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## Application of concentration conductivity measurement (CCM) for porosity and density profiling in granular media

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### ABSTRACT

Porosity and pore structure are critical parameters in geotechnical engineering which influence the stiffness and permeability of granular materials. Traditional wave-based techniques, such as bender element testing, often require complex equipment, are susceptible to noise, and rely on stiffness-to-density conversions that introduce uncertainties in porosity inference. This study introduces the Concentration Conductivity Measurement (CCM) technique as a novel, non-destructive alternative for porosity and formation factor measurement using electrical conductivity. The CCM technique was validated through calibration tests on various sands and glass beads where a strong correlation was demonstrated with empirical models and literature data. The findings exhibit CCM sensors ability to provide reliable measurements under different material typologies prepared with varying compaction efforts. The method also alleviates the shortcomings of existing techniques. Unlike wave-based methods, CCM requires simpler equipment and is not susceptible to be affected by background noise which makes the method particularly suitable for geotechnical laboratory applications. This study provides a practical and versatile framework for porosity profiling with CCM and it advances the state of the art on granular media characterization. The study also demonstrates the significant potential of the technique for applications in soil mechanics and geotechnical modelling by comparing the findings to the data in the existing literature.

### 1. Introduction

There is a long history of utilization of electrical conductivity measurements in the fields of petroleum engineering and hydrogeophysics to measure the subsurface properties of porous media such as porosity. Beyond reservoir engineering and hydrogeophysics, determination of porosity, or its closely related conjugate void ratio, of a porous media is relevant in a diverse range of applications such as heterogeneous catalysis, energy technologies including fuel cells and batteries, and geology [48]. Additionally, most of the above-mentioned fields made extensive use of electrical conductivity or resistivity measurements (which are inverses or reciprocals of each other) to determine the density or formation of porous media. Furthermore, in the field of sediment dynamics, sediment concentration determination and flow speed measurements in dredging [36] and river engineering applications [31] electrical conductivity measurements have been employed to measure the concentration of the suspended material in aqueous solutions and bed erosion in rivers. Despite the widespread use of the electrical conductivity measurements to determine concentration of solutes and porosity of mixtures in a diverse range of geo-sciences, the uptake of the electrical conductivity measurements in geotechnical engineering

practice has not extended beyond water content, saturation, and occasionally salinity measurements. Generally, in geotechnical engineering practice, the electrical conductivity measurements were often employed to measure water content [35,18,43], degree of saturation [19], characterization of porous media structure [39], sand erosion [53] and rarely bulk density [8,6].

The range of electrical conductivity measurements to quantify the porosity of a porous media was possible due to the pioneering fundamental work undertaken by Maxwell, Bruggeman, and Archie. Earlier work on electrical conductivity of mixtures by Maxwell [24] and others [21–22,22,21,32] have culminated in the Bruggeman's correlation which is widely used in effective medium approximation models to define the conductivity of a porous media. Building on the above-mentioned previous work (and especially the work conducted by Sundberg [47] which was done a decade earlier than Archie's work but it was published much later according to the account given by Worthington [54], in 1942, Archie developed an empirical formula to correlate bulk resistivity of saturated soil to the pore fluid resistivity and porosity of the granular packing [3]. According to this empirical formula, the resistivity of soil ( $\rho$ ) can be related to the resistivity of the pore fluid ( $\rho_w$ ) in the following manner:

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$$\rho = a \times \rho_w \times n^{-m} \quad (1)$$

where  $n$  is the porosity and  $a$  and  $m$  are fitting and cementation parameters, respectively. The value of  $m$  depends on the interconnectivity of the pore network and tortuosity and it is typically 1.3 for clean unconsolidated sands according to Archie [3]. The empirical formula developed by Archie relies on what is known as electrical mixing models where it is assumed that the electrical conductivity of saturated porous media consisting of a single conducting phase (such as interstitial pore water) which is distributed in a nonconducting phase (such as sand grains) is proportional to the conductivity of the conducting phase. In simpler terms, for a saturated granular soil matrix, it is assumed that the conduction mainly occurs through the pore fluid and thus conductivity of the media is proportional to the porosity or void ratio of the soil matrix. The overall or bulk conductivity is also dependent on the conductivity of the pore fluid itself for example, it is widely known that with increasing salinity, the bulk electrical conductivity of the soil–water mixture increases. Archie [3] came up with a coefficient to define the proportionality in bulk electrical conductivity, termed as the formation factor (FF), and he has shown that this factor depends on the porosity of the fabric of the soil where formation factor is expressed as [43]:

$$FF = \frac{\sigma_{pf}}{\sigma_{bulk}} = \frac{a}{n^m} \quad (2)$$

where  $\sigma_{pf}$  is the electrical conductivity of the pore fluid and  $\sigma_{bulk}$  is the bulk electrical conductivity of the soil–water mixture. 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 [41,5,14].

