) Standard now also considers mineralized tailings for reporting mineral resources and reserves (PERC, 2017). On the other hand, re-investigation of tailings is necessary for the assessment of environmental and eco-toxicological risks (Oyarzún et al., 2012; Ussath et al., 2017).

A study from Chile, where Cu, Ag, Au have been mined since the 1830s, shows that erosion and discharge from historic tailings pose a considerable source of pollution (Oyarzún et al., 2012).

Assessing the feasibility for future exploitation of tailings requires a thorough understanding of the mineral composition, the spatial distribution and the quantity of metals in tailings. Typically, complex conditions are closely linked to the tailings´ history, controlled by factors, such the variability in the chemical composition of the extracted ore, changes in the processing technology, or physical factors, such as gravitational separation during tailings discharge (Pan et al. 2014). Traditional approaches for geochemical surveys on tailings combine drilling, sampling and laboratory coupled with 3-D modelling.

The Chinese Geological Survey evaluated 26 large tailings dams based on 291 drill holes, arranged in 50- to 100-m-spaced transects and combined with the analyses of almost 10,000 samples with 1 m depth resolution (Pan et al., 2014). The development of faster and more cost-effective tools to investigate tailings for secondary mining remains challenging. Recently, X-ray fluorescence (XRF)-based measurements successfully identified zones of metal enrichment in tailings by XRF-scanning of drill cores (Kuhn et al. 2016) or hand-held XRF measurements on tailings surfaces combined with traditional chemical assaying (Bodénan et al., 2015;

Ussath et al., 2017). These applications, however, still require costly drilling and sampling procedures.

The lack of efficient in-situ screening tools providing quick and reliable data of both the geochemical and geotechnical parameters on tailings led to the development of an advanced direct sensing probe using state-of-the-art technology for in-situ geotechnical site investigation, known as cone penetration testing (CPT). CPT determines the lithology, physical and mechanical properties of the soil and the hydrogeological regime of the subsurface (Lunne, Robertson & Powell, 1992). Fugro, a worldwide specialist in CPT tests, has developed an innovative system, which combines a CPT cone with an X-Ray Fluorescence Tool (XRF-CPT) (e.g. see Schwank et al., 2016; Martac et al., 2018).

The current standard Fugro XRF-CPT cone detects metals, such as Fe, Co, Ni, Cu, Zn, As, Se, Mo, Hg and Pb with element-specific lower detection limits ranging from 100 to 1000 ppm. The detection limit and the resolution depend on the measurement time, the soil matrix and the occurrence of interferences with other elements. The appropriate analytical protocol can be refined depending on target elements and the project-specific tasks and requirements.

2 METHODS

2.1 *The XRF-CPT Probe*

Like standard CPT, the XRF-CPT cone is statically pushed into the ground at a rate of about 2 cm/s deployed by a 20-ton-CPT crawler. CPT measurements digitally record the cone resistance, sleeve friction, and pore pressure every second. Automated soil classification is carried out according to the simplified chart method after Robertson et al. (1986). Moreover, the heavy metal concentrations are simultaneously detected by the XRF system, which is enclosed in a sub behind the standard CPT cone. Metal detection is based on the emission of characteristic “secondary” (or fluorescent) X-rays from a material that has been excited by high-energy X-rays. The built-in X-ray tube generates a bundled X-ray beam, directed into the host lithology through a window in the cone housing. The system can measure in the unsaturated as well as saturated zone (Fig. 1).

In this study, the XRF system was equipped with a W-anode 40 kV X-ray tube and silicon drift detector. The device was calibrated with characterized tailing material typical for the region before and after the in-situ data acquisition. The heavy metals were identified and quantified based on comparing measured energy spectra with reference spectra using specialized software. Data validation was based on the comparison between metal concentrations determined by the XRF-CPT system and traditional lab analyses of site-specific samples (n = 19).

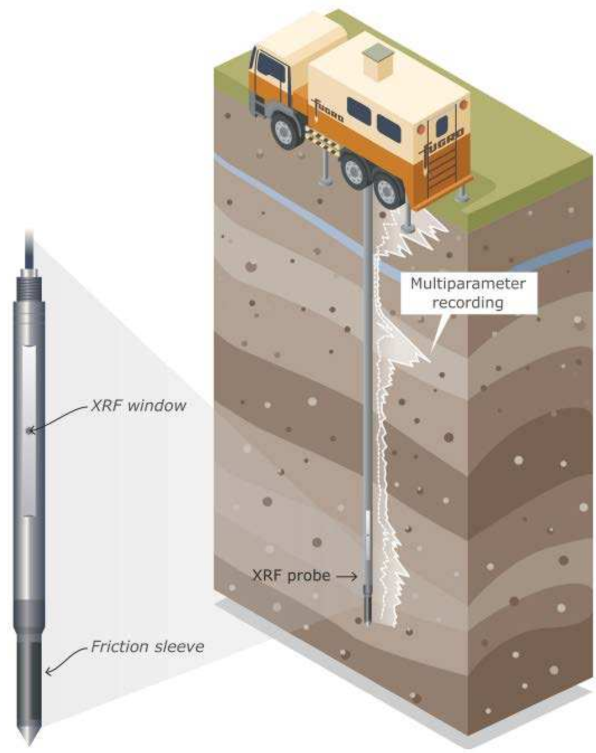

Figure 1. Schematic illustration of the application of the Fugro XRF-CPT multiparameter probe.

