

Geoelectric Measurements of Internally Unstable Soils

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ABSTRACT

Internally unstable soil, specifically underfilled gap-graded soil are prone to suffusion, a mechanism of internal erosion where fine particles migrate under hydraulic flow. Over time, suffusion results in the gradual washout of finer particles, which can ultimately lead to structural failure. Conventional techniques for suffusion assessment rely on laboratory-based stability criteria, which are effective but invasive and does not provide real time monitoring. This study explores the potential of geoelectric measurements as a non-invasive alternative to identify internally unstable soil and differentiate between underfilled and overfilled fabric. Direct Current (DC) resistivity measurements were conducted on sand-gravel mixtures with 20% and 40% finer fraction. Two key geoelectric parameters, formation factor and surface conductivity, were calculated. These parameters are essential for understanding the electrical properties of the soil mixtures and were correlated to conventional soil parameters. The results showed that geoelectric parameters can effectively differentiate between underfilled and overfilled fabric. Moreover, the findings exhibit a high degree of repeatability, indicating reliable measurements. These results provide a solid foundation for the potential application of geoelectric measurements as a non-invasive method for monitoring suffusion.

INTRODUCTION

Internally unstable soils are often found in geotechnical structures such as dam foundations, embankments, and filters, especially with gap-graded particle size distribution. Gap-graded soil consists of broad range of particles size with an absence of certain particle size fractions. This gap in the particle size distribution results in the formation of two distinct particle size groups, commonly referred to as the finer fraction and the coarser fraction. Gap-graded soils are typically classified based on the proportion of finer and coarser fractions, categorising them as either underfilled or overfilled. Overfilled fabric consists of soil matrix dominated by finer fraction in which coarse particles are floating within the matrix formed by the finer fraction. In overfilled fabric, stress transfer is mainly governed by both finer particles and coarser particles (Sufian et al., 2021). In contrast, underfilled fabric consists of coarse dominated matrix in which the finer fraction is located in the voids of coarser fraction. In this case, the finer fraction does not contribute to

stress transfer. Shire et al., (2014) conducted a study on idealised gap-graded soils and showed that soil with fines content (f_c) $< 25\%$ can be considered as underfilled, whereas soil with $f_c > 35\%$ can be considered as overfilled. Underfilled soil fabric is particularly prone to suffusion, as the fines are free to move through the interconnected pore spaces. Suffusion is a mechanism of internal erosion by which fine soil particles are transported by seepage flow through the pores of coarser particles. Within this process, the coarser particles remain stationary, facilitating effective stress transfer predominantly through the coarse soil matrix.

A substantial amount of research has been conducted in the past few decades to understand the suffusion phenomenon. Researchers have undertaken a series of experimental inquiries to comprehend the mechanisms underlying suffusion. Different types of experimental apparatus were developed, such as, flexible wall permeameter and rigid wall permeameter (Kenney and Lau 1985; Chang and Zhang, 2011; Luo et al., 2020). These conventional methods have made a significant contribution to understand the mechanism underlying suffusion. Despite their utility in geotechnical engineering, these approaches have several notable disadvantages. They require a complex setup and are costly, often necessitating significant investment in sophisticated equipment and maintenance. The testing procedures are time-consuming, involving extensive sample preparation and the achievement of equilibrium states to replicate in-situ conditions accurately. Additionally, researchers have made efforts to advance suffusion comprehension through numerical studies (Zhang et al., 2019; Yang et al., 2020). Numerical studies have provided various insights into suffusion at micro scale. However, these studies have mainly considered idealised soil particles.

The existing experimental methods are capable of studying the suffusion mechanism at a laboratory scale, while numerical methods have primarily focused on the particle scale. Suffusion, however, is driven by mechanisms at the particle scale and alters the properties of soil at larger scales. Existing studies do not have the ability to address the large-scale mechanical properties and particle scale properties, simultaneously.

