Soils and Rocks
An International Journal of Geotechnical and Geoenvironmental Engineering
www.soilsandrocks.com
ISSN 1980-9743
ISSN-e 2675-5475

# Field measurement of hydraulic conductivity in a compacted filtered iron ore tailings stack using mini-infiltrometer tests

Talita Menegaz[1#], Júlia Sattomura Nascimento[1], João Paulo de Sousa Silva[2], Crisley Guimarães Amaral[2], Marcus Vinícius Lima Dias[2], Yuri Gouvea Correa[2], Fernando Antônio Medeiros Marinho[1]

Article

**Keywords**
Compacted filtered tailings
Iron ore tailings
In situ hydraulic conductivity
Mine waste management

**Abstract**

This paper presents a field-based assessment of near-surface hydraulic conductivity in a compacted filtered iron ore tailings stack using mini-infiltrometer tests. A total of 115 in situ measurements were performed on the compacted surface, providing a dataset for evaluating the variability of near-surface field measurements under controlled suction conditions. The mini-infiltrometer results are interpreted as hydraulic conductivity values associated with the pressure head applied at the porous disk–tailings interface, not necessarily as fully saturated hydraulic conductivity. The measured values ranged from $1.14 \times 10^{-7}$ m/s to $4.59 \times 10^{-6}$ m/s, with an arithmetic mean of $1.31 \times 10^{-6}$ m/s, a median of $1.20 \times 10^{-6}$ m/s, and a geometric mean of $1.12 \times 10^{-6}$ m/s. Although the results were concentrated around $10^{-6}$ m/s, the coefficient of variation was approximately 56.9%, indicating relevant relative variability. Most values were located between $5.0 \times 10^{-7}$ m/s and $3.0 \times 10^{-6}$ m/s, supporting the use of the geometric mean as a representative central estimate for engineering analyses. The influence of imposed suction ($h_0$) was also examined; however, no systematic dependence on the applied values was identified. Comparison with published data shows that the results fall within the range reported for compacted and filtered tailings, while reinforcing that hydraulic conductivity cannot be inferred from void ratio alone. The study highlights the importance of direct field measurements for supporting seepage analyses, transient flow modelling, water balance assessments, and hydraulic characterization of filtered tailings stacks.

## 1. Introduction

Filtered tailings disposal has become an increasingly relevant alternative to conventional slurry-based tailings storage, particularly because it enables higher water recovery, reduces the volume of water stored in the facility, and allows the construction of compacted, unsaturated deposits. In the case of iron ore tailings, this approach is especially important in regions where regulatory, environmental, and operational constraints have intensified the search for safer disposal systems. However, the performance of filtered tailings stacks depends not only on achieving adequate compaction, but also on understanding how water enters, moves, and redistributes within the compacted tailings mass.

Hydraulic conductivity is one of the key parameters controlling this response. It governs infiltration during rainfall, internal seepage, drainage efficiency, moisture redistribution, and the development or dissipation of pore water pressures. In filtered tailings stacks, where the material is commonly placed at low to intermediate degrees of saturation, the hydraulic response is strongly linked to unsaturated flow conditions. Therefore, both the hydraulic conductivity and the unsaturated hydraulic conductivity function are relevant for evaluating whether rainfall infiltration will remain near the surface, migrate downward, accumulate above less permeable zones, or contribute to the formation of locally saturated regions. As discussed by Ulrich (2019), filtered tailings facilities should not be assumed to remain permanently unsaturated. Depending on the initial water content, climatic boundary conditions, hydraulic conductivity, suction, confining stress, stiffness, and loading rate, rainfall infiltration and internal moisture redistribution may lead to local or temporary saturation. In an initially unsaturated material, this process first causes a reduction in suction, associated with an increase in pore water pressure relative to the initial hydraulic condition. This transient pore water pressure buildup may progress to positive pore water pressures, affecting the mechanical response of the stack.

#Corresponding author. E-mail address: t.menegaz@usp.br
[1]Universidade de São Paulo, Departamento de Geociências, São Paulo, SP, Brasil.
[2]VALE, Departamento de Geotecnia, Belo Horizonte, MG, Brasil.

Submitted on June 18, 2026; Final Acceptance on September 24, 2026; Discussion open until February 28, 2026.
Editor: Renato P. Cunha
https://doi.org/10.28927/SR.2026.012426

This is an Open Access article distributed under the terms of the Creative Commons Attribution license (https://creativecommons.org/licenses/by/4.0/), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

The importance of hydraulic conductivity becomes more evident under tropical or wet climatic conditions, where intense and recurrent rainfall may significantly modify the water content of the stack. Dias Neto et al. (2025) showed that the hydraulic and stability responses of filtered iron ore tailings stacks are strongly affected by void ratio, material heterogeneity, and eventual undercompaction. Their numerical analyses indicated that lower void ratios tend to limit seepage and preserve matric suction, whereas undercompacted conditions may lead to rapid saturation, perched water tables, increased pore pressures, and reduced factors of safety. These findings reinforce that hydraulic conductivity is not only a seepage parameter, but also a controlling variable in the hydromechanical performance of filtered tailings stacks.

Compaction directly affects hydraulic conductivity by modifying void ratio, pore size distribution, and the internal structure of the tailings. Garcia et al. (2026) showed that the compaction state may influence water retention and hydraulic conductivity, thereby controlling infiltration, suction development, and moisture redistribution in filtered tailings stacks. Their results also indicated that variations in void ratio can exert a dominant influence on internal suction response under atmospheric boundary conditions. Similarly, Gan et al. (2019), studying iron tailings, emphasized that permeability is affected by fine particle content, depositional structure, and degree of compaction, and that conventional predictive equations may be inadequate when these factors are not considered. This aspect is particularly important for compacted iron ore tailings because compaction changes the void ratio, pore connectivity, and preferential flow paths. As a result, hydraulic conductivity measured or estimated under laboratory conditions, or obtained from empirical correlations, may not fully represent the hydraulic response of the material in the field.

Previous studies have also indicated that reliable hydraulic conductivity data for compacted filtered iron ore tailings remain limited. Portes & Espósito (2013) highlighted the scarcity of technical information on filtered iron ore tailings and emphasized the need for field and laboratory testing to improve predictions of dry stack performance. More recent studies have advanced the understanding of filtered tailings behavior, especially regarding compaction, moisture redistribution, unsaturated flow, and stability. However, the literature review conducted in this study shows that the number of published hydraulic conductivity data remains limited, and field measurements in compacted filtered tailings stacks are particularly scarce. This limitation is significant because hydraulic conductivity is highly site-specific and depends on material gradation, compaction conditions and field-scale heterogeneity. Therefore, direct in situ measurements are essential to provide representative parameters for seepage analyses, transient flow modelling, water balance assessments, and stability evaluations.

