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Effect of lamination and mixture on thermal conductivity of granular soil systems

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ABSTRACT: Safe and reliable operation of submarine cables depends critically on the thermal properties of the surrounding soils that dictate heat dissipation efficiency and cables' ampacity ratings. Naturally stratified or finely laminated soils are often encountered along cables' extensive routes. While features of soil laminations are often disrupted during sample collection or cable installation, they may remain intact in large areas surrounding the cables, inducing significant variabilities in soils' structures and states that could impact their thermal performance. This paper presents an experimental research programme into the influence of soil layering or lamination conditions on the thermal conductivity of granular soils. Measurements were taken using a customised thermal needle-based device on three binary mixtures formed by silt and sand materials of siliceous mineralogy. The findings indicate that the particle size distributions of the fines within the soil matrix - whether laminated or uniformly mixed - affect sample dry density, interparticle contact, and, consequently, the soil mixtures' apparent thermal conductivities. Dry density was found to be the predominant factor influencing the measured thermal conductivity values, irrespective of relative fines content. Empirical correlations between normalised thermal conductivity and soil dry density are proposed to trace the thermal conductivities of dry and submerged mixtures across varying fines distribution modes. Practical implications of the research findings for submarine cable design and other geotechnical systems are also discussed.

Keywords: soil thermal conductivity; submarine high-voltage cables; laminated soils; artificial mixtures; heat transfer

1 INTRODUCTION

Heat transfer in soils is central to the design and operation of a wide range of engineered geosystems, including thermal storage facilities (Brosseau et al., 2005), renewable geothermal systems (Rivera et al., 2017), and nuclear water disposal schemes (Xu et al., 2016). The proliferation of offshore renewable infrastructure driven by regional and global decarbonisation goals has posed significant demands for submarine cables.

The design and selection of submarine high-voltage (HV) cables are governed by cable ampacity, which is the maximum level of current that can be safely transported in cable without exceeding its temperature rating (usually set to 90°C) and causing any damage to the insulation or conductor (Dix et al., 2017). Cable temperature depends critically on its internal structure and the thermal properties of surrounding soils, which govern heat dissipation efficiency and influence current rating, insulation materials, burial depth and other aspects (Deu et al., 2023). Accurate characterisation of thermal conductivity of geomaterials is crucial to the safe and cost-effective design of offshore cables (Carbon Trust, 2024).

Marine sedimentary conditions may result in layered or laminated soil deposits (Kemp Alan, 1996), where variations in composition lead to different thermal properties. However, cable installation processes, such as trenching and backfilling (Worzyk, 2009), can disrupt these natural stratifications, causing intermixing of the burial soils around HV cables

(Figure 1). Potential differences in the state and properties of natural and post-installation soils pose challenges in determining representative thermal conductivity parameters for cable design. Soils' anisotropy and heterogeneity characteristics are often overlooked in research and commercial thermal conductivity tests (Emeana et al., 2016).

While most laboratory testing campaigns rely on in-situ 'natural' (or 'undisturbed') samples, non-cohesive sample are often heavily disturbed, requiring laboratory reconstitution to form uniform mixtures for thermal property measurements. These mixtures may partly reproduce the characteristics of backfill materials but not the natural sediments. reported that the thermal characteristics and heat transfer patterns of stratified soils differ significantly from those of uniform materials.

This study explores the differences in thermal properties between laminated and mixed soil conditions and investigates the influence of fines distribution within soil matrices on thermal properties. Binary granular soil samples were employed that were either thoroughly mixed or characterised by laminations. The mixtures were formed by silt or sands of siliceous origin and covered a range of relative fines contents and particle size ratios.

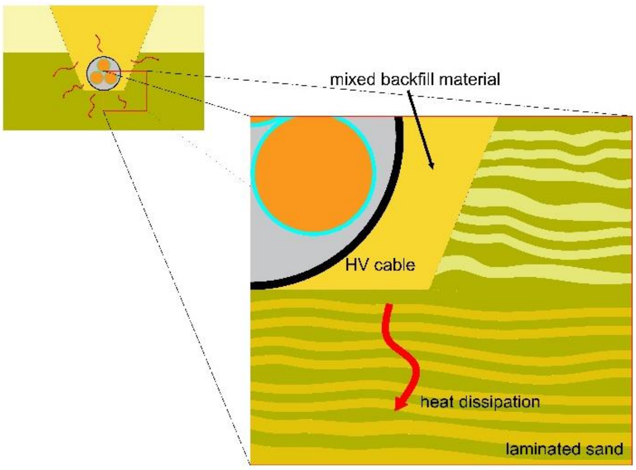

Figure 1. Cable installed in layered or laminated grounds

2 TEST EQUIPMENT AND MATERIALS

2.1 Experiment device

A customised thermal test device equipped with a TR-3 thermal needle probe was developed to measure thermal conductivity according to the transient heat method (ASTM, 2022). As shown in Figure 2, the apparatus consists of four main components: thermal needle probe, control panel, power supply and a computer.