In its broadest sense, there are two distinct methods of soil electrical conductivity measurements which can be classified as contact or non-contact sensing [28]. While the contact-based methods utilize a wide array of probes which make contact with the soil, non-contact methods rely on the principle of electromagnetic induction to infer soil properties. Contact methods are relevant for laboratory-scale work and various probes have been developed to answer this need. A lesser known contact based method is the so-called Conductivity-type Concentration Meter (CCM) which can be utilized to profile the structural properties of a soil deposit in terms of porosity and formation. This study seeks to introduce a case where CCMs were used to measure the along-the-depth porosity profile of granular materials such as sands and glass beads. CCMs are a valuable addition to the conventional instrumentation methods as they allow non-destructive and high frequency testing of soil matrix properties. Techniques relying on wave propagation such as bender elements [4,7] or other stress wave dependent methods [45] can also be used to same avail but these sensors can be affected by noisy environments and the interpretation of their results often require expert judgement. Stress-wave based sensors rely on the wave arrival lag to indicate the stiffness of the matrix and this information can be used to back-calculate the void ratio or the porosity, but their use cannot be extended to, for instance, inference of the permeability of a granular matrix. Additionally, bender elements require complicated electronic interfaces which must be capable of very high sampling rates. CCM sensors on the other hand can be placed as an array to monitor the density changes in the soil with relative ease and simpler electronics. This contribution will elaborate on an exemplar laboratory use case for CCM sensors where porosity and formation factor of granular materials are determined for laboratory use. Acquired results are also compared with the results available in the literature and a good agreement has been found.

## 2. Materials and methodology

### 2.1. CCM sensors

Using the proportionality principle outlined above [3], Delft Hydraulics, predecessor of present day Deltares, developed the Conductivity-type Concentration Meter (CCM). The measurement principle relies on the change of the bulk conductivity of the soil–water mixture upon inflicting changes in the mixture such as sand addition into water. It is assumed that the surface conductivity of the sands are small enough to be neglected and as non-conductive sand is added to the mixture, the conductivity will decrease. The assumption of conductivity decrease has been theorized by earlier work mentioned above, for instance with the mixing formula of Lord Rayleigh [32], and experimentally proven by many contemporary works such as Robinson and Friedman [38] and Dijkstra et al. [8]. While CCM method was not adopted in geotechnical laboratory practice, its utility have been explored in a limited number of studies where the solid concentration in suspension flows [50,51] and transport flow rates in sediments [9] were investigated.

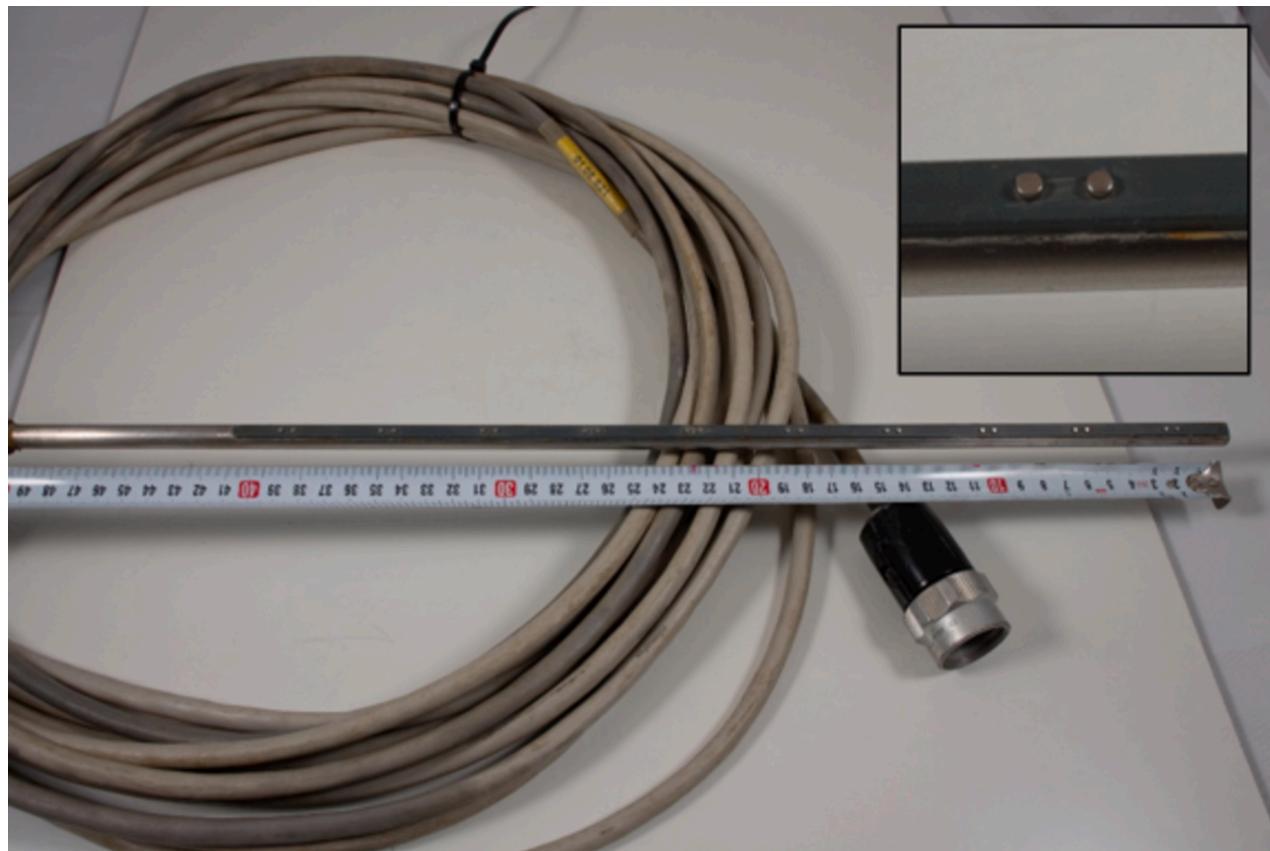
In the present testing case, the CCM electrode pair were interfaced with a signal conditioner and a data acquisition system consisting of a 16-bitsanalog to digital converter (ADC) and a PC. The signal conditioner, analog to digital converter, the data acquisition software were developed in-house and the signal to noise (SNR) ratio of the system was 70 db. In the configuration of the CCM probe illustrated in Fig. 1, a total of 10 CCM electrode pairs are distributed over a length of 400 mm. The first CCM electrode pair, which is also illustrated in the inset photograph within Fig. 1, is located 25 mm away from the tip of the probe. The following CCM pairs are placed 40 mm away from each other and data a sampling rate of 10 Hz is used in the tests. The center-to-center distance between the titanium CCM electrodes in each pair is 5 mm. Each CCM pair is able to measure the electrical conductivity of its surroundings with an adjustable excitation voltage of up to 10 V.