In this context, the present study evaluates the hydraulic conductivity of a compacted filtered iron ore tailings stack based on more than 100 field tests performed using a mini-infiltrometer. The field measurements are compared with hydraulic conductivity data reported in the literature for iron ore tailings and compacted filtered tailings. This comparison provides a basis for assessing the representativeness of field values, the range of variability observed in situ, and the relevance of direct measurements for the hydraulic characterization of filtered tailings stacks.

## 2. Literature data

Published data on the hydraulic conductivity of iron ore tailings indicate that this parameter is controlled by a combination of material characteristics, depositional history, compaction state, and testing conditions. Although hydraulic conductivity is often interpreted in relation to void ratio, the available literature shows that void ratio alone is not sufficient to explain the hydraulic response of tailings. Materials with similar void ratios may exhibit hydraulic conductivity values differing by several orders of magnitude due to differences in particle size distribution, fines and slime content, mineralogy, pore-size distribution, fabric, stress history, and method of deposition or placement.

Hydraulically deposited tailings generally tend to present higher hydraulic conductivity values than compacted filtered tailings, especially when segregation during deposition produces coarser zones with larger and more connected pores. This behavior was observed by Santos (2004), who reported comparatively high hydraulic conductivity values for hydraulically deposited iron ore tailings from the Monjolo tailings storage facility. In contrast, filtered and compacted tailings usually exhibit lower hydraulic conductivity because filtration and mechanical compaction promote denser particle arrangements and reduce pore connectivity.

The influence of fines content is consistently reported as one of the main controls on hydraulic conductivity. Studies involving filtered iron ore tailings with larger proportions of ultrafine particles and clay-sized fractions, such as those reported by Tebechrani Neto et al. (2025) and Dias Neto et al. (2024), showed hydraulic conductivity values reaching the order of $10^{-9}$ to $10^{-8}$ m/s. These results demonstrate that even relatively small variations in the fine fraction may strongly affect pore connectivity and water flow. Similar conclusions were reached by Nadai et al. (2023), who evaluated mixtures of flotation and slime tailings and showed that increasing slime content reduces hydraulic conductivity by modifying the pore-size distribution.

Compaction and stress state also influence hydraulic conductivity, but their effect is not independent of fabric and grain-size distribution. Carneiro et al. (2023), Santos et al. (2024), and Gan et al. (2019) showed that compacted or confined tailings tend to present lower hydraulic conductivity than loose or hydraulically deposited materials. However, changes in void ratio alone do not fully explain the measured differences. The method of compaction, particle rearrangement, and development of preferential or disconnected pore paths may produce distinct hydraulic responses even for comparable densities.

Field and laboratory measurements may also differ because they involve different scales, boundary conditions, specimen preparation procedures, and degrees of material disturbance. Nascimento (2024), for example, reported both laboratory and field hydraulic conductivity values for tailings from a kyanite mining deposit and observed that laboratory values covered a wider range and reached higher magnitudes than field measurements. This reinforces the importance of combining laboratory characterization with direct field measurements when representative hydraulic parameters are required for seepage analyses, transient flow modelling, and water balance assessments.

Overall, the literature indicates that hydraulic conductivity in iron ore tailings is governed by the interaction among void ratio, particle size distribution, fines content, mineralogy, depositional method, compaction procedure, stress history, and fabric. Therefore, predictive relationships based only on void ratio should be applied with caution, particularly when comparing tailings from different sources or disposal technologies. This background supports the need for site-specific field measurements, especially in compacted filtered tailings stacks, where hydraulic behavior may be strongly affected by near-surface conditions and construction-induced heterogeneity.

## 3. Materials and methods

### 3.1 Site description and material characteristics

The study site is one of the world's largest filtered tailings operations. Approximately 30,000 to 40,000 tonnes of filtered tailings are deposited and compacted daily. The facility, located in the Quadrilátero Ferrífero region, southeastern Brazil, is expected to contain approximately 120 million $m^3$ of tailings and waste rock at the end of its operational life. The final landform will exceed 100 m in height, with maximum deposit thicknesses approaching 80 m due to the inclined natural topography.

The beneficiation process generates two distinct waste streams. Flotation tailings are mechanically dewatered and transported to the filtered stack, whereas the finer slimes produced during desliming are hydraulically disposed of in a conventional tailings storage facility. Consequently, the filtered stack is composed predominantly of compacted flotation tailings. The material is deposited in loose lifts approximately 1.5 m thick, spread by bulldozers to layers not exceeding 0.6 m, and subsequently compacted using a 20-tonne smooth vibratory roller. Field quality control is performed using the Hilf compaction method, and a minimum degree of compaction of 98% is required during construction.

The investigated material consists of non-plastic flotation tailings composed primarily of quartz and iron oxides. The material is classified as silty sand or sandy silt and exhibits specific gravity values ranging from approximately 3.1 to 3.5. Because plasticity is absent, the mechanical behavior is primarily governed by density, particle arrangement and effective stress. Consequently, compaction becomes a key parameter controlling the small-strain stiffness and deformation behavior of the filtered tailings.

### 3.2 Field testing program

The field-testing programme comprised 115 in situ mini-infiltrometer measurements performed on the compacted surface of the filtered tailings stack. The tests were distributed within the planned investigation area, with repeated measurements at selected locations to capture local variability (Appendix A). Figure 1 shows the spatial distribution of the 77 georeferenced testing points for which location and elevation data were available.

### 3.3 Mini-infiltrometer method

Field hydraulic conductivity was evaluated using a mini-infiltrometer, a portable device designed to measure water infiltration at the surface of porous materials under a controlled imposed suction. Tension and disk infiltrometers have been widely used to estimate near saturated and unsaturated hydraulic conductivity because the imposed negative pressure head restricts flow to pores that are hydraulically active at the selected suction, reducing the direct influence of large macropores compared with ponded infiltration tests (Perroux & White, 1988; Ankeny et al., 1991). This feature is particularly useful for compacted filtered tailings, where hydraulic response may vary significantly over short distances due to changes in compaction, surface condition, fines distribution, and pore connectivity.

The mini-infiltrometer consists of a lower water reservoir connected to a porous disk placed in contact with the ground surface and an upper bubble chamber that controls the applied suction. The device operates according to the Mariotte bottle principle: as water leaves the reservoir and infiltrates into the material, air enters the bubble chamber only when the water level reaches the air-entry tube, thereby maintaining an approximately constant pressure head at the porous disk despite the falling water level in the reservoir. The main components of the equipment and the hydraulic principle adopted in the test are shown schematically in Figure 2.

The suction imposed during the mini-infiltrometer test should be interpreted as a hydraulic boundary condition applied at the porous disk-soil interface, rather than as a suction uniformly transmitted to the soil mass. This negative pressure head controls the hydraulic condition under which water enters the material and, consequently, determines which pore domains are active during infiltration. Therefore, the test does not necessarily measure the fully saturated hydraulic conductivity, but rather the hydraulic conductivity associated with the selected pressure head. If the imposed suction is lower than the air-entry value of the material, the main pore network remains water-filled, and the measured value may be interpreted as a near-saturated hydraulic conductivity.