Geoelectric methods can fill this gap, as we can compute the same geoelectric parameters at different scales non-invasively without disturbing the soil (Friedman, 2005). One such method is Direct Current (DC) resistivity, a geoelectrical technique widely used to assess subsurface properties by measuring the electrical resistivity of soils and sediments (Binley and Slater, 2020). This method uses a set of electrodes to inject current in the soil and calculated the voltage difference in the medium by another set of electrodes. The electrical conduction mainly occurs within the voids of the soil through the pore fluid. The electrical response of soil depends on several factors, including water content, pore structure, and surface conductivity, making DC resistivity a powerful tool for characterising internally unstable gap-graded soils. This technique is especially beneficial due to its non-invasive nature and applicability in both laboratory and field environments. The two main parameters obtained from this method are the formation factor (F) and surface conductivity (σ_{surf}), both of which have a strong connection to the porosity of soil and the connectivity of pore space. If soil can be consistently classified using geoelectric parameters, it can also be used as an indirect measure of porosity and how it changes over time due to

mechanisms like suffusion. With this approach, soil stability could be continuously monitored in the field, enabling the early identification of possible failure risks.

The objective of this study is to evaluate the potential of geoelectric methods to characterise internally unstable gap-graded mixtures. DC resistivity method was used to measure geoelectric parameters for underfilled and overfilled soil fabric. By calculating the correlation of geoelectric parameters with fabric condition and porosity this study aims to lay the foundation for utilising geoelectric technique to identify suffusion-prone soils and monitor variations in pore structure under practical circumstances by examining geoelectric parameters such as formation factor and surface conductivity.

MATERIALS AND METHODS

Experimental setup and geoelectric parameters

Geoelectrical measurements were conducted using a cup shaped sample holder with four electrodes embedded in it. The sample holder was built by 3D printing with a height of 17 mm and a diameter of 70 mm. The sample holder consists, two current electrodes (A and B) to inject an alternating electrical current into the sample, and two potential electrodes (M and N) to measure the voltage drop. This four-electrode arrangement increases the accuracy of the measured impedance by reducing electrode polarisation effects. Revil et al., (2018) used similar design to compute complex conductivity of tight sandstone. Multi Frequency Impedance Analyser (MFIA) by Zurich Instruments was used to inject current and measure the voltage drop in the sample. The device applies an alternating current (AC) signal and records the resulting impedance as an output from the sample. MFIA is capable of operating over a broad frequency range, whereas the scope of this study is limited to measurements at a frequency of 1 Hz, where electrode polarisation effects are negligible, and conductivity of medium can be reliably assessed. Figure 1 shows the experimental setup and connections between the sample holder and MFIA.

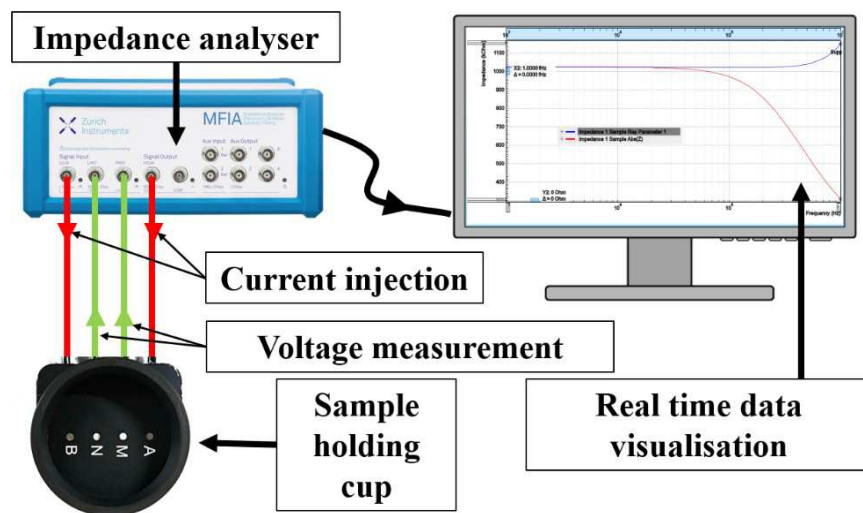


Figure 1: Experimental setup

The impedance analyser provides the complex impedance (Z^*), which is subsequently converted to complex electrical conductivity (σ^*) using the relation:

$$\sigma^* = \frac{1}{K_g Z^*}$$

Here, K_g is the geometric factor, a calibration constant that accounts for the configuration of electrodes. K_g was calculated by calibration of sample holder by measuring the conductivity of range of fluids having different conductivity levels. The imaginary component of σ^* is beyond the scope of this study, and its magnitude is negligible compared to the real component of σ^* . Therefore, all reported values of conductivity in this study will represent the real part of conductivity, denoted as (σ). Key geoelectric parameters, such as surface conductivity (σ_{surf}) and the formation factor (F), can be derived from the measured conductivity values. These parameters are essential for describing the pore structure and connectivity of pores in gap-graded soils.

