Density Determination of Granular Materials – A Novel Electrical Conductivity Based Method

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ABSTRACT: In geotechnical laboratory practice, determination of the density of a granular specimen throughout the course of testing is a key concern. The density or the packing of the granular media can be translated into the stiffness of the material which may increase or decrease depending on the type of the experiment, applied loading, boundary condition, and many other contributing factors. While there are some wave speed dependent measurement techniques available, the equipment required or the difficulty in examining the acquired results limits the applicability and practicality of such techniques. For example, bender element testing requires reasonably complicated electronics interfaces capable of very high sampling rates. Moreover, other bespoke techniques which rely on the wave propagation speed are plagued by the background noise generated in the tests and their use is often limited to geotechnical centrifuge domain. Beyond these inherent shortcomings associated with the wave propagation measurement techniques, the conversion from stiffness to the density of the material also requires correlations which might further limit their use for density measurements. Although the electrical conductivity/resistivity measurements are widely recognized as a means to infer soil moisture content or salinity, the electrical resistivity of the granular media could also be used as an indicator of the packing density. This contribution shares a novel technique of density measurement utilizing electrical conductivity. The contribution elaborates on the working principle of the sensors and highlights results of a series of calibration tests conducted at Deltares.

1 INTRODUCTION

Despite the widespread use of electrical conductivity-based measurement techniques in neighboring fields, in geotechnical engineering practice, the use of conductivity measurements is confined to salinity and water content measurements alone (Cengiz et al., 2025). Generally, in geotechnical engineering practice, the electrical conductivity measurements are often employed to measure water content (Rhoades et al., 1976; Kalinski and Kelly, 1993; Sebastian and Bathe, 2009), degree of saturation (Kibria and Hossain, 2012), characterization of porous media structure (Rouquerol et al., 1994), sand erosion (Weegenaar et al., 2015) and rarely bulk density (Dijkstra et al., 2012; Bertermann and Schwarz, 2018).

Despite this limited use, reliable density (or porosity) tracking during geotechnical laboratory testing is central to interpreting stiffness and permeability evolution in granular media. Wave-based techniques such as bender elements require specialized high-speed electronics, are sensitive to ambient noise, and convert stiffness to density via correlations that introduce uncertainty. An alternative is to exploit bulk electrical conductivity, which in saturated granular media is governed primarily by the pore fluid pathways and therefore relates to porosity and the formation factor. The formation factor is an important parameter in quantifying the structure of porous materials and besides the relation shown above, it is known that the formation factor also correlates well with the permeability of granular media (Schopper, 1966; Bernabé et al., 2011; Ghanbarian and Male, 2021). Building on this principle, this study employs a compact, multi-electrode Conductivity-type Concentration Meter (CCM) to profile porosity and density in sands and glass beads using simple, noise-robust measurements. The contribution summarizes the CCM sensing principle, calibration, and a glass-tank validation campaign, and demonstrates: (i) a strong correlation between electrical conductivity and porosity; and (ii) formation-factor trends consistent with Archie-type (Archie, 1942) relationships for clean granular materials. The approach reduces instrumentation complexity compared to wave-based methods and is well suited to routine laboratory use. The present contribution builds on and expands the dataset provided by (Cengiz et al., 2025) by way of additional calibration tests on a diverse array of sands and artificial granular materials. Specifically, this study illustrates additional calibration test series conducted on Toyoura sand, Baskarp B25 sand, a sand/silt mixture, and two additional glass beads with uniform particle sizes of glass beads of 100–200 µm and 300–400 µm were added.

2 CONDUCTIVITY, RESISTIVITY, AND FORMATION FACTOR

Electrical conduction in saturated granular media follows effective-medium mixing concepts developed for composite materials (Maxwell, 1873; Lorentz, 1880; Lorenz, 1880; Rayleigh, 1892), culminating in the widely used Bruggeman correlation for porous media (Tjaden et al., 2016). Building on this groundwork, Archie formulated an empirical relation linking bulk resistivity to pore-fluid resistivity and porosity for saturated granular packs (Archie, 1942), while acknowledging earlier but later-published insights by Sundberg (1970) as discussed by Worthington (1993). The relation is

$$\rho = a \times \rho_w \times n^{-m} \tag{1}$$

where n is porosity, a is a fitting factor, and m is a cementation exponent governed by pore connectivity and tortuosity; for clean, unconsolidated sands, m is taken as 1.3 (Archie, 1942).