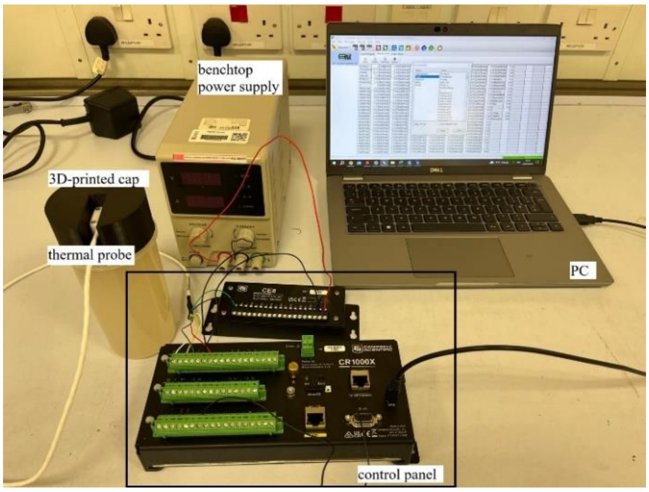

Figure 2. Customised thermal needle device

The thermal needle probe, which was inserted along the central axis of the cylindrical specimens, applied a constant heat flux along its length for 100s in the heating stage. A thermistor was located midway within the probe and recorded the temperature response over time (Zhou et al., 2024). Thermal conductivity was calculated based on the known heat input per unit length of the probe (Q) and the inverse slope of the linear portion of temperature-time data plotted on semilogarithmic scale, as described in the following equation:

$$\lambda = \frac{Q}{4\pi\Delta T}\ln\left(\frac{t_2}{t_1}\right) \quad (1)$$

where ΔT is the temperature gradient between two measurements at time t_1 and t_2. The system enabled accurate thermal conductivity measurements within the range of 0.1–4 $W \cdot m^{-1} \cdot K^{-1}$ with an enhanced accuracy of ±2%.

2.2 Test materials

The binary mixtures tested in this study were prepared by pairing three granular soils: Leighton Buzzard fraction B sand (LB, coarse sand), Redhill sand (RH, fine sand) and Silica flour (SiF, silt). The primary properties of these materials, including mean grain size (D_{50}) and maximum and minimum void ratios (e_{max} and e_{min}), are summarised in Table 1. Particle size distributions are presented in Figure 3. All these materials are predominantly quartz-based, with LB and RH featuring subangular to subrounded grains and medium to high sphericity.

Table 1. Summary of soil properties

Soil type	D_{50} [mm]	e_{max} [-]	e_{min} [-]
Leighton Buzzard B sand	0.88	0.84	0.53
Redhill sand	0.17	1.04	0.61
Silica flour	0.053	1.332	0.563

*Data from Zdravkovic (1996) & de Leeuw et al. (2021)

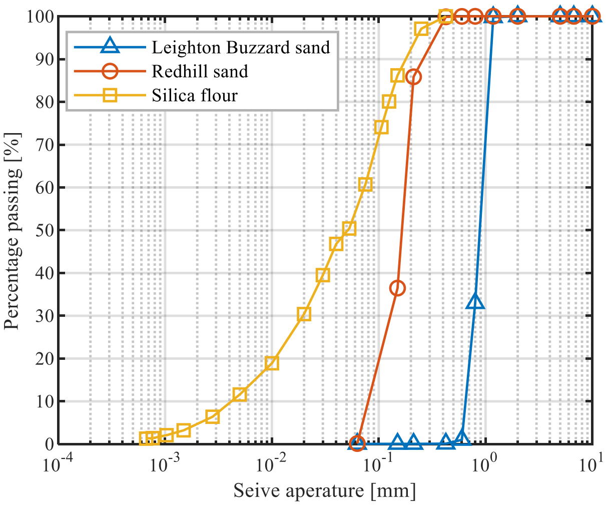

Figure 3. Particle size distributions of the tested soils

2.3 Test procedures and programme

Two types of specimens were prepared with these paired soils: uniform mixtures and laminated samples, as illustrated in Figure 4 for LB & SiF mixtures. A range of material proportions was employed for each soil type, as quantified by relative fines content (*RFC*) defined as:

$$RFC = \frac{m_{fine}}{m_{total}} \quad (2)$$

where m_{fine} is the mass of the finer material and m_{total} is the total sample mass. The material proportions of the tested mixtures are summarised in Table 2.