In non-conductive porous media, electrical charge is mainly transported by the movement of ions through two mechanisms: (i) conduction through ions dissolved in the pore fluid that fills the interconnected pore spaces; and (ii) conduction through ions in the electrical double layer (EDL) that forms at the interface between the particle and the fluid. When the conductivity of pore fluid is very low ($\sigma_w < 10^{-3}$ S/m), the conduction through second mechanism dominates. The conductivity of medium in this condition is termed as surface conductivity. In contrast, at high pore fluid conductivity ($\sigma_w > 10^{-1}$ S/m), the contribution of surface conduction becomes negligible, and conduction through first mechanism dominates. Archie, (1942) showed that, in this region, the relationship between σ and σ_w follows a linear trend, as described by

$$F = \frac{\sigma_w}{\sigma}$$

Here, F is the formation factor which is a dimensionless parameter that characterises the influence of the pore structure on electrical conductivity. Higher values of F , which are usually found in well compacted materials, signify a more resistive medium with less fluid connectivity. Whereas lower F values correspond to more interconnected porous structures, allowing easier ion transport. F is primarily governed by the porosity and the connectivity of the pore network.

Materials and sample preparation.

The materials used in this study consist of sand and gravels, combined in controlled proportions to form gap-graded mixtures. Two different sand-gravel mixtures were used with 20% and 40% sand content, to represent underfilled and overfilled fabric, respectively. The proportion of sand and gravel for each mixture was based on percentage by mass. In this paper sand is referred as the finer fraction and the proportion of sand as the fines content (f_c). The specific gravity of sand and gravel was 2.66 and 2.84, respectively. Figure 2 shows the particle size distribution of materials used. The particle size distribution of the selected sand and gravel was chosen to ensure that the resulting mixtures exhibit gap-graded characteristics prone to suffusion, satisfying the condition $D_{85}^C / D_{15}^F > 7$ where 15% of the coarser particles are small than D_{15}^C and 85% of the finer particles

are smaller than D_{85}^F (Fannin and Moffat, 2006). For selected size of sand and gravels in this study, $D_{15}^C / D_{85}^F \approx 8$.

To investigate the geoelectric properties of these mixtures under varying pore fluid conditions, four different NaCl solutions with electrical conductivities of 10^{-4} S/m, 10^{-2} S/m, 10^0 S/m, and 10^1 S/m were used as pore-filling fluids. These solutions allow the evaluation of both surface conductivity at low pore fluid conductivity and formation factor at high pore fluid conductivity.

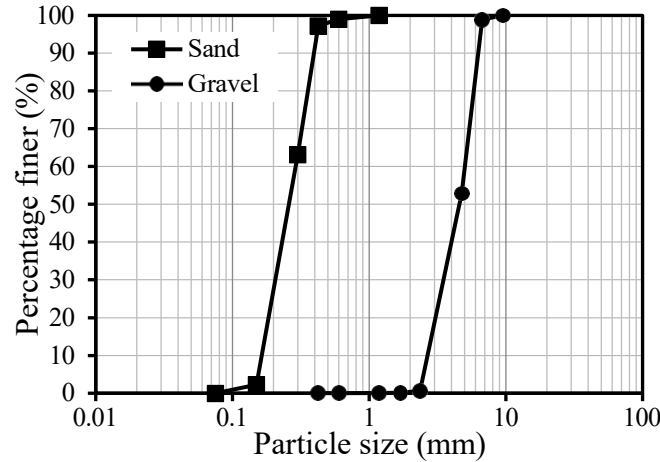


Figure 2: Particle size distribution curve

The gap-graded mixtures were prepared using a systematic approach to ensure consistency and repeatability. Firstly, the materials were oven dried to remove any residual moisture, followed by mixing of sand and gravel in desired proportions by weight. To enhance compaction and minimise segregation during sample preparation, 5% pore filling fluid (by weight) was added to the dry mixture and thoroughly mixed to achieve uniform moisture distribution. In order to achieve a consistent density, the prepared mixture was then put into the testing cell in three layers, each of which was compacted using 50 tamping. Following the compaction of sample, the top surface was carefully levelled by removing excess material to ensure a uniform sample height. To prevent the structure of the soil and minimise trapped air, the saturation with the pore filling fluid was performed meticulously with the help of a porous stone.