The CCM system consists of an electrode pair as sensor (two-electrode system), a cable to the signal conditioner, a signal conditioner and a data acquisition system. The CCM signal conditioner measures the conductivity of the medium between the electrodes by setting an AC-voltage and measuring the current. Ohm's law states that conductivity is proportional to the measured current. The signal conditioner does this by generating an AC signal of 10 kHz with a fixed voltage. This signal is applied to a transformer, to electrically isolate the electrodes from the other electrodes pairs. The current in the transformer, and thereby the current in the electrodes, is amplified and converted to a voltage. The height of the peaks in the (AC) voltage are detected and filtered with a 2nd order low-pass Bessel filter with a cutoff frequency of 320 Hz. This signal is acquired by the data acquisition system.

Rinaldi and Cuestas [37] defines the bulk conductivity ( $\sigma_{bulk}^*$ ) of a soil system under constant excitation frequency as follows:

$$\sigma_{bulk}^* = \sigma_o + \omega \epsilon_o k'' \quad (3)$$

where  $\sigma_o$  is the ohmic low-frequency conductivity,  $\omega$  is the angular frequency,  $\epsilon_o$  is the vacuum permittivity constant at  $8.85 \times 10^{-12}$  F/m, and  $k''$  is the imaginary component of complex dielectric permittivity which corresponds to the permittivity measured out of phase ( $90^\circ$ ) with the electrical field considered. The term  $\sigma_o$  in the equation above represents the charge mobility through the electrolyte and the second term with the angular frequency is related to the mobility through the double layer [43]. The double layer, which is also referred to as double diffuse layer in clays, is sensitive to electrical excitation frequencies higher than 100 kHz and ions might be released from the double layer at higher frequencies which causes a further increase in bulk the electrical conductivity [46]. However, for most granular soils, at lower frequencies than the above-mentioned threshold, the electrical conductivity of soils is independent of the excitation frequency [27,40,37]. Therefore, for

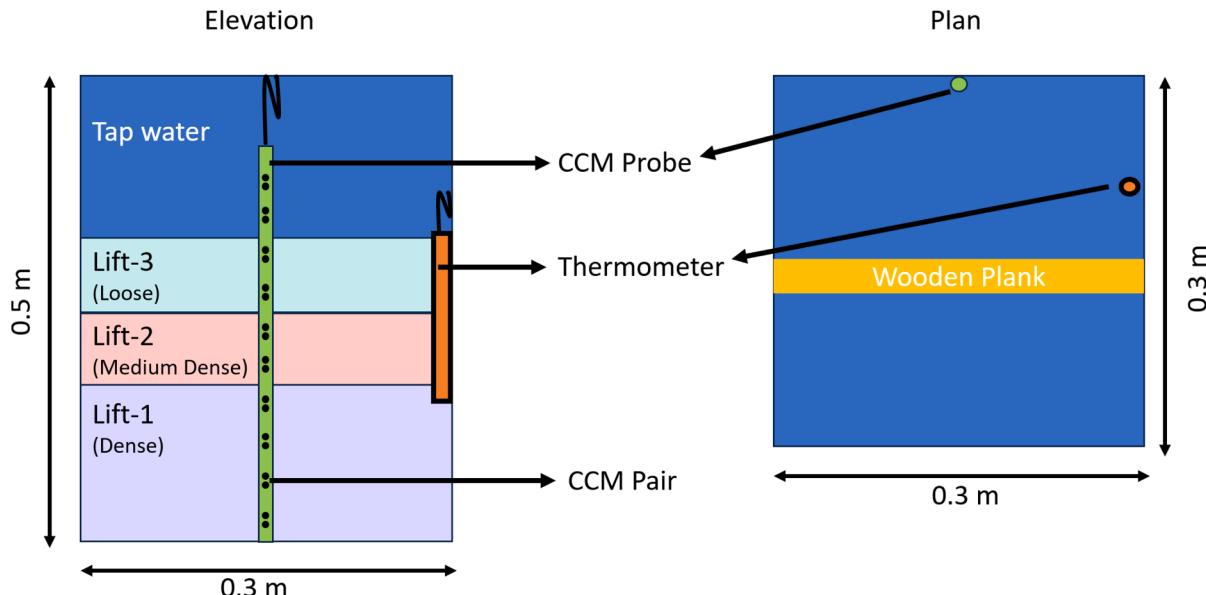


**Fig. 1.** A photograph of the 400-mm-long CCM probe which houses 10 CCM electrode pairs.

most cases, the total conductivity of the media is equal to the ohmic conductivity. Within this study, the excitation frequency of 10 kHz applied to the CCMs and based on the reasoning above, it could be argued that the measured electrical conductivity is also independent of the frequency applied.