This mixing-law view assumes current travels primarily through the conducting pore fluid embedded in a non-conducting grain skeleton; hence bulk conductivity scales with both porosity and the conductivity of the pore fluid itself, which increases with salinity (Miller et al., 1988; Rhoades, 1996). Archie expressed this proportionality via the formation factor (FF):

$$FF = \frac{\sigma_{pf}}{\sigma_{bulk}} = \frac{a}{n^m} \tag{2}$$

where σ_{pf} and σ_{bulk} are the pore-fluid and bulk conductivities, respectively. FF serves as a structure descriptor and correlates consistently with permeability in granular media (Schopper, 1966; Bernabé et al., 2011; Ghanbarian and Male, 2021). In this contribution, FF will be primarily used to correlate the porosity of the granular assemblies to their measured conductivities. materials and methods.

3 MATERIALS AND METHODS

3.1 Conductivity-type Concentration Meter (CCM) Probes and Calibration

The Conductivity-type Concentration Meter (CCM) is a probe that measures bulk electrical conductivity of a soil-water mixture between paired electrodes. Current flow is assumed to occur primarily through the pore fluid, while surface conduction on clean quartz is negligible under the present conditions. The probe used houses 10 electrode pairs along a 400 mm shaft; the first pair is 25 mm from the tip, with 40 mm spacing between subsequent pairs and 5 mm centre-to-centre within each pair. Each pair is driven by an AC excitation at 10 kHz with an adjustable voltage up to 10 V. The signal conditioner provides transformer isolation, converts the electrode current to a voltage, detects peak amplitude, and applies a second-order low-pass Bessel filter with a 320 Hz cutoff. Signals are acquired with a 16-bit ADC at 10 Hz. The measured signal-to-noise ratio of the chain is 70 dB. For granular soils at the applied frequency, the measured conductivity can be taken as frequency-independent and equal to the ohmic component.

Each electrode pair is calibrated in potassium chloride (KCl) solutions of known molar concentration, spanning distilled water to 0.00228 mol/L. Reference conductivities at 25 °C are obtained with a laboratory meter (Cond 315i, Wissenschaftlich-Technische Werkstatten GmbH) and used to determine a linear conversion from the probe's voltage output to electrical conductivity in µS/cm. Across the 10 pairs, the individual regressions are highly linear (as depicted in Figure 1), with coefficients of determination typically between 0.996 and 0.999.

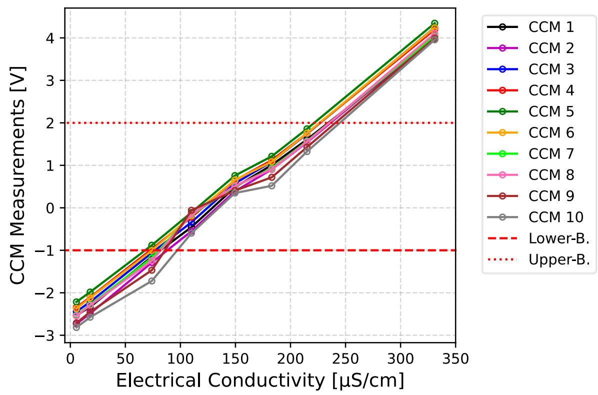

Figure 1. Calibration plots pertaining to the CCM sensors, the red dotted lines show where most silica sands are represented.

The average slope is approximately 1/49.3 V/(µS/cm) and the average intercept is approximately -2.5 V, which are subsequently used to convert raw signals to conductivity for each pair. The measured conductivities are also corrected for the ambient temperature (as conductivity is often corrected to 25 °C). Based on the laboratory investigations, a linear temperature correction factor was determined. The correction is expressed in the following manner:

$$\Delta EC_{corr} = k \times \Delta t \tag{3}$$

where ΔEC_{corr} is the increment of electrical conductivity to be summed over the measured electrical conductivity, k is the scalar multiplier used to correct the measured value and its value is 11.36 µS/cm/°C. Δt is the difference between the temperature at which the measurement took place and the preselected correction temperature which is 25 °C.

3.2 Granular Materials and Testing Methods

Table 1 illustrates the basic properties of the commercially available sands used in the present study. While Geba, Baskarp B15, S90, and M31 were previously elaborated in the study conducted by Cengiz et al. (2025), the present study aims to expand the dataset with the addition of Toyoura and Baskarp B25 sands. Furthermore, the present study also includes additional uniformly sized glass beads (again, commercially available) which have particle sizes varying between 100–200 µm and 300–400 µm.

During the preparation of the granular beds, the CCM probe and temperature sensor was placed in the testing tank inundated under water for 24 hours to allow of equalization of temperatures and baseline benchmarking. The test tank and explanations on the granular lift structure are illustrated in Figure 2.