RESULTS AND DISCUSSION

The variation of electrical conductivity (σ) of soil with respect to pore fluid conductivity (σ_w) for both mixtures is presented in Figure 3. A particular mixture composition is represented by each subplot, with twelve data points per mixture representing four distinct pore fluid conductivities each repeated 3 times. The observed consistent values across the repeated measurements suggests a high degree of experimental repeatability. A distinct trend is observed in both mixtures. In the low pore fluid conductivity region, σ is higher than the σ_w , suggesting the influence of surface conductivity effects. In contrast, in the high pore fluid conductivity region, the σ closely follows σ_w and eventually becomes lower than σ_w , indicating a transition where the conductive contribution is predominantly controlled by the pore fluid rather than surface conduction. The linear fit of the

datapoints shown in Figure 3, validate the clear linear relationship between σ and σ_w in the high-conductivity range. The slope of the linear fit in this region was used to calculate F . On the other hand, σ_{surf} was calculated by the conductivity of soil at $\sigma_w = 10^{-4}$ S/m.

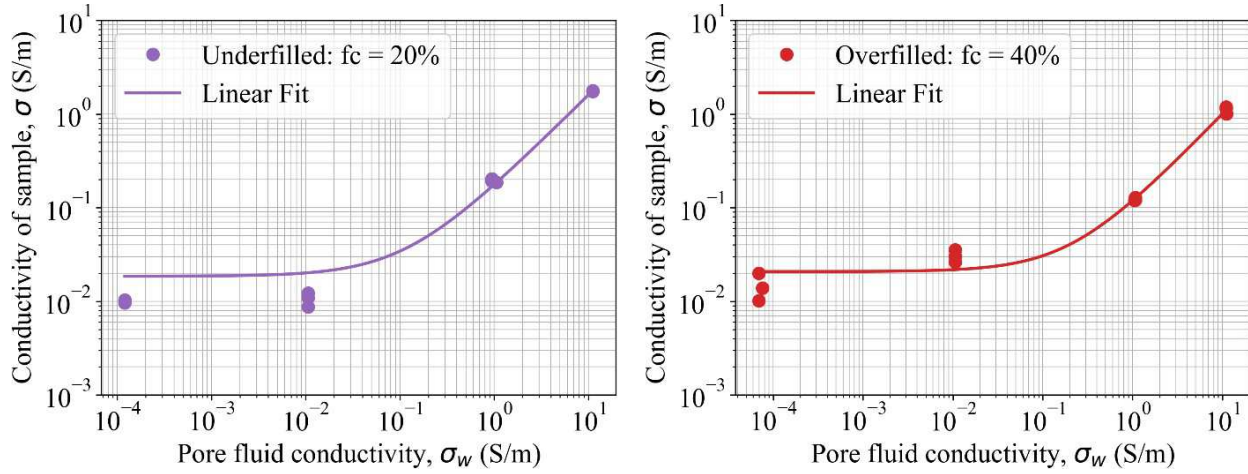


Figure 3: Electrical conductivity of underfilled and overfilled mixture

The obtained values of σ_{surf} and F are presented in Table 1. The obtained values are consistent with previous findings (Weller et al., 2013). σ_{surf} was increased by increasing fines content. This can be attributed to the greater surface area of finer particles compared to coarse particles, leading to higher ability of charge transport through surface. In addition, as f_c increases, from underfilled fabric to overfilled fabric, it leads to higher connectivity between particles which enhances electrical charge transport along the electrical double layer leading to higher σ_{surf} . The observed values indicate the sensitivity of σ_{surf} with variations in fines content.

Significant increase in F was observed when moving from underfill fabric to overfilled fabric. The increase in F values can be attributed to the fines occupying void spaces between coarse particles, leading to a denser packing and reduced pore connectivity, thereby increasing the tortuosity of electrical pathways. Measured porosity of the mixtures, follows the expected inverse relationship with F . These results show the sensitivity of geoelectric parameters to fines content and ability to differentiate underfilled and overfilled fabric. In addition, the formation factor shows strong correlation with porosity.