## 2.2. Test method

Previous studies delving into the resistivity of soils [19,44] have utilized a resistivity box type apparatus as prescribed by AASHTO T288-91 [1]. Due to the shape and size of the CCM probe used, the present study made use of a glass tank to carry out the conductivity/resistivity measurements similar to the resistivity box prescribed in the AASHTO



**Fig. 2.** A sketch of the experimental setup with the intended densities of different lifts, the wooden plank shown on the right hand side image is only utilized in tests involving glass beads.

standard. The glass tank was 500 mm deep and had an inner planar area of 300 mm by 300 mm. Fig. 2 shows a sketch of the experimental setup where the positioning of the instruments and different sand layers (or lifts) pluviated underwater are also illustrated. A wooden plank is used only in tests utilizing glass beads to reduce the effective volume of the tank.

The testing commenced with filling of the tank with tap water and allowing the temperature gradients to equal out for a minimum duration of 24h. During the 24h period, both CCM sensors and the thermometer probe were inundated under water and affixed to their intended locations within the tank and the sensors were allowed to record the ambient measurements in tap water. Following the initial 24h period, the addition of granular materials into the tank was undertaken. The granular materials used were five different sands and a single type of uniformly graded glass beads.

In order to realize different granular packings within the tank, sands were introduced to the tap-water-filled tank in several layers. The first layer was placed by gradual addition of sand with constant tamping until the tank was filled with 25 kg of sand. Following the placement of the initial layer, the sand was further compacted with a vibratory needle. The second layer was built above the first one by addition of 10 kg of sand with the same method but for the second layer, no vibratory compaction was used. The third layer was also made up of 10 kg of sand and it was allowed to settle on top of the second layer and no compactive effort was applied. The resulting sand bed with the above prescribed placement methodology had three distinct layers which were detectable by the CCM sensors used. Following the completion of sand addition, the assembly was allowed to rest for an additional 24h and measurements of electrical conductivity and temperature was taken during this duration. Once the sensor readings were recorded for a minimum of 24 h with the sand, the dismantling of the sample was carried out, and ring samples were cut from the sand to determine the density of the material.

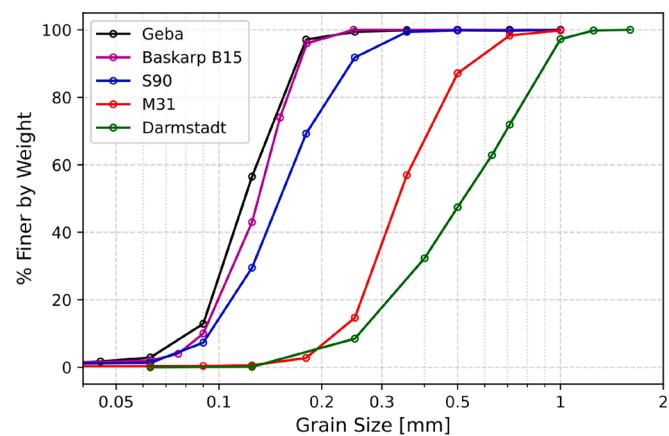
Due to the limited availability of the glass beds, the test method was slightly modified whereby the volume of the glass tank was reduced by a wooden plank to allow for the buildup of sample height to cover the CCM sensors distributed over the probe while leaving the two of the topmost CCM pairs above the covered area. A total of 20 kg of glass beads were used and two lifts were constructed utilizing 10 kg of material. While the first lift was placed with continuous tamping, the second lift was gently poured and allowed to settle within the tank.

### 2.3. Materials

Table 1 illustrates the types and basic properties of the granular materials used together with the Unified Soil Classification Scheme (USCS) [49] group of each sand material. In addition to the properties tabulated in Table 1, Fig. 3 illustrates the grain size distribution curves for the sands used in the experimental program. As can be seen from Fig. 3, the sand materials were selected to cover a wide range of grain sizes. Since the tests aimed at porosity determination by electrical conductivity measurements, it was theorized that by using sand materials of different gradations, a wide range of porosities can be achieved

**Table 1**  
Properties of the granular materials used.

	Sands				
	Geba	Baskarp B15	S90	M31	Darmstadt
$G_s$	2.67	2.65	2.66	2.65	2.62
$e_{min}$	0.64	0.55	0.64	0.49	0.46
$e_{max}$	1.07	0.89	0.93	0.76	0.80
$D_{10}$ (mm)	0.08	0.08	0.09	0.22	0.26
$D_{30}$ (mm)	0.10	0.10	0.12	0.28	0.38
$D_{60}$ (mm)	0.13	0.14	0.16	0.36	0.59
$c_u$	1.63	1.75	1.78	1.64	2.27
$c_c$	0.96	0.89	1.01	0.99	0.94
USCS	SP	SP	SP	SP	SP



**Fig. 3.** Grain size distribution curves of the sands used in the experimental campaign.

within the test volume. In geotechnical laboratory practice, in general, the porosity or the relative density could be controlled by altering the compactive effort but in the case of the experiments presented herein, the compactive effort was limited due to the brittle nature of the glass container used in the tests. The glass container was deliberately selected in order to ascertain that the model boundaries did not conduct electricity. Beyond the naturally occurring sands, uniform glass beads of 200–300  $\mu\text{m}$  diameter was also used to assess the resulting conductivity and formation factor to cross-check the results with existing works on electrical conductivity and empirical formulas. Finally, Fig. 4 illustrates microscope images of all sands and the uniformly sized glass beads used in the experiments.