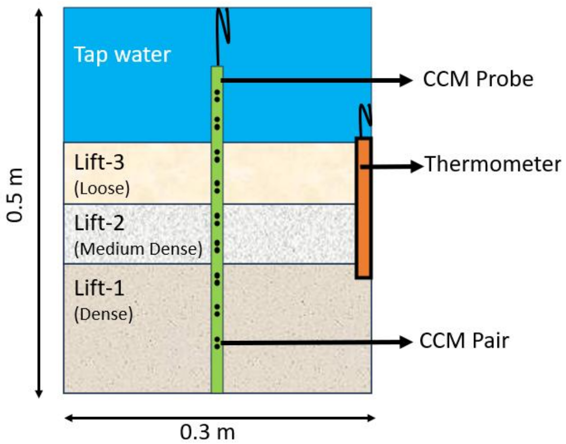

Figure 2. A sketch of the calibration test setup and depiction of the lifts.

Initially, the first lift was constructed to a dense state by gradual underwater placement with continuous tamping followed by vibratory compaction. After completion of the dense lift, a second medium-dense lift was placed using the same placement procedure but without vibratory compaction. Finally, a third loose lift was gently poured and allowed to settle under its own weight. These three lifts therefore represented dense, medium-dense, and loose packings produced by decreasing compactive effort, and the along-depth porosity of each layer was investigated from the temperature-corrected CCM conductivity profiles. Furthermore, density measurements were taken from the basal dense layer with a sampler ring and the actual density acquired from sampling was checked against the measured density with CCM probes.

The sampler ring is produced bespoke for undisturbed sand sampling and it has an inner diameter of 100 mm with a height of 40 mm.

Table 1. Properties of the used sands.

Material	G_s	e_{min}	e_{max}	USCS
Geba	2.67	0.64	1.07	SP
Baskarp B15	2.65	0.55	0.89	SP
S90	2.66	0.64	0.93	SP
M31	2.65	0.49	0.76	SP
Darmstadt	2.62	0.46	0.80	SP
Toyoura	2.65	0.62	0.98	SP
Baskarp B25	2.65	0.54	0.85	SP

4 RESULTS

Figure 3 illustrates the vertical porosity profile of the tested sands as measured by the CCM sensors at 10 different elevations over the length of the CCM probe. The deliberate relative density contrast applied via variation of the compactive effort in various lifts has culminated in the observed density differences. While Figure 3 alone does not present the usefulness of the porosity measurement method with CCM sensors, Figure 4 illustrates a comparative plot of the measured versus actual (acquired via physical sampling) porosity of the sand beds tested. In general, a good agreement is observed with the density values acquired via ring sampling and CCM measurements.

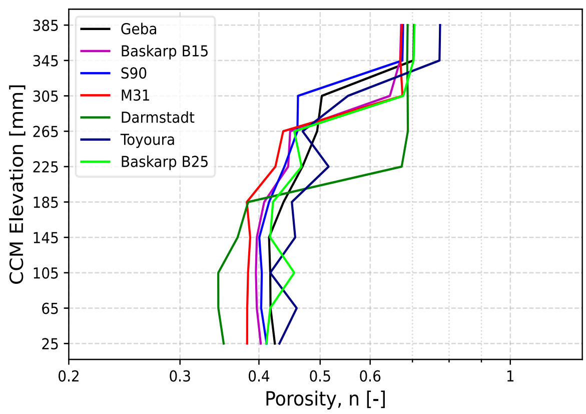

Figure 3. Vertical porosity profile of the tested sands.

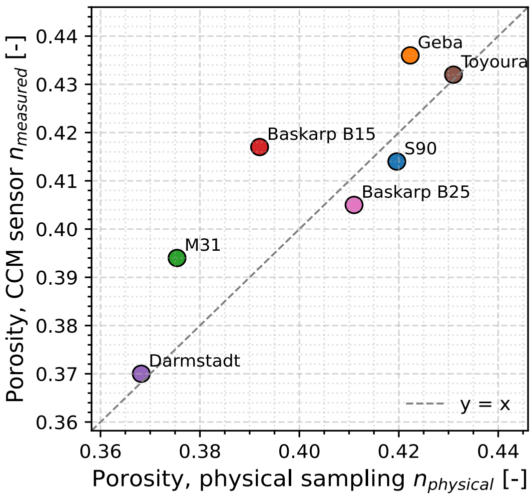

Figure 4. Comparative plot of the porosity ring samples vs CCM measurements.