CC BY

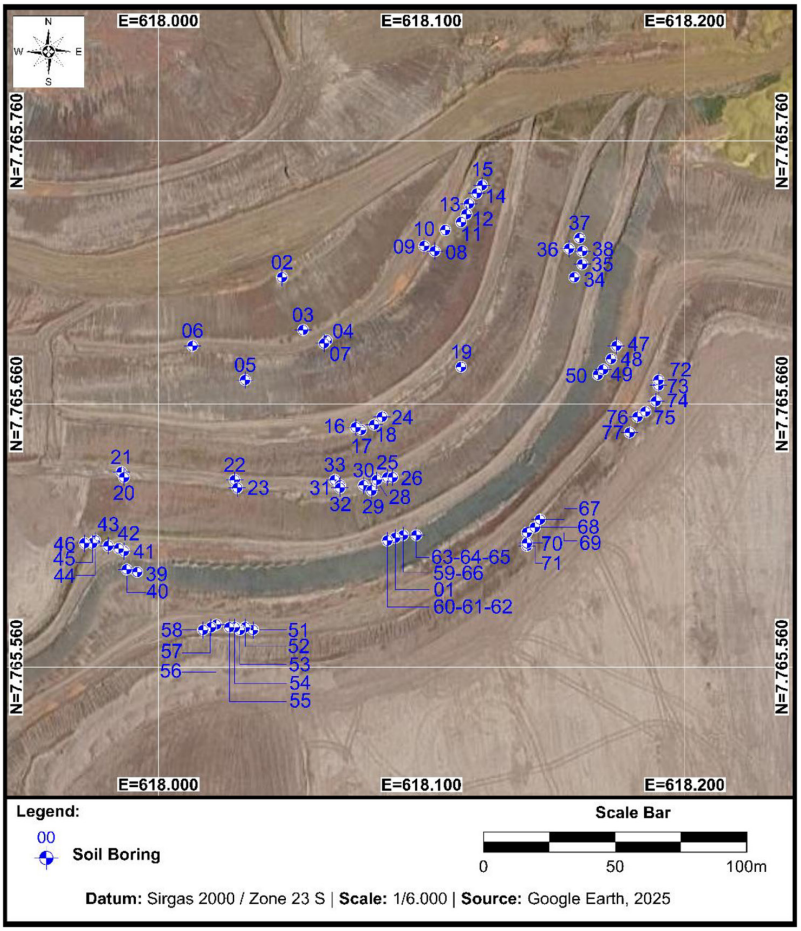



**Figure 1.** Location of the 77 georeferenced mini-infiltrometer testing points plotted on the compacted surface the filtered tailings stack.

Conversely, if the imposed suction is equal to or greater than the air-entry value, larger pores are progressively excluded from the flow process, and the measured hydraulic conductivity represents an unsaturated condition. This distinction is especially important for compacted filtered iron ore tailings, whose hydraulic response may be strongly affected by particle size distribution and fines content, pore connectivity, and compaction-induced fabric. In materials with very low air-entry values, even the minimum suction imposed by the equipment may already exclude part of the pore network, and the result should therefore be reported as hydraulic conductivity at the imposed suction rather than as saturated or near-saturated hydraulic conductivity.

Before each test, the surface should be prepared to ensure adequate contact between the porous disk and the compacted tailings. Loose particles are carefully removed, while avoiding disturbance of the compacted layer. The disk is then placed on the surface, and the decrease in water level in the reservoir is recorded as a function of elapsed time. These readings are converted into cumulative infiltration using the cross-sectional area of the reservoir and the contact area of the disk. The resulting cumulative infiltration curve is used to estimate the hydraulic conductivity corresponding to the applied suction.

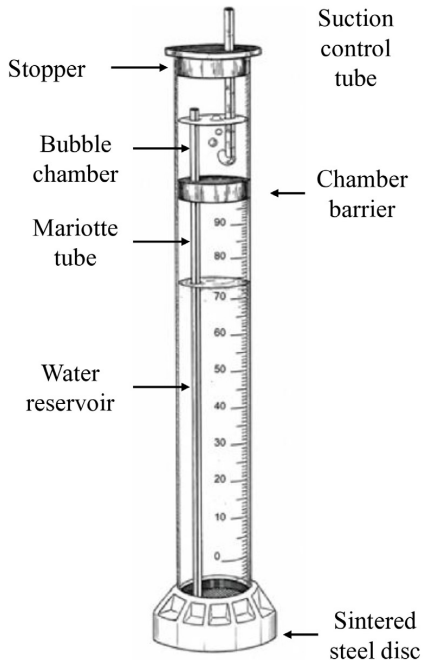



**Figure 2.** Schematic representation of the mini-infiltrometer used for field hydraulic conductivity measurements.

The interpretation adopted for mini-infiltrometer data is commonly based on the transient infiltration formulation proposed for disk infiltrometer measurements. The general form of the infiltration equation is consistent with classical infiltration theory, in which the early-time response is dominated by capillarity and the later-time response includes the contribution of gravity-driven flow (Philip, 1957; Wooding, 1968). In the simplified approach proposed by Zhang (1997), cumulative infiltration is represented by Equation 1:

$$I = C_1 t + C_2 \sqrt{t} \quad (1)$$

where $I$ is the cumulative infiltration, $t$ is time, and $C_1$ and $C_2$ are fitting parameters obtained from the measured infiltration curve. In this formulation, $C_1$ is associated with hydraulic conductivity and $C_2$ is associated with sorptivity and represents the capillary contribution to early-time infiltration. The hydraulic conductivity at the imposed suction is then estimated as shown in Equation 2:

$$k = \frac{C_1}{A_c} \quad (2)$$

where $k$ is the hydraulic conductivity corresponding to the imposed suction and $A_c$ is a dimensionless correction factor. The correction factor $A_c$ was obtained from the formulation proposed by Zhang (1997), which relates $A_c$ to the radius of the porous disk, the imposed pressure head, and the water retention parameters $\alpha$ and $n$.

In this study, more than 100 mini-infiltrometer tests were performed on the surface of a compacted filtered iron ore tailings stack. The large number of measurements was intended to characterize near-surface hydraulic response under field conditions and to assess whether hydraulic conductivity measurements can also serve as an indicator of spatial heterogeneity in the compacted surface. Because hydraulic conductivity in tailings may be affected by particle size distribution, fines and slime content, compaction condition, moisture state, fabric, surface preparation, and pore connectivity, the mini-infiltrometer results provide a direct field-based parameter for comparison with literature data and for use in seepage and transient infiltration analyses.

It should be noted that the mini-infiltrometer provides a near-surface measurement over a relatively small volume of material. Therefore, the results are sensitive to local surface conditions, contact quality between the disk and the ground, initial water content, air entrapment, layering, and small-scale heterogeneity. Despite these limitations, the method is useful for compacted filtered tailings because it is fast, repeatable, minimally invasive, and capable of generating a sufficiently large dataset to evaluate spatial variability under field conditions.