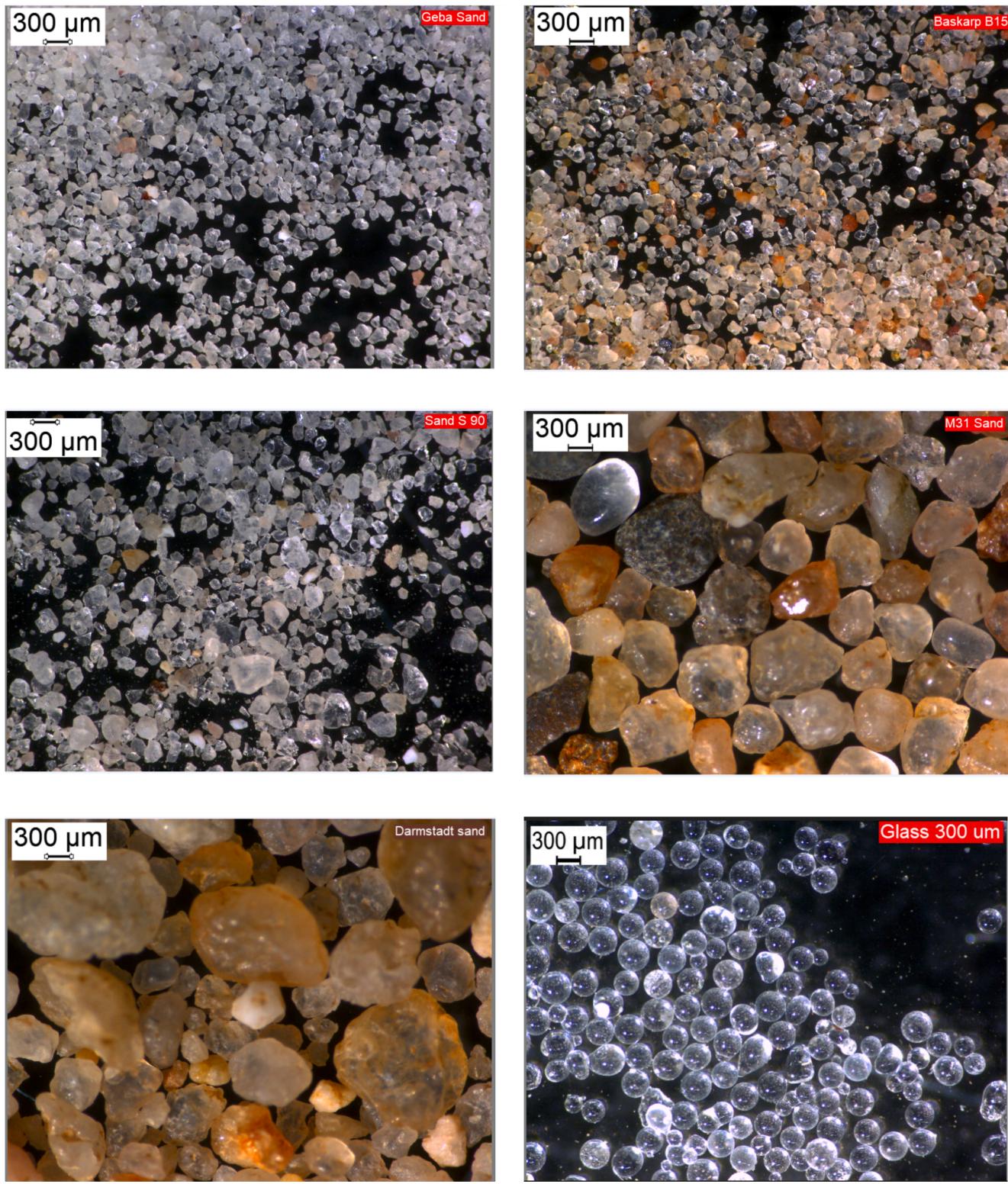
### 3. CCM sensor calibration

#### 3.1. KCl calibration

The calibration of any electrical conductivity probe can be undertaken by immersing the probe in a solution of known salinity [10]. The salinity of the solution will determine the electrical conductivity and if the process is repeated through a series of solutions with successively increasing salinity, then a calibration curve can be formed. In this study, solutions of KCl (Potassium Chloride) with different molar concentrations were utilized. The conductivity measurements of the solutions were made with Tetracon 325 probe interfaced with Cond 315i handheld conductivity meter produced by Wissenschaftlich-Technische Werkstätten GmbH. Electrical conductivity has been customarily reported in micromhos per centimeter ( $\mu\text{mho}/\text{cm}$ ) or in millimhos per centimeter ( $\text{mmho}/\text{cm}$ ) [34]. In accordance with the International System of Units (SI) [23], the reciprocal of the ohm is the Siemen (S) and, in this system, electrical conductivity is expressed as  $\text{dS}/\text{m}$ . In the present work, the preferred units for brevity and conciseness of presentation are  $\mu\text{S}/\text{cm}$ . Fig. 5 illustrates the electrical conductivity measurements taken by 10 CCM pairs when immersed in KCl solutions of varying salinity levels. The molar concentration of the solutions used and corresponding corrected electrical conductivities for 25 °C is given in Table 2. Table 3 tabulates the resulting calibration factors for the CCM sensor pairs as a consequence of the KCl solution calibrations.