Uniformly mixed binary mixtures were prepared by blending the soils thoroughly before pouring them slowly into a cylindrical testing mould to minimise particle segregation (Roshankhah et al., 2021). Each specimen was divided into five layers and the soil mass per layer was determined by trial prior to the experiment. Finally, the initial mass and height of the specimen were measured to determine the initial dry density. Specimens were submerged using a pre-buried tube extending along the full height to the base of the mould and connected to an elevated water tank, allowing water to displace air within the specimen. While full saturation may not be guaranteed using this method, any impact on the overall trends for thermal conductivity against varying *RFC* were deemed undiscernible, as shown later.

Laminated specimens were prepared with relative fines content ranging from 0 to 0.5 and 0.6 to 1, corresponding to 0 to 10 layers and 8 to 0 layers of laminations, respectively, with the lower portion material serving as the interlayers as shown in Figure 4. The thermal probe was positioned by a 3D-printed top cap (Figure 2) along the central axis of the cylindrical specimen of 7 cm in diameter and 15 cm in height.

Table 2. Experimental programme of binary mixtures

Uniform mixtures & Laminations	LB & SiF	LB & RH	RH & SiF
D_{50} ratio	16.6	5.2	11.1
Relative fines content (*RFC*)	0	0	0
	0.1	/	/
	0.2	0.2	0.2
	0.3	/	/
	0.4	0.4	0.4
	0.5	0.5	0.5
	0.6	0.6	0.6
	0.7	/	/
	0.8	0.8	0.8
	0.9	/	/
	1	1	1

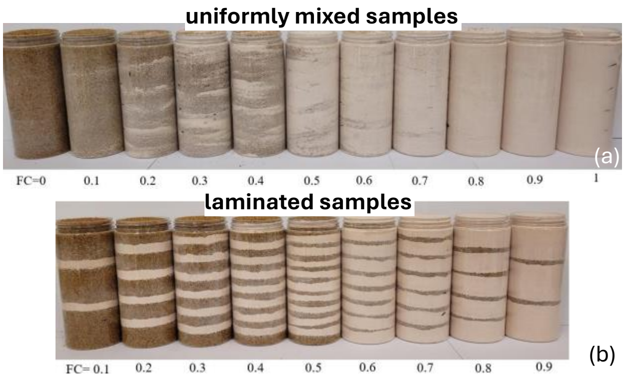

Figure 4. Examples of (a) uniformly mixed and (b) laminated samples of LB & SiF mixtures

3 RESULTS AND DISCUSSIONS

3.1 Results

The experimental results of the uniform mixtures and laminated samples of Leighton Buzzard Fraction B sand and Silica Flour are considered first. Figure 5 illustrate the variations of dry density and thermal conductivity against relative fines content (*RFC*) for both the submerged and dry specimens.

Figure 5 (a) shows that the dry densities (or volumes) of the uniformly mixed specimens vary systematically with relative fines contents, exhibiting a distinct convex pattern with dry density maxima at *RFC* = 0.5. The pattern appears to be independent of the sample's saturation state (dry or submerged). This trend reflects soil particle rearrangement with finer particles filling the voids between larger grains, as reported by Park and Santamarina (2017).

In contrast, the dry densities of the laminated samples show greater variabilities as *RFC* increases. This can be attributed to mixing effects at the lamination interfaces and challenges in controlling precisely the height (or density) of each layer during sample preparation. Additionally, the submerged specimens tend to exhibit higher dry densities than the dry specimens, possibly due to water lubrication at particle contacts that facilitates densification.