## 4. Analysis and results

For the 115 field test results, the hydraulic conductivity (k) ranged from $1.14 \times 10^{-7}$ m/s to $4.59 \times 10^{-6}$ m/s, with an arithmetic mean of $1.314 \times 10^{-6}$ m/s, a median of $1.201 \times 10^{-6}$ m/s, and a geometric mean of $1.116 \times 10^{-6}$ m/s. Although this range spans less than two orders of magnitude, the variability remains substantial when expressed in relative terms. The coefficient of variation, approximately 56.9%, indicates that hydraulic conductivity exhibits field-measurement variability within the analyzed dataset.

Such variability is consistent with permeability measurements commonly reported for geotechnical materials, where relatively small differences in soil structure and fabric may lead to pronounced variations in hydraulic conductivity. Nevertheless, this dispersion should not be overlooked. The predominance of values around $10^{-6}$ m/s supports the adoption of a representative conductivity within this order of magnitude for engineering analyses. In addition, the absence of pronounced outliers reinforces the suitability of using central tendency measures, particularly the geometric mean, when defining hydraulic parameters for seepage, infiltration, and unsaturated flow modeling.

Most measurements are distributed between $5.0 \times 10^{-7}$ m/s and $3.0 \times 10^{-6}$ m/s. Within this range, 96 of the 115 observations are included, corresponding to approximately 84% of the database. The lower and upper tails of the distribution contain relatively few observations, with only two measurements below $2.5 \times 10^{-7}$ m/s and three measurements above $3.0 \times 10^{-6}$ m/s. This pattern suggests that, despite the natural spatial variability expected for hydraulic conductivity, extreme values are uncommon.

The histogram in Figure 3 exhibits a moderately asymmetric distribution, characterized by a concentration of observations around the central classes and progressively decreasing frequencies toward both extremes. Such behavior is consistent with hydraulic conductivity datasets commonly reported for granular geomaterials and mine tailings, where variability arises from local differences in particle arrangement, density, fabric, and fines distribution. Nevertheless, the relatively narrow concentration of results around the modal interval indicates that the tested material presents a relatively consistent response in logarithmic scale across the investigated area.

The analysis was also performed as a function of the suction level imposed by the Mariotte reservoir, expressed as $h_0$. From a conceptual standpoint, when different $h_0$ values are adopted during testing, the resulting hydraulic conductivity value should be associated with the corresponding applied suction, since the hydraulic boundary condition may influence flow behavior within the system, particularly in unsaturated materials. Therefore, linking each permeability measurement to its respective $h_0$ value is important for data traceability and for the physical interpretation of the results.

CC BY

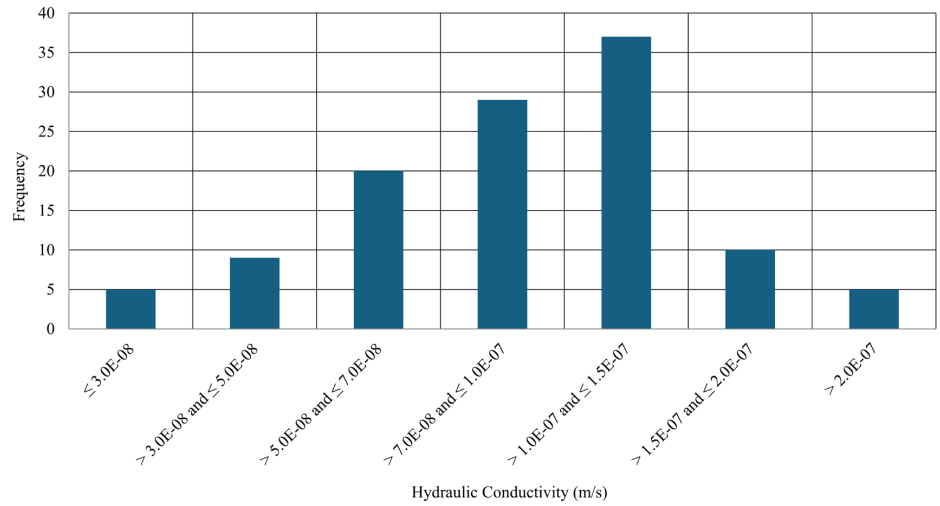



**Figure 3.** Distribution of hydraulic conductivity values obtained from field tests.

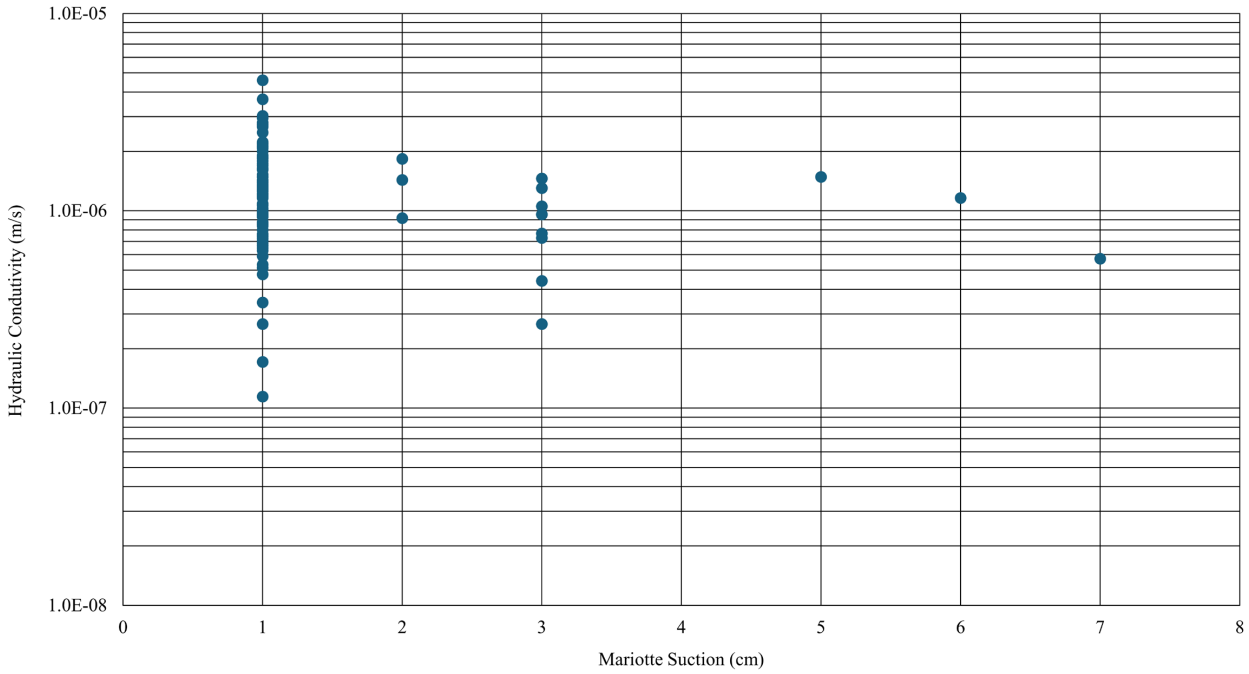



**Figure 4.** Hydraulic conductivity at the imposed suction as a function of the magnitude of the Mariotte suction, $|h_0|$.