#### 3.2. Factors affecting electric conductivity in soils and temperature effects

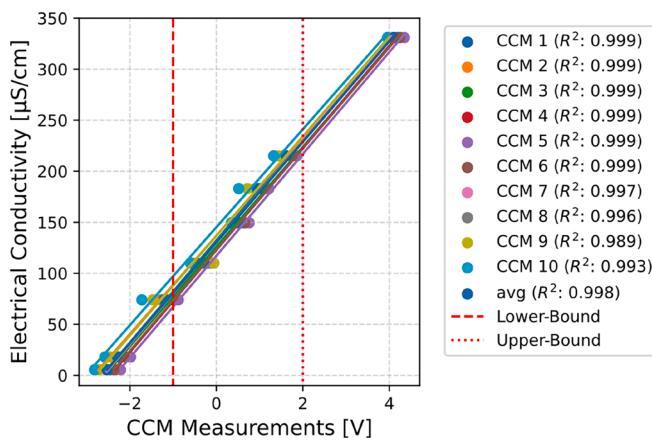
Friedman [11] summarized the factors affecting the electrical conductivity in soils in three major categories. The first category of factors has to do with the presence and distribution of materials in solid, liquid, and gaseous state within the soil matrix. The relative ratios of these phases and the structural composition of the matrix, for example



**Fig. 4.** Microscope images of Geba, Baskarp B15, S90, M31, and Darmstadt sands together with an image of the glass beads.

cementation of the grains, will dictate the electrical conductivity to a large extent. Factors of secondary importance, according to Friedman [11], are the important solid particle quantifiers, which are relatively time-invariable particle shape and orientation, particle-size distribution, cation exchange capacity (CEC), and wettability. The third category consists of the relevant soil solution attributes, and as these properties change quickly in response to alterations in management and

environmental conditions such as ionic strength, cation composition, and temperature. In the present study, the effects of the factors in the first category on the electrical conductivity are investigated while correcting for the temperature effects. The factors in the second category are mostly kept constant in order to make comparisons between different samples. The effects of the third category are artefacts of the testing conditions which can affect the outcomes of the electrical



**Fig. 5.** Electrical conductivity measurements of CCM sensors immersed in KCl solutions with different concentrations.

**Table 2**

Molar concentrations of KCl salinity and electrical conductivity (EC) of the solutions used for probe calibration.

KCl (mol/L)	KCl (g/L)	EC (μS/cm @25 °C)
Distilled Water	0	5.5
0.0001	0.007455	18
0.0005	0.037274	74
0.00076	0.056656	110
0.001	0.074548	149.5
0.00128	0.095421	183
0.00148	0.110331	215
0.00228	0.169969	331

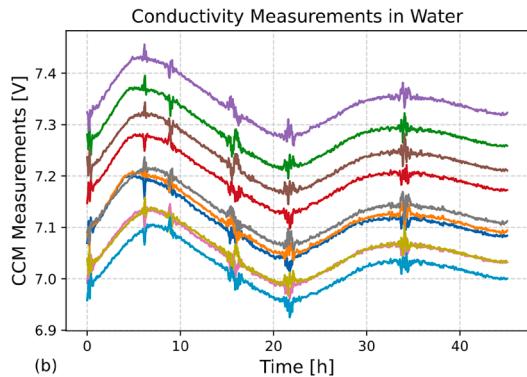
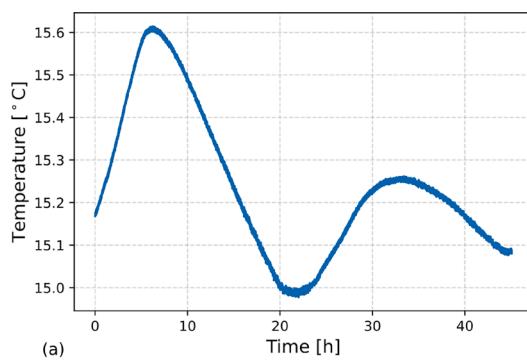
**Table 3**

CCM sensors' calibration parameters resulting from the calibration exercise.

Sensor	Slope $(\frac{\mu S}{cm \times V})$	Intercept $(\frac{\mu S}{cm})$	Coeff. of Determination
CCM 1	49.963	132.054	0.999
CCM 2	48.258	136.890	0.999
CCM 3	48.865	126.087	0.999
CCM 4	50.056	122.776	0.999
CCM 5	49.938	117.119	0.999
CCM 6	49.641	123.046	0.999
CCM 7	49.850	130.257	0.997
CCM 8	49.347	130.580	0.996
CCM 9	48.747	136.644	0.989
CCM 10	48.009	145.137	0.993
Average	49.318	130.140	0.998

conductivity and therefore, any effects brought about by these should be corrected.

Electrolytic conductivity (unlike metallic conductivity) increases with temperature at a rate of approximately 1.9% per degree Centigrade and since each ion has a different temperature coefficient, for precise work, conductivity ideally should be determined at 25 °C [34]. Testing campaigns often utilize thermometers [57] or thermocouples [43] to keep track of the changes in the specimen temperature during testing where conductivity of soils are measured. In order to study the effects of temperature variations on the CCM measurements, the probe was allowed to come to thermal equilibrium with the ambient temperature for a minimum duration of 24h and following that period, conductivity measurements were acquired from the CCMs for a duration of about two days in the measurement tank filled with tap water. Fig. 6a illustrates the temperature value measured within tap water and Fig. 6b illustrates the raw CCM sensor measurements during this period in Volts. In Fig. 6b it can be seen that different CCM sensor pairs possess inherent