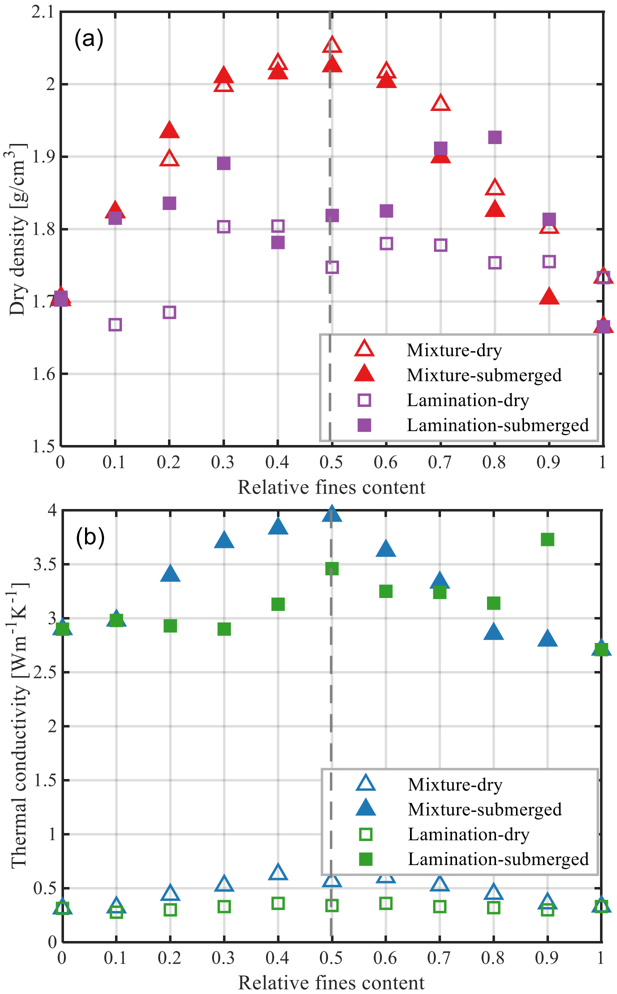

Figure 5. Trends for (a) dry density and (b) thermal conductivity with various RFC for samples of LB & SiF

Figure 5(b) presents the measured thermal conductivities of uniformly mixed and laminated samples against varying *RFC*s. The uniform mixtures generally manifest higher thermal conductivities than the laminated samples, with exceptions for two submerged samples at *RFC*s of 0.8 and 0.9 (with the latter being likely affected by a random system error and thus can be disregarded). Across all sample configuration and conditions - laminated or uniformly mixed, dry or submerged - typical convex trends can be observed with thermal conductivity peaking at *RFC* of ≈0.5 for the submerged specimens and 0.4 for the dry specimens. The submerged samples show substantially higher thermal conductivities than their dry counterparts by an order of magnitude. The trends resemble the dry density patterns with varying *RFC* and more pronounced convexity can be observed with the uniform mixtures compared to the laminated samples. The overall patterns indicate that dry density dominates the thermal properties of soil mixtures.

Similar observations were reported by Roshankhah et al. (2021) that thermal conductivity of sand-silt mixtures may exceed that of their parent sand or silt components, which can be attributed to enhanced packing dry density and particle contacts. The number of heat-transfer contact points per unit volume increases as finer particles fill the voids between coarser grains (Yun and Santamarina, 2008).

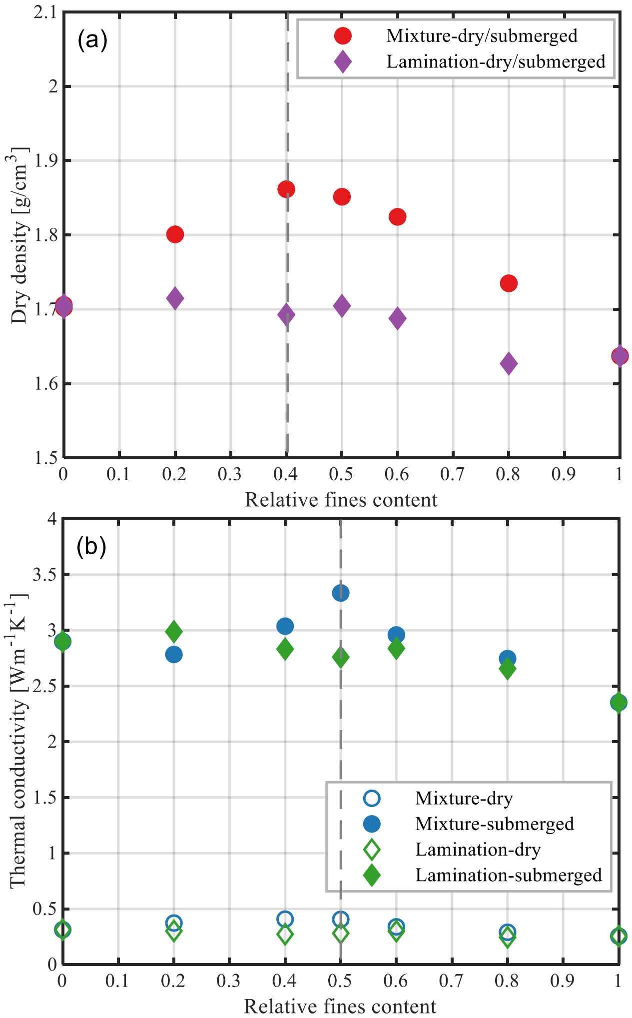

Figure 6. Trends for (a) dry density and (b) thermal conductivity with various RFC for samples of LB & RH