2.2 *Field deployment*

The study combined a geotechnical and geochemical site investigation across a tailing body at 38 different locations to assess the amount and distribution of target elements for potential secondary mining. In this case, continuous XRF-measurements were integrated at 0.3 m depth intervals.

The screening data on target parameters related to lithology and geotechnics, with respect to heavy metal concentration were visualized in vertical profiles using Fugro´s GeODin software (Fig. 2). Subsequently, 2-D cross sections of elemental concentrations were generated and used to simulate the 3-D metal distribution (Fig. 3) based on several cut-offs.

3 RESULTS

The in-situ XRF-CPT investigations of the tailings body revealed distinct vertical variations in metal concentration at all tested sites (Fig. 2). While the metal concentrations in the upper portion of the tailings body remained generally low, all profiles displayed an increase in metal contents towards the bottom, particularly below 20 m depth (Fig. 2 and 3).

Below 10 m depth, enrichment layers of Cu, Zn and Pb concentrations as illustrated in Fig. 2 at ~12 m and 22-23 m below ground level were observed in several profiles. The qualitative screening of measured XRF spectra data showed that no significant concentrations of other precious metals were present.

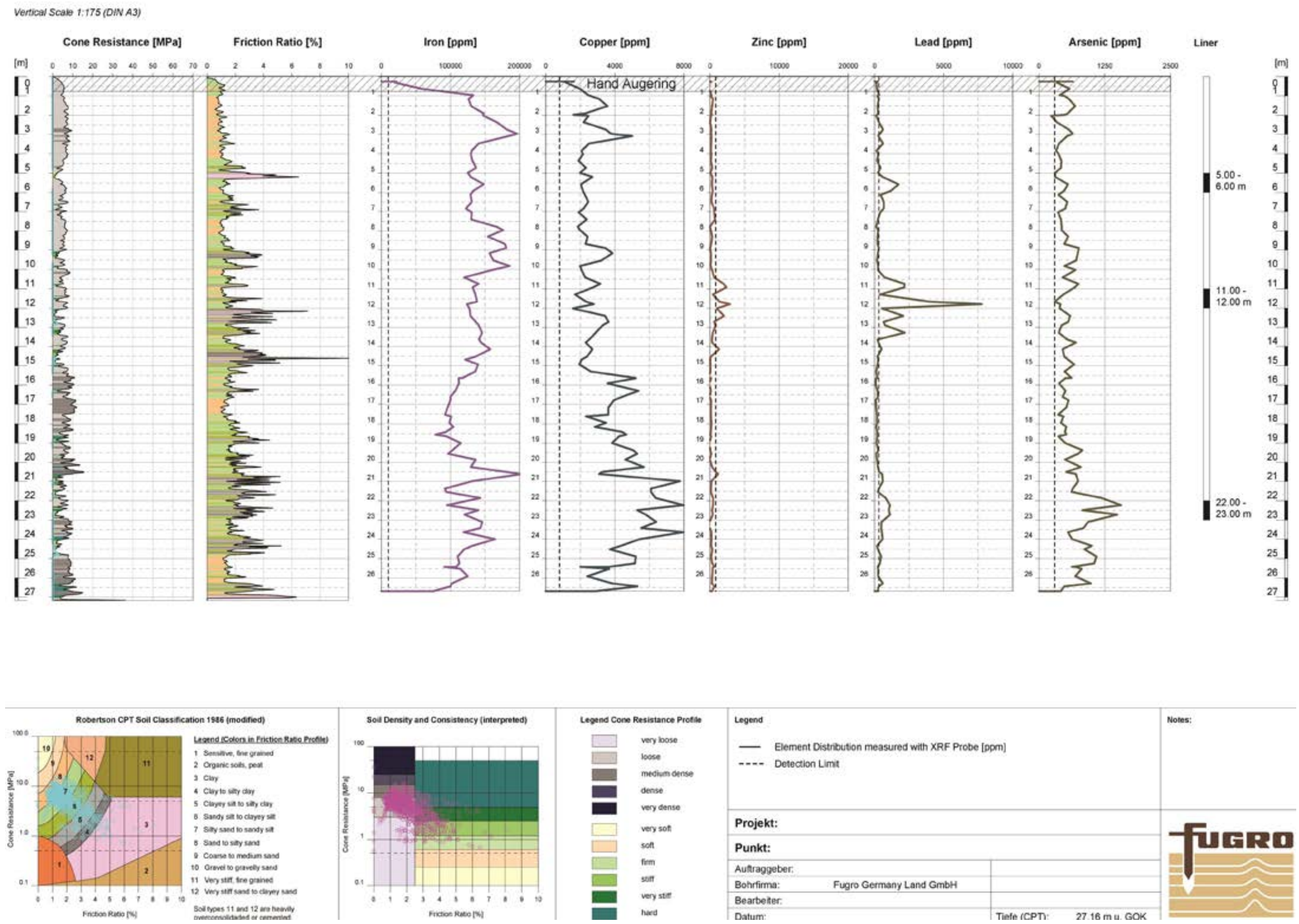

Figure 2. XRF-CPT log of geotechnical & geochemical parameters.

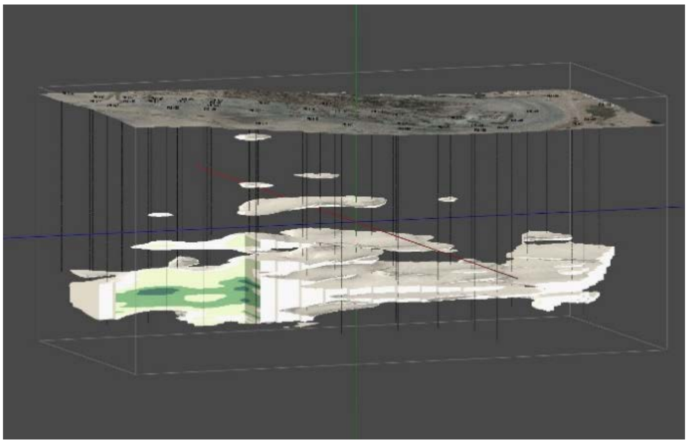

Figure 3. Modelled 3-D copper distribution, darker green shows higher concentration.

4 DISCUSSION

Tailings are often characterized by a fine-grained and soft texture (Fig. 2), which can be easily penetrated by Fugro's CPT technique. The XRF-CPT probe allows for a fast screening of element concentrations in tailing bodies, at high resolution and in real time. The CPT delivers additional in-situ data on soil types and the stability of the tailing material. Field-proven grid optimization capabilities allowed for the fast 3-D field delineation of metal-enriched horizons.

With a daily productivity of 80 to 100 m, depending on site conditions, the XRF-CPT tool proved to be a rapid screening instrument for the spatial distribution of target metals and lithology with depth.

The 0.3 m vertical resolution chosen for the XRF screening in this tailing investigation was proven to be sufficient to identify metal-enriched horizons within a reasonable time and cost frame. By optimizing the penetration rate and the measurement time, the vertical resolution could be further optimized. At sites where the tailings are covered by shallow water (like ponds), the probe can be advanced from small jack-up platforms or pontoons.