Figure 4 presents the variation of hydraulic conductivity as a function of the suction applied through the Mariotte reservoir. Despite the conceptual importance of this association, no sufficiently consistent trend was identified to justify separating the $k$ values into distinct $h_0$ classes for parameter selection purposes. Furthermore, the number of measurements is not evenly distributed among the different $h_0$ levels, with a predominance of results corresponding to $h_0 = -1$ cm. For some $h_0$ values, only one or a few measurements are available, which limits any robust statistical comparison between different suction conditions. Consequently, although the association between $k$ and $h_0$ should be preserved within the database, the statistical analysis did not reveal any systematic variability related to $h_0$ that would justify adopting different hydraulic conductivity values for each applied suction level.

In general, the results indicate that hydraulic conductivity can be represented by a central value on the order of $10^{-6}$ m/s. Most measurements are concentrated between approximately $5 \times 10^{-7}$ m/s and $2 \times 10^{-6}$ m/s, although a limited number of values extend toward both lower and higher ranges. The data obtained under different Mariotte suction heads show no clear systematic dependence of hydraulic

conductivity on the imposed suction within the investigated interval (1–7 cm), suggesting that the measured variability is primarily associated with the intrinsic heterogeneity of the material rather than with the test configuration. For practical applications, a representative hydraulic conductivity on the order of $10^{-6}$ m/s may be adopted for seepage and unsaturated flow analyses. Nevertheless, the observed variability should not be disregarded, as local differences in particle arrangement, density, and fabric may influence transient flow simulations, wetting front advancement, and the prediction of hydraulic responses under unsaturated conditions.

### 4.1 Qualitative spatial assessment of hydraulic conductivity

A spatial assessment of the field tests indicates that hydraulic conductivity exhibits some variability across the investigated surface, without evidence of a continuous spatial pattern or a clearly defined hydraulic gradient. This level of dispersion is consistent with the heterogeneous nature of compacted filtered tailings surfaces, where relatively small variations in compaction conditions, surface structure, and local fabric may influence the measured hydraulic response.

Although a general range of hydraulic behavior can be identified, the variability observed between neighboring test locations suggests that hydraulic conductivity is strongly controlled by local heterogeneities. It should be emphasized, however, that this assessment is essentially qualitative and based on the relative spatial distribution of the measurement points.

Nevertheless, the distribution of the test locations demonstrates that the experimental program adequately covered different sectors of the investigated area, allowing the identification of zones exhibiting distinct hydraulic responses and confirming the importance of distributed field measurements for characterizing the surface hydraulic variability of compacted filtered tailings stacks.

### 4.2 Comparison with literature data

Figure 5 compares the hydraulic conductivity values obtained in the present study with published data for iron ore tailings and related mining residues. The compiled database includes hydraulically deposited tailings, filtered tailings, compacted dry-stack materials, laboratory measurements, and field measurements. The literature data span approximately five orders of magnitude, from about $10^{-9}$ to $10^{-4}$ m/s, confirming the broad variability of hydraulic conductivity in tailings materials and the strong influence of material type, depositional history, and fabric.

The hydraulic conductivity values measured in the present study range from $1.14 \times 10^{-7}$ m/s to $4.59 \times 10^{-6}$ m/s, with most values concentrated around $10^{-6}$ m/s. As shown in Figure 5, these measurements occupy an intermediate position within the compiled database and fall within the range commonly reported for filtered and compacted iron ore tailings.

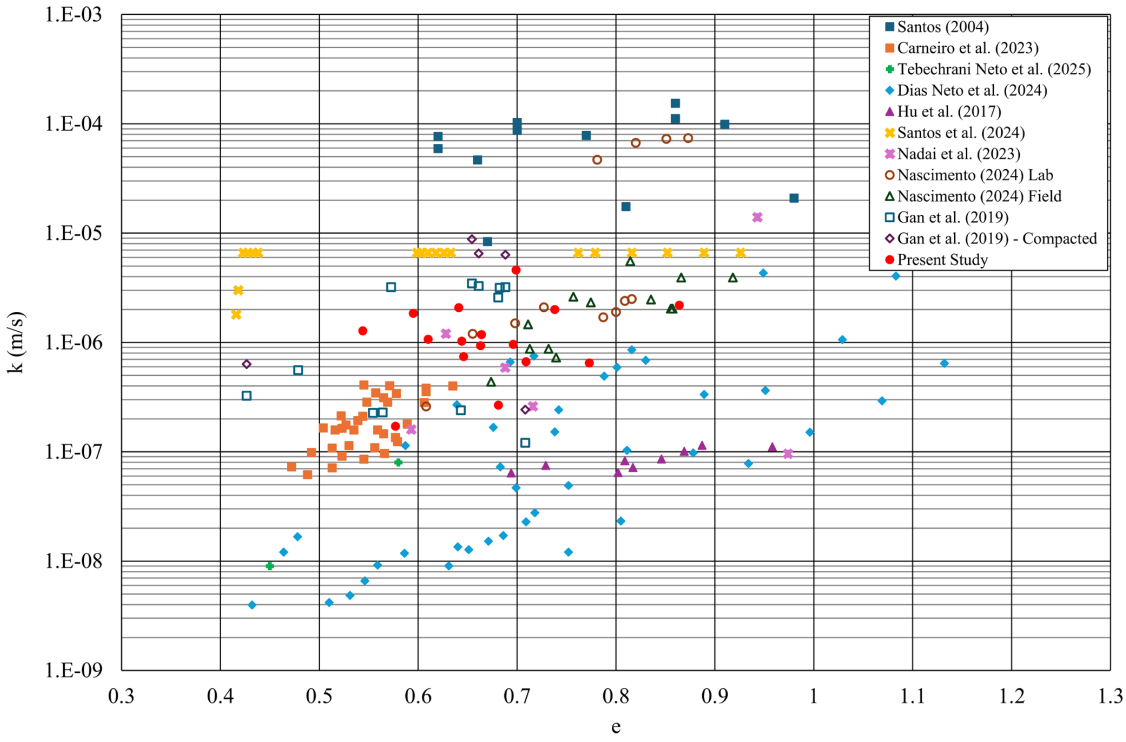



**Figure 5.** Hydraulic conductivity ($k$) as a function of void ratio ($e$) for iron ore tailings and related mining residues reported in the literature, including the results of the present study.

Compared with the overall literature dataset, the present results exhibit a relatively narrow spread on a logarithmic scale. This indicates that, although relevant field-measurement variability exists, the hydraulic response of the investigated compacted surface is comparatively constrained relative to the broader range reported for iron ore tailings.