Results for the LB & RH and RH & SiF mixtures are presented in Figure 6 and Figure 7, respectively. The dry or submerged state appeared to have negligible effect on the dry densities achieved for these two mixtures. As shown in Figure 6(a), the LB & RH mixtures exhibit similar trends to those previously observed with the LB & SiF mixtures. The dry density-relative fines content trend for the uniform mixtures exhibits a convex pattern with dry density culminating at *RFC* ≈ 0.4, while no similar trend can be observed with the laminated samples. The thermal conductivity trends shown in Figure 6(b) are aligned with the dry density patterns, with the laminated samples generally manifesting lower thermal conductivities than the uniform mixtures under both submerged and dry conditions.

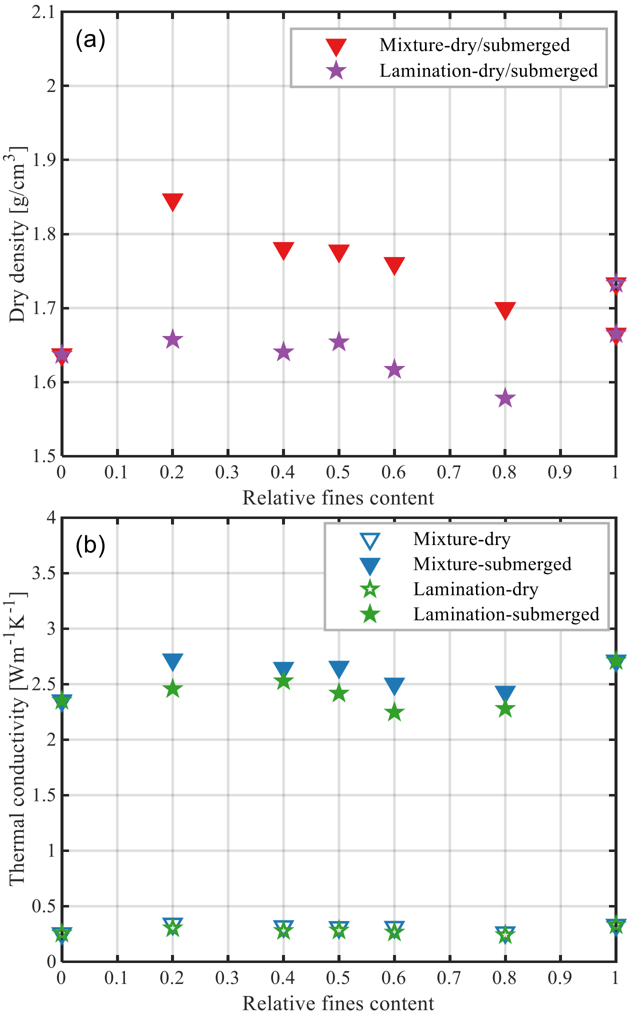

Figure 7. Trends for (a) dry density and (b) thermal conductivity with various RFC for samples of RH & SiF

The RH & SiF mixtures appear to develop slightly different trends with the maximum dry density occurring at a lower *RFC* of 0.2, as shown in Figure 7(a). This might be attributed to the finer mean particle (D_{50}) of the parent material, compared to the much coarser LB sand in the other two mixtures (see Table 2). The RH & SiF mixtures exhibit generally decreasing dry densities as *RFC* increases and lower density values than the other two mixtures. As shown in Figure 7(b), the measured thermal conductivities manifest similar patterns to those of the densities, with consistently lower conductivity values being observed with the laminated samples, conforming to the observations for the other materials and conditions.