The innovative XRF-CPT screening has a low environmental impact and is a flexible and versatile method to deliver a continuous log of elemental concentration and lithology with depth. The 3-D modelled copper distribution shown in Fig. 3 highlights an economically interesting copper layer at the base of the tailings body and allowing to assess the potential mass vs. volume relationship necessary to guide decision-makers in the re-mining process. It demonstrates a clear advantage compared to conventional approaches for tailings characterization involving sampling and lab analysis (e.g. Kuhn et al., 2016, Ussath et al., 2017) that require rigid predefined investigation strategies and time-consuming and costly field campaigns. In addition, this study stresses the importance of applying deeper (more than 20 m) in-situ measurements, as metal-rich layers may be observed at depths exceeding 10 m. Especially for older tailings, with potentially physical and chemical remobilization at depth, shallow investigations may not be representative of deeper horizons. The newly developed XRF-CPT probe has easily identified target horizons for commercially attractive application of secondary mining of copper-rich horizons. The high-resolution XRF-CPT data allows for a precise 3-D delineation of metal-containing layers, supporting on-site decisions and optimized sampling strategies. In addition, the tool detects geotechnical site conditions relevant for decisions for future design of re-mining activities and the processing methodologies.

5 CONCLUSIONS

Fugro´s XRF-CPT is a next-generation tailings exploration technology. Being fully compatible with Fugro's current push equipment ensures a full transfer of CPT mobile and flexible characteristics, allowing its worldwide application. Applicable under the strictest health and safety requirements with no hazardous waste, no soil cuttings and minimum site disturbance, the presented application of XRF-CPT is more cost-effective and less invasive compared to conventional approaches and minimizes physical soil sampling.

Further developments of the XRF-CPT probe regarding broader detectable element range as well as maximum sounding depth are envisioned. Several probe configurations optimized for lighter elements such as Ti, Co, V, Mn as well as heavier elements such as Pd, Cd, Sn, Sb will soon be ready for testing. A key step would also be the conversion from analog to digital signal broadcast, which would improve detection limits and allow for deeper sounding depths of up to 60 m.

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