Table 1: Obtained geoelectric parameters

Soil Fabric	Surface conductivity, σ_{surf} (mS/m)	Formation factor (F)	Porosity (ϕ)
Underfilled ($f_c = 20\%$)	10.08	6.47	0.4
Overfilled ($f_c = 40\%$)	14.65	10.33	0.33

CONCLUSION

This study demonstrates the potential of geoelectric measurements in characterising internally unstable gap-graded sand-gravel mixtures by evaluating two key parameters, surface conductivity (σ_{surf}) and formation factor (F). Additionally, conventional methods for assessment of suffusion are often invasive and labour-intensive, whereas this approach provides a non-destructive alternative with direct correlation to fundamental soil properties such as porosity. DC resistivity measurements were performed with a cup size sample holder on two gap-graded mixtures with 20% and 40% fines content. The results were found out to be highly repeatable, showing the reliability of experimental setup and testing procedure. The results indicated that both surface conductivity and formation factor are highly sensitive to soil fabric and can effectively distinguish between underfilled and overfilled fabric. By increasing the fines content from 20% to 40%, porosity of the soil decreased whereas, both the geoelectric parameters significantly increased.

In all, this study showed that geoelectric method have the potential to monitor internal changes in soil fabric. Future research should aim to capture how geoelectric parameters vary over a wider range of fines content to increase their applicability. In addition, further study should also concentrate on applying these measurements to field-scale studies and dynamic suffusion experiments in order to ensure their applications in geotechnical monitoring and risk assessment.

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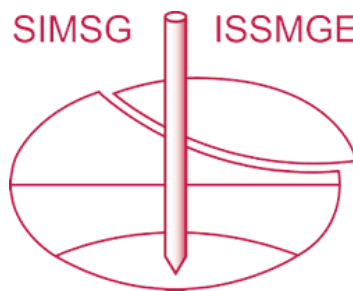
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REFERENCES

- Archie, G. E. (1942). The electrical resistivity log as an aid in determining some reservoir characteristics. *Transactions of the AIME*, 146(01), 54-62.
- Binley, A., & Slater, L. (2020). Resistivity and induced polarization: Theory and applications to the near-surface earth. *Cambridge University Press*.
- Chang, D. S., & Zhang, L. M. (2011). A stress-controlled erosion apparatus for studying internal erosion in soils. *Geotechnical Testing Journal*, 34(6), 579-589.
- Fannin, R. J., & Moffat, R. (2006). Observations on internal stability of cohesionless soils. *Geotechnique*, 56(7), 497-500.
- Friedman, S. P. (2005). Soil properties influencing apparent electrical conductivity: a review. *Computers and electronics in agriculture*, 46(1-3), 45-70.
- Kenney, T. C., & Lau, D. (1985). Internal stability of granular filters. *Canadian geotechnical journal*, 22(2), 215-225.

- Luo, Y., Luo, B., & Xiao, M. (2020). Effect of deviator stress on the initiation of suffusion. *Acta Geotechnica*, 15, 1607-1617.
- Revil, A., Coperey, A., Deng, Y., Cerepi, A., & Seleznev, N. (2018). Complex conductivity of tight sandstones. *Geophysics*, 83(2), E55-E74.
- Shire, T., O'sullivan, C., Hanley, K. J., & Fannin, R. J. (2014). Fabric and effective stress distribution in internally unstable soils. *Journal of geotechnical and geoenvironmental engineering*, 140(12), 04014072.
- Sufian, A., Artigaut, M., Shire, T., & O'Sullivan, C. (2021). Influence of fabric on stress distribution in gap-graded soil. *Journal of Geotechnical and Geoenvironmental Engineering*, 147(5), 04021016.
- Weller, A., Slater, L., & Nordsiek, S. (2013). On the relationship between induced polarization and surface conductivity: Implications for petrophysical interpretation of electrical measurements. *Geophysics*, 78(5), D315-D325.
- Yang, J., Yin, Z. Y., Laouafa, F., & Hicher, P. Y. (2020). Hydromechanical modeling of granular soils considering internal erosion. *Canadian Geotechnical Journal*, 57(2), 157-172.
- Zhang, F., Li, M., Peng, M., Chen, C., & Zhang, L. (2019). Three-dimensional DEM modeling of the stress-strain behavior for the gap-graded soils subjected to internal erosion. *Acta Geotechnica*, 14, 487-503.

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