Figure 5 further illustrates the versatility and feasibility of CCMs. Here, data acquired from the literature is illustrated together with the measurements made in the present study. The data illustrated in Figure 5 come from the following sources:

- Garba et al. (2019)have investigated the characteristic formation factor versus porosity relationships for natural sands acquired from two different beaches in Western Australia. Thes e are Scarborough and Cottesloe.
- Koch et al. (2011) carried out electrical conductivity measurements on granular quartz samples over a very wide range of average grain diameters from fine sand to fine gravel.
- Jackson et al. (1978) investigated the resistivity-porosity-particle shape relationships for eight different marine sands, the values were reported by Revil et al. (2012).

It must be noted that there is a lack of FF versus porosity data in the currently available literature. Therefore, additional data was included in the present plots shown in Figure 5 where some of the materials do not fall into the category of clean sands (beach sands acquired from Western Australia).

The plots shown in Figure 5 illustrate that, for clean silica sands, porosity can be reliably inferred from the formation factor as seen in the combined dataset, including the present measurements and literature values. All the plotted values collapse within a narrow Archie envelope with cementation exponent m between about 1.2 and 1.7. Despite variations in material source and packing, the great majority of points fall inside this range which is indicative of the FF–porosity transfer being robust for clean silica sands.

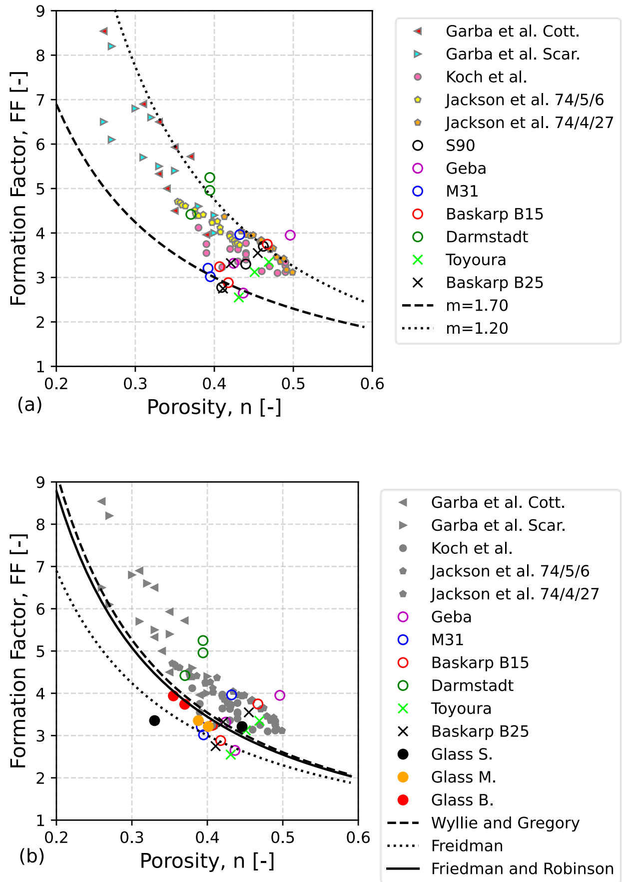

Figure 5. Formation factor versus porosity plots for various data reported in the literature overlain with the present measurements.

The glass beads plot consistently on or slightly above the reference trend in Figure 5b, which is attributable to their uniform shape and limited surface conduction. This behavior supports the interpretation that surface characteristics introduce minute, systematic offsets, and that effective-medium mixing relations remain applicable and reliable for artificial, narrowly graded materials such as glass beads.

5 CONCLUSIONS

A compact multi-electrode CCM probe provides a practical, non-destructive means to profile porosity (density) in saturated granular media using simple electronics and noise-robust measurements. Furthermore, pair-wise KCl calibration yields a stable linear response (typically high coefficients of determination), and a straightforward linear temperature correction further increases the robustness of the use of these sensors. The conductivity-porosity mapping shows good agreement with independent density checks from ring samples, confirming that bulk electrical conductivity can be used directly for porosity estimation in clean sands.

For the studied materials, formation-factor trends align with Archie-type behavior. This can be seen in the envelope that the data points from both the literature and the current study fall in (with an estimated cementation factor estimation of 1.2-1.7). Similar findings are also observed for glass beads with varying particle sizes. Glass beads in general followed the analytical formation factor porosity curve better. This might be due to the limited surface conduction and uniform particle shape.

The new calibration series on Toyoura, Baskarp B25, a sand–silt mixture, and two glass-bead gradations generalize the method across material typologies and compaction states which demonstrates transferability and usability of the approach adopted herein where the electrical conductivity is mapped to formation factor and porosity. This approach also necessitates temperature correction as discussed above.

Finally, the method proposed herein is shown to be robust and usable in laboratory conditions. Extending the usage to field conditions will require additional steps especially in marine environments where the conductivity of the pore water is inherently large due to the salinity of the interstitial water.

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