The field measurements obtained in this study are substantially lower than those reported by Santos (2004) for hydraulically deposited iron ore tailings from the Monjolo Tailings Storage Facility, where hydraulic conductivity values commonly range from approximately $2 \times 10^{-5}$ m/s to more than $1 \times 10^{-4}$ m/s. This difference is consistent with the contrasting depositional processes involved. Hydraulic deposition may promote particle segregation and the formation of coarser, highly permeable zones, whereas filtration followed by mechanical compaction tends to reduce pore connectivity and produce a denser hydraulic fabric.

A closer agreement is observed with the datasets reported by Carneiro et al. (2023), Nascimento (2024), and Gan et al. (2019). Carneiro et al. (2023) investigated filtered iron ore tailings from the Quadrilátero Ferrífero and reported hydraulic conductivity values predominantly between $10^{-7}$ and $10^{-6}$ m/s. Nascimento (2024) evaluated compacted kyanite and iron ore tailings using both laboratory and field measurements, obtaining values that partially overlap those measured in the present study. Similarly, the compacted specimens reported by Gan et al. (2019) exhibit hydraulic conductivity values within the same order of magnitude as the present field data. This overlap suggests that the investigated material exhibits a hydraulic response representative of compacted filtered tailings subjected to controlled placement and densification.

In contrast, the datasets of Tebechrani Neto et al. (2025) and Dias Neto et al. (2024) generally define the lower envelope of the compiled database. Tebechrani Neto et al. (2025) reported hydraulic conductivity values reaching approximately $10^{-8}$ m/s for filtered iron ore tailings with elevated fines content, while Dias Neto et al. (2024) obtained values extending from approximately $10^{-9}$ m/s to $10^{-6}$ m/s over a broad range of void ratios. The substantially lower conductivities observed in these studies highlight the strong influence of particle-size distribution, ultrafine fractions, and pore-size characteristics on hydraulic behavior. Even at similar void ratios, hydraulic conductivity may vary by several orders of magnitude depending on the resulting microstructure.

The comparison also confirms that void ratio alone cannot adequately explain the hydraulic behavior of iron ore tailings. In the range of void ratios commonly associated with compacted filtered tailings, Figure 5 shows that hydraulic conductivity may vary by several orders of magnitude depending on particle size distribution, fines content, mineralogical composition, compaction method, stress history, and pore architecture. Therefore, although an overall tendency of increasing hydraulic conductivity with increasing void ratio can be recognized, the scatter in the data demonstrates that density must be interpreted together with the resulting material fabric.

The position of the present dataset within the compiled database indicates that the investigated filtered tailings stack exhibits hydraulic conductivity values characteristic of compacted and operationally densified tailings. The results further demonstrate the importance of direct field measurements, since the measured hydraulic response reflects the combined effects of material properties, compaction state, surface condition, and field heterogeneity. Consequently, the field-derived hydraulic conductivity values provide a robust basis for seepage analyses, transient infiltration modelling, water balance assessments, and the evaluation of the hydraulic performance of filtered tailings storage facilities.

## 5. Conclusions

This study presented a field-based evaluation of hydraulic conductivity in a compacted filtered iron ore tailings stack using 115 mini-infiltrometer tests performed under operational field conditions. The extensive testing program provides a representative basis for assessing the hydraulic behavior of the compacted surface layer and contributes to addressing the limited availability of field hydraulic conductivity data for filtered tailings facilities.

The measured hydraulic conductivity values ranged from $1.14 \times 10^{-7}$ m/s to $4.59 \times 10^{-6}$ m/s, with an arithmetic mean of $1.314 \times 10^{-6}$ m/s, and a median of $1.201 \times 10^{-6}$ m/s. Although the coefficient of variation reached 56.9%, most measurements were concentrated within the order of $10^{-6}$ m/s, indicating a relatively consistent response in logarithmic scale despite the natural heterogeneity of the compacted tailings surface. For engineering applications involving seepage analyses, infiltration assessments, and unsaturated flow modelling, the geometric mean value of $1.116 \times 10^{-6}$ m/s is considered the most representative measure of central tendency.

The results demonstrate that near-surface variability remains an important characteristic of compacted filtered tailings stacks. Hydraulic conductivity varied across the investigated area, with no clear continuous spatial trend or unique hydraulic gradient being identified. The observed variability is attributed to local differences in compaction conditions, surface structure, particle arrangement, and pore connectivity, highlighting the importance of distributed field measurements for capturing the hydraulic heterogeneity of large-scale tailings deposits.

The study also emphasizes the importance of correctly interpreting mini-infiltrometer measurements. The suction imposed by the Mariotte reservoir should be viewed as a hydraulic boundary condition acting at the disk–tailings interface rather than as a suction uniformly transmitted throughout the material. Consequently, the measured values correspond to hydraulic conductivity associated with the applied pressure head and may represent near-saturated

or unsaturated conditions depending on the relationship between the imposed suction and the air-entry value of the material. This distinction is particularly relevant for compacted filtered tailings, whose hydraulic response is strongly governed by pore-size distribution, fines content, and compaction-induced fabric.

Although hydraulic conductivity values should remain associated with their respective Mariotte suction levels ($h_0$) for traceability and physical interpretation, no systematic dependence of hydraulic conductivity on the imposed suction was identified within the investigated range of 1–7 cm.

Comparison with published datasets demonstrated that the hydraulic conductivity values obtained in this study occupy an intermediate position within the broader database of iron ore tailings and are consistent with values commonly reported for compacted and filtered tailings. In contrast, substantially higher conductivities are associated with hydraulically deposited tailings, while lower values are generally observed in materials containing larger proportions of ultrafine particles and clay-sized fractions. The comparison further showed that materials exhibiting similar void ratios may present hydraulic conductivity values differing by several orders of magnitude. This finding confirms that hydraulic conductivity cannot be adequately predicted from void ratio alone and is strongly influenced by particle-size distribution, fines content, mineralogical composition, depositional history, compaction procedures, stress history, and pore architecture.

Overall, the results reinforce the importance of extensive field testing for the hydraulic characterization of filtered tailings stacks and provide a representative dataset for seepage analyses, transient infiltration modelling, water balance studies, and the evaluation of the long-term hydromechanical performance of compacted filtered tailings facilities. More broadly, the study demonstrates that direct field measurements remain essential for defining representative hydraulic parameters and for reducing uncertainties associated with the design, operation, and performance assessment of filtered tailings storage systems.

## Acknowledgements

The authors gratefully acknowledge Vale S.A. for the logistical support provided during the field-testing program and for making the data used in this study available. The authors also acknowledge the Institute of Geosciences of the University of São Paulo (IGc-USP) for the institutional support provided for the execution of the tests and the development of the research activities reported in this paper.

## Declaration of interest

The authors have no conflicts of interest to declare. All co-authors have observed and affirmed the contents of the paper and there is no financial interest to report.