3.2 Overall trends and normalisation

Figure 8 plots normalised measured thermal conductivity (λ) against dry density (ρ_d) by the respective values of pure quartz (λ_q = 7.69 Wm^{-1}K^{-1} (Haigh, 2012), ρ_q = 2.65g/cm^3). The dataset includes all measurements on the uniform mixtures (M) and laminated samples (L), as well as on the individual parent materials, distinguishing the submerged and dry states. A linear trend can be identified for each state, with the corresponding correlations and coefficients of determination (R^2) being given in Figure 8. The dry density (ρ_d) is bounded by the minimum and maximum densities of each parent material or mixture. The trends confirm that, in this particular case where the material components share the same mineralogical composition, the differences in thermal conductivity between the uniform mixtures and laminated samples can be primarily attributed to their packing densities.

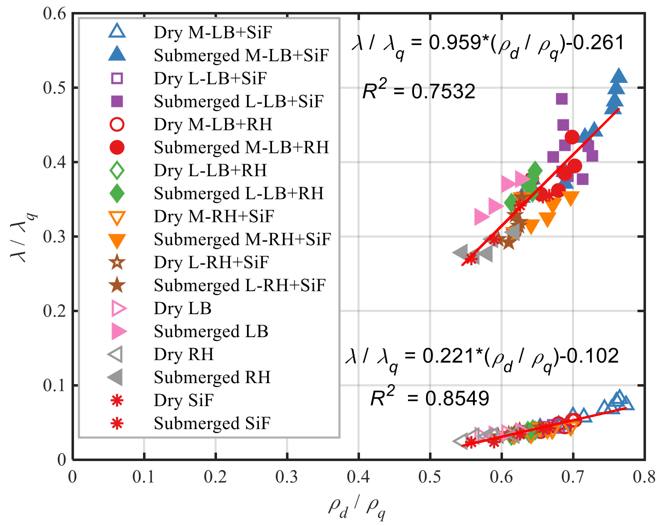

Figure 8. Correlations for normalised thermal conductivity and dry density

These experimental observations suggest two key implications for cable design: (i) Laboratory measurements of thermal conductivity may be overestimated if in-situ density is not accurately characterised and reproduced in the laboratory measurements on mixed and reconstituted specimens that do not preserve any in-situ lamination features; (ii)

The thermal conductivity of backfill materials may differ from (and potentially exceed) that of the undisturbed laminated soils further away from the buried cables. Nevertheless, the study indicated that dry density plays a dominant role in soil mixture's apparent thermal conductivity. Accurate assessment of dry densities and any potential differences between in-situ states and laboratory conditions and between natural deposits and backfill materials is critical for reliable thermal conductivity characterisation and submarine cable design.

4 CONCLUSIONS

This study investigated the effects on the thermal conductivity of fines distribution within granular soil matrices - whether laminated or uniformly mixed. Three sets of binary mixtures with siliceous parent materials were considered. The following conclusions can be drawn:

- The relative fines content significantly influences the mixtures' densities. Laminated (or layered) specimens generally developed lower dry densities, in comparison with the mixed samples, as fines filled the voids between coarser grains. This effect can be further enhanced as the disparity in particle size increases.
- Broadly similar patterns were observed of thermal conductivity and dry density against relative fines content, with both being affected by particle size and relative fines content. Consequently, the laminated samples generally exhibited lower thermal conductivity than the uniform mixtures. Empirical correlations between normalised thermal conductivity and soil dry density were proposed for the parent materials and mixtures of identical mineralogy.
- For practical applications, it is essential to account for potential density variations due to in-situ sampling and laboratory reconstitution, especially when dealing with laminated or layered grounds. Differences between natural deposits and backfill materials should also be assessed. Factors contributing to these potential differences may be quantified and integrated to enhance cable design, serving as the next step of this study.

AUTHOR CONTRIBUTION STATEMENT

Zhixin Zhou: Conceptualization, Methodology, Data curation, Formal analysis, Investigation, Validation, Visualization, Writing-original draft. **Andrea Diambra**: Conceptualization, Methodology, Supervision, Writing-Reviewing and Editing. **Tingfa Liu**: Conceptualization, Methodology, Supervision, Writing-Reviewing and Editing. **Erdin Ibraim**: Conceptualization, Methodology, Supervision, Writing-Reviewing. **Mia Reichow:** Investigation, Writing-reviewing. **Tengyun Wen:** Investigation, Writing-reviewing. **Paul Stock**: Conceptualization, Methodology, Writing-Reviewing. **Timothy Brown**: Conceptualization, Methodology, Writing-Reviewing. **Justin Dix**: Conceptualization, Methodology, Writing-Reviewing. **Chris Brandish-Lowe**: Conceptualization, Methodology, Writing-Reviewing.

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