**Fig. 6.** Temperature variations during the two-day measurement period.

differences in terms of the measured values. The variation of the raw measurements is due to the unique nature of the sensor where cable and sensor impedance affect the outcomes of the measurements. Similar factors are also considered in Time Domain Reflectometry measurements where geometric constant of the probe is also considered [29,10]. The raw measurements illustrated in Fig. 6b are converted to electrical conductivity measurements by making use of the calibration parameters illustrated in Table 3. The resulting curves are not corrected for temperature changes and the temperature change trends can be clearly observed in the curves illustrated with the blue background in Fig. 7. Once the temperature correction is applied to the curves, the curves shift upwards meaning that the amplitude of conductivity increases, and the effect of temperature fluctuations are not as pronounced. The temperature correction was done by assuming a linear relationship with the increase in temperature and the measured electrical conductivity. Under the studied conditions, with the set of CCM sensors used, the temperature correction was applied in the following form:

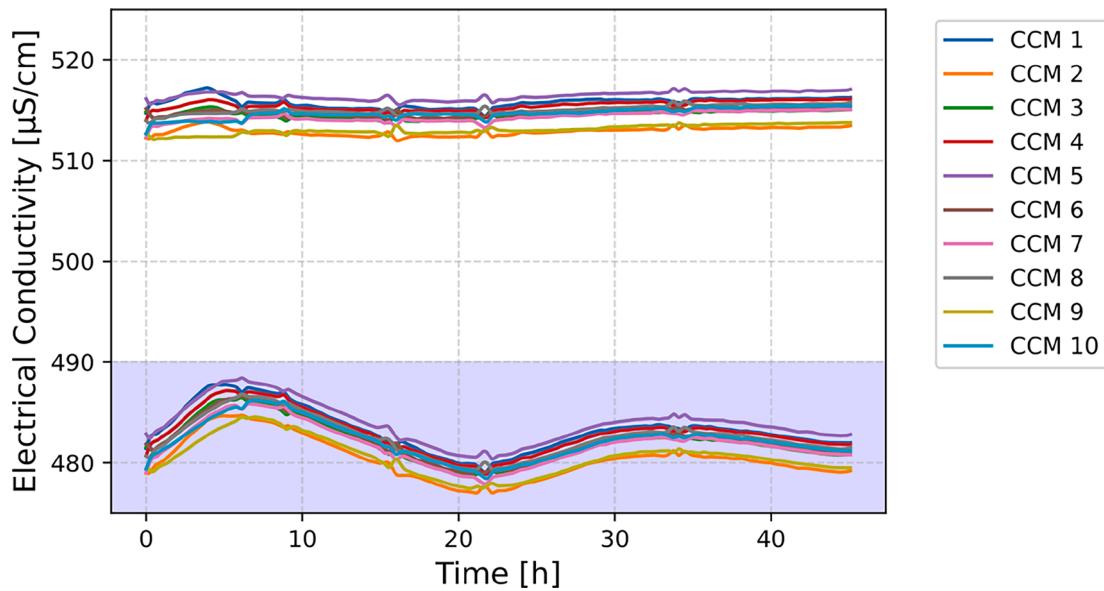
$$\Delta EC_{corr} = k \times \Delta t \quad (4)$$

where  $\Delta EC_{corr}$  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 with units of  $\mu S/cm/^\circ C$ , and  $\Delta t$  is the difference between the temperature at which the measurement took place and the desired correction temperature. In this study, the value of the  $k$  scalar multiplier is  $11.36 \mu S/cm/^\circ C$ . Lastly, the minor fluctuations in Fig. 7 are thought to be artefacts of electro-magnetic disturbances which can be explained by the surrounding equipment being triggered at different times during the experiments.

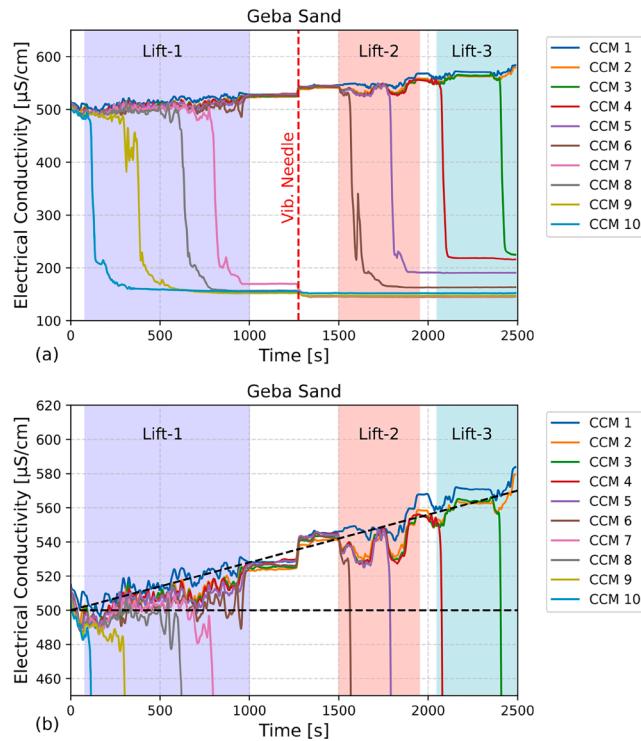
#### 4. CCM measurements in sand matrix

##### 4.1. Measurement of sand porosity for natural sands

Fig. 8 illustrates the sand addition process for the test involving Geba



**Fig. 7.** Electrical conductivity measurements in time domain for uncorrected (within the blue background) and corrected CCM measurements.