## Authors' contributions

Talita Menegaz: data curation, formal analysis, visualization, writing – original draft, writing – review & editing. Júlia Sattomura Nascimento: data curation, formal analysis, writing – review & editing. João Paulo de Sousa Silva: data curation, writing – review & editing. Crisley Guimarães Amaral: investigation, methodology, writing – review & editing. Marcus Vinícius Lima Dias: investigation, methodology, writing – review & editing. Yuri Gouvea Correa: data curation, formal analysis, writing – review & editing. Fernando Antônio Medeiros Marinho: conceptualization, methodology, data curation, formal analysis, supervision, project administration, writing – original draft, writing – review & editing.

## Data availability

Data generated and analyzed in the course of the current study are not publicly available due to confidentiality agreements, but a limited dataset can be made available by the corresponding author upon reasonable request.

## Declaration of use of generative artificial intelligence

This work was prepared without the assistance of any generative artificial intelligence (GenAI) tools or services. All aspects of the manuscript were developed solely by the authors, who take full responsibility for the content of this publication.

## List of symbols and abbreviations

| | |
|---|---|
| $e$ | Void ratio |
| $h_0$ | Pressure head imposed by the Mariotte reservoir at the porous disk–soil interface |
| $\|h_0\|$ | Magnitude of the suction imposed by the Mariotte reservoir |
| $k$ | Hydraulic conductivity |
| $n$ | Van Genuchten fitting parameter |
| $t$ | Elapsed time during the infiltration test |
| $A_c$ | Dimensionless correction factor used to estimate hydraulic conductivity from the fitted infiltration parameter |
| $C_1$ | Fitting parameter obtained from the cumulative infiltration curve, associated with hydraulic conductivity |
| $C_2$ | Fitting parameter obtained from the cumulative infiltration curve, associated with the capillary contribution to infiltration |
| $I$ | Cumulative infiltration |
| $\alpha$ | Water retention parameter, commonly associated with the inverse of the air-entry pressure |

CC BY

## References


Ankeny, M.D., Ahmed, M., Kaspar, T.C., & Horton, R. (1991). Simple field method for determining unsaturated hydraulic conductivity. *Soil Science Society of America Journal*, *55*(2), 467-470. https://doi.org/10.2136/sssaj1991.03615995005500020028x.

Carneiro, J.J.V., Marques, E.A.G., Viana da Fonseca, A.J.P., Ferraz, R.L., & Oliveira, Â.H.C. (2023). Characterization of an iron ore tailing sample and the evaluation of its representativeness. *Geotechnical and Geological Engineering*, *41*(5), 2833-2852. https://doi.org/10.1007/s10706-023-02430-8.

Dias Neto, S.L.S., Ferraz, R.L., da Silva, T.O., Marques, E.A.G., Pitanga, H.N., & Cândido, E.S. (2024). Hydraulic characteristics of silt-sized iron ore tailings. *Geotechnical and Geological Engineering*, *42*(5), 3731-3753. https://doi.org/10.1007/s10706-024-02755-y.

Dias Neto, S.L.S., Ferraz, R.L., da Silva, T.O., Marques, E.A.G., Pitanga, H.N., & Cândido, E.S. (2025). Numerical evaluation of hydraulic and stability responses in filtered tailings stacks under variable construction conditions. *Geotechnical and Geological Engineering*, *43*(7), 337. https://doi.org/10.1007/s10706-025-03321-w.

Gan, D., Yang, X., & Zhang, Y. (2019). Permeability prediction of iron tailings including degree of compaction and structure. *Complexity*, *2019*(1), 3591628. https://doi.org/10.1155/2019/3591628.

Garcia, L.B.L., Gomes, G.J.C., Rosa, F.A., Vargas Junior, E.A., & Lemos Junior, M.A. (2026). Moisture dynamics in filtered tailings stacks: compaction effects and unsaturated hydraulic parameter uncertainty. *Geotechnical and Geological Engineering*, *44*(1), 3. https://doi.org/10.1007/s10706-025-03519-y.

Nadai, F.M., Marinho, F.A.M., & Silva, J.P.S. (2023). SWRC interpretation of iron ore tailings blends focusing on saturation assessment of dry stacking. *International Journal of Geotechnical Engineering*, *17*(5), 764-777. https://doi.org/10.1080/19386362.2023.2297493.

Nascimento, J.S. (2024). *Determinação da condutividade hidráulica do material da Pilha de Disposição de Estéril e Rejeito Cianita (PDER Cianita) por meio de infiltrômetro de campo* [Undergraduate thesis]. University of São Paulo (in Portuguese).

Perroux, K.M., & White, I. (1988). Designs for disc permeameters. *Soil Science Society of America Journal*, *52*(5), 1205-1215. https://doi.org/10.2136/sssaj1988.03615995005200050001x.

Philip, J.R. (1957). The theory of infiltration: 1. The infiltration equation and its solution. *Soil Science*, *83*(5), 345-357. https://doi.org/10.1097/00010694-195705000-00002.

Portes, A.M.C., & Espósito, T. (2013). Performance analysis for filtered iron ore tailings disposal. In R.J. Jewell, A.B. Fourie, J. Caldwell, & J. Pimenta (Eds.), *Paste 2013: Proceedings of the 16th International Seminar on Paste and Thickened Tailings* (pp. 211-224). Perth: Australian Centre for Geomechanics. https://doi.org/10.36487/ACG_rep/1363_16_Portes.

Santos, A.G. (2004). *Influência do teor de ferro na condutividade hidráulica saturada de um rejeito de minério de ferro* [Master's dissertation]. Universidade Federal de Ouro Preto (in Portuguese).

Santos, R.A., Delgado, B.G., Rissoli, A.L.C., Silva, J.P.S., & Casagrande, M.D.T. (2024). Influence of initial compaction and confining pressure on the hydraulic conductivity of compacted iron ore tailings. *E3S Web of Conferences*, *544*, 14005. https://doi.org/10.1051/e3sconf/202454414005.

Tebechrani Neto, A., Wagner, A.C., Carvalho, J.V.A., & Consoli, N.C. (2025). Effects of fines content, molding water content, and density on behavior of compacted filtered iron ore tailings. *Acta Geotechnica*, *20*(8), 4031-4049. https://doi.org/10.1007/s11440-025-02616-9.

Ulrich, B. (2019). Practical thoughts regarding filtered tailings. In A.J.C. Paterson, A.B. Fourie, & D. Reid (Eds.), *Paste 2019: Proceedings of the 22nd International Conference on Paste, Thickened and Filtered Tailings* (pp. 71-79). Perth: Australian Centre for Geomechanics. https://doi.org/10.36487/ACG_rep/1910_01_Ulrich.

Wooding, R.A. (1968). Steady infiltration from a shallow circular pond. *Water Resources Research*, *4*(6), 1259-1273. https://doi.org/10.1029/WR004i006p01259.

Zhang, R. (1997). Determination of soil sorptivity and hydraulic conductivity from the disk infiltrometer. *Soil Science Society of America Journal*, *61*(4), 1024-1030. https://doi.org/10.2136/sssaj1997.03615995006100040005x.

**Appendix A.** Location and elevation of 77 of 115 testing points.

| ID | NAME | NORTH | EAST | ELEVATION |
|---|---|---|---|---|
| 1 | AM-TR-05(-1)B | 7765609 | 618090 | 1344 |
| 2 | AM-TR-05(-2) | 7765708 | 618047 | 1344 |
| 3 | AM-TR-09(-1)B | 7765688 | 618055 | 1326 |
| 4 | AM-TR-09(-1)C | 7765684 | 618064 | 1326 |
| 5 | AM-TR-09(-1)D | 7765669 | 618033 | 1322 |
| 6 | AM-TR-09(-1)E | 7765682 | 618013 | 1329 |
| 7 | AM-TR-09(-6) | 7765683 | 618063 | 1329 |
| 8 | AM-TR-11(-1)B | 7765718 | 618105 | 1336 |
| 9 | AM-TR-11(-1)C | 7765720 | 618101 | 1327 |
| 10 | AM-TR-11(-1)D | 7765726 | 618109 | 1325 |
| 11 | AM-TR-11(-1)E | 7765729 | 618115 | 1328 |
| 12 | AM-TR-11(-1)F | 7765732 | 618117 | 1329 |
| 13 | AM-TR-11(-1)G | 7765736 | 618118 | 1331 |
| 14 | AM-TR-11(-1)H | 7765740 | 618121 | 1332 |
| 15 | AM-TR-11(-1)i | 7765743 | 618123 | 1333 |
| 16 | AM-TR-13(-1)B | 7765651 | 618075 | 1340 |
| 17 | AM-TR-13(-1)C | 7765650 | 618077 | 1342 |
| 18 | AM-TR-13(-1)D | 7765652 | 618082 | 1337 |
| 19 | AM-TR-14(-7) | 7765674 | 618115 | 1334 |
| 20 | AM-TR-16(-1)B | 7765632 | 617987 | 1339 |
| 21 | AM-TR-16(-1)C | 7765634 | 617986 | 1339 |
| 22 | AM-TR-17(-1)B | 7765631 | 618029 | 1345 |
| 23 | AM-TR-17(-1)C | 7765628 | 618030 | 1342 |
| 24 | AM-TR-18 | 7765655 | 618085 | 1293 |
| 25 | AM-TR-18(-1)B | 7765632 | 618087 | 1340 |
| 26 | AM-TR-18(-1)C | 7765632 | 618089 | 1340 |
| 27 | AM-TR-18(-1)D | 7765631 | 618083 | 1335 |
| 28 | AM-TR-18(-1)E | 7765631 | 618083 | 1337 |
| 29 | AM-TR-18(-1)F | 7765627 | 618081 | 1340 |
| 30 | AM-TR-18(-1)G | 7765629 | 618078 | 1344 |
| 31 | AM-TR-18(-1)H | 7765629 | 618069 | 1347 |
| 32 | AM-TR-18(-1)i | 7765628 | 618069 | 1345 |
| 33 | AM-TR-18(-1)J | 7765631 | 618067 | 1347 |
| 34 | AM-TR-20(-1)B | 7765708 | 618158 | 1348 |
| 35 | AM-TR-20(-1)C | 7765713 | 618161 | 1348 |
| 36 | AM-TR-20(-1)D | 7765719 | 618156 | 1348 |
| 37 | AM-TR-20(-1)E | 7765723 | 618160 | 1348 |
| 38 | AM-TR-20(-1)F | 7765718 | 618161 | 1348 |
| 39 | AM-TR-21(-1)B | 7765596 | 617992 | 1337 |
| 40 | AM-TR-21(-1)C | 7765597 | 617988 | 1339 |
| 41 | AM-TR-21(-1)D | 7765604 | 617987 | 1338 |
| 42 | AM-TR-21(-1)E | 7765605 | 617985 | 1338 |
| 43 | AM-TR-21(-1)F | 7765606 | 617981 | 1340 |

**Appendix A.** Continued...

| ID | NAME | NORTH | EAST | ELEVATION |
|---|---|---|---|---|
| 44 | AM-TR-21(-1)G | 7765608 | 617976 | 1340 |
| 45 | AM-TR-21(-1)H | 7765607 | 617975 | 1341 |
| 46 | AM-TR-21(-1)i | 7765607 | 617972 | 1341 |
| 47 | AM-TR-25(-1)B | 7765682 | 618174 | 1341 |
| 48 | AM-TR-25(-1)C | 7765677 | 618172 | 1345 |
| 49 | AM-TR-25(-1)D | 7765673 | 618169 | 1346 |
| 50 | AM-TR-25(-1)E | 7765671 | 618167 | 1347 |
| 51 | AM-TR-27(-1)B | 7765574 | 618036 | 1344 |
| 52 | AM-TR-27(-1)C | 7765575 | 618033 | 1350 |
| 53 | AM-TR-27(-1)D | 7765574 | 618031 | 1354 |
| 54 | AM-TR-27(-1)E | 7765575 | 618029 | 1357 |
| 55 | AM-TR-27(-1)F | 7765575 | 618027 | 1357 |
| 56 | AM-TR-27(-1)G | 7765576 | 618022 | 1356 |
| 57 | AM-TR-27(-1)H | 7765575 | 618020 | 1357 |
| 58 | AM-TR-27(-1)i | 7765574 | 618017 | 1357 |
| 59 | AM-TR-28(-1)B | 7765610 | 618093 | 1349 |
| 60 | AM-TR-28(-1)C | 7765608 | 618087 | 1349 |
| 61 | AM-TR-28(-2)A | 7765608 | 618087 | 1349 |
| 62 | AM-TR-28(-2)B | 7765608 | 618087 | 1349 |
| 63 | AM-TR-28(-3)A | 7765610 | 618098 | 1349 |
| 64 | AM-TR-28(-3)B | 7765610 | 618098 | 1349 |
| 65 | AM-TR-28(-3)C | 7765610 | 618098 | 1349 |
| 66 | AM-TR-28(-5) | 7765610 | 618093 | 1349 |
| 67 | AM-TR-29(-1)B | 7765616 | 618145 | 1357 |
| 68 | AM-TR-29(-1)C | 7765613 | 618143 | 1357 |
| 69 | AM-TR-29(-1)D | 7765611 | 618140 | 1358 |
| 70 | AM-TR-29(-1)E | 7765607 | 618140 | 1359 |
| 71 | AM-TR-29(-1)F | 7765606 | 618140 | 1371 |
| 72 | AM-TR-30(-1)B | 7765669 | 618190 | 1367 |
| 73 | AM-TR-30(-1)C | 7765667 | 618190 | 1367 |
| 74 | AM-TR-30(-1)D | 7765661 | 618189 | 1363 |
| 75 | AM-TR-30(-1)E | 7765657 | 618185 | 1362 |
| 76 | AM-TR-30(-1)F | 7765655 | 618182 | 1361 |
| 77 | AM-TR-30(-1)G | 7765649 | 618179 | 1359 |