**Fig. 8.** Evolution of electrical conductivity over time as Geba sand is introduced into the experimental setup; (a) full depiction of the curves and (b) focused abscissa to highlight drift in conductivity measurements.

sand where the electrical conductivity measurements are illustrated in time domain. In Fig. 8a, the background of the plots is highlighted with different colors to indicate the duration in which different lifts of sand are added as per Fig. 2. The trends of reducing electrical conductivity are in line with the addition of sand where the CCM probes which are covered with a sandy layer indicate significant drop in electrical conductivity due to blocked transmission paths by sand grains. It should be noted that in all tests, CCM1 and CCM2 sensor pairs were kept outside of the soil matrix so that the electrical conductivity of the aqueous (water) phase can be monitored. The test results indicate a drift in the electrical

conductivity of the water which might be explained by the presence of free ions in the aqueous solution of soil and water. It is well established that the overall or bulk electrical conductivity for soil mixtures with little clay content depend on the electrical conductivity of the pore fluid and several researchers [35,15,25] have shown that soils with pore fluid of high ionic strength are more conductive than soils with pore fluid of low ionic strength [42]. Therefore, it is possible that some sands used in the experimental program released a larger concentration of free ions into the pore water upon their addition to the aqueous solution of sand and tap water. Following this assumption, it is thought that some sands contained more free ions which might explain the increased conductivity in the measurements of the topmost to CCM sensors which monitor the conductivity of the water above the sand. Similar increases in the pore water conductivity are reported for the so-called dirty sands [56] and oil sands [52], sand clay mixtures [2] where ionic concentration in the pore space is increased due to impurities in the sand. The presence of clays might altogether increase the conductivity of the porous media if double diffuse layer relaxation occurs which does not explain the conductivity increase seen in the tests conducted within the scope of this study since no appreciable quantity of clay sized particles were present in the granular materials used and the measurement frequency was not high enough to induce relaxation.

Beyond the effects of gradually increasing electrical conductivity, the moment of vibratory needle introduction is also visible in the plots illustrated in Fig. 8 and this moment in time is marked by a dashed line. It is seen that upon introduction of the vibratory needle, the electrical conductivity of the materials placed in Lift-1 exhibit a mild drop in conductivity which indicates further densification of the soil matrix. It is also seen that the electrical conductivity measured in the water devoid of sand increases at this exact instance which can hint migration of free ions from Lift-1 into the water. It is probable that the turbulence introduced by the vibratory needle might have caused the concentration of the free ions previously locked in the soil matrix to migrate into the aqueous part of the mix which caused the marked increase in electrical conductivity at that particular instant. In Fig. 8b, the increase trend is shown in greater detail by adjusting the axes of the plot. It is seen that there is a constant drift in electrical conductivity of the material and as articulated above, it is hypothesized that the free ions contained within the sand increase the electrical conductivity. Another notable observation is the increase in the measured temperature of the soil–water mixture at during the vibratory needle operation. It is possible that the seemingly instantaneous increase in the temperature might increase the

solubility of the water slightly which might only partially explain the conductivity peaks observed. Fig. 9 illustrates the measured temperature within the glass tank where the temperature peaks due to vibratory needle operation can be observed. It should be noted that in order to prevent particle breakage, no vibratory needle compaction applied in the tests with glass beads. Lastly, it should be noted that all electrical conductivity time-histories illustrated in the present subsection are corrected for temperature. Finally it should be noted that the average conductivity of the aqueous solution is about 500  $\mu\text{S}/\text{cm}$  as illustrated by the curves at the onset of the experiments.

Similar results of increasing electrical conductivity were also observed in other sands used in the experimental program. These sands include M31 and Darmstadt sands. Baskarp B15 and S90 sands on the other hand, did not exhibit fluctuations in the overall electrical conductivity response of the soil–water mixture upon gradual introduction of the sand. Fig. 10 and Fig. 11 illustrate the electrical conductivity time-histories for Baskarp B15 and S90 sands, respectively. It should be noted that the assumption of electrical flow only occurring in the interstitial pore water is valid as the sands do not contain appreciable amounts of clay and the electrical conductivity of the liquid phase, as seen in Fig. 8 is in the order of 500  $\mu\text{S}/\text{cm}$  which is an order of magnitude larger than that of the quartz surface conductivity of 54  $\mu\text{S}/\text{cm}$  as reported by Miller et al. [26]. Fig. 12 and Fig. 13 illustrate the results for M31 and Darmstadt sand, respectively.

In all sand addition tests, the onset of vibratory needle compaction caused an increase in the density of the sand material in the first lift which is the only material present during the compaction. The increase in the density of the sand is also accompanied by an increase in the conductivity of the water phase of the mixture which, as indicated above, might be associated with the release of ions into the water.

Upon examination of the test results for all sands, it is hypothesized that it is possible that some sands used in the experimental program released a larger concentration of free ions into the pore water upon addition to the aqueous solution of sand and tap water. Following this assumption, it is also possible that some sands contained more free ions which might explain the increased conductivity in the measurements of the topmost to CCM sensors which monitor the conductivity of the matrix above the sand. The increase of the conductivity of water due to disturbance caused by the vibratory needle is less visible in M31 and Darmstadt sand mixtures. This is evident from the increase in conductivity measurements acquired from the aqueous phase during introduction of additional materials which are highlighted by the colored backgrounds in the figures below. Furthermore, the difference between CCM7 and the other sensors (CCM8, CCM9, CCM10) can be attributed to its specific location within the experimental setup. As the needle's vibrations diminish with distance, CCM7 likely experienced a greater degree of compaction and subsequent ion release compared to the

sensors further away.

#### 4.2. Electrical conductivity porosity correlation

The electrical conductivity measurements illustrated above were coupled with the measurements of the specimen volumes measurements during the infill of different lifts and ring sampler measurements done post testing to back-calculate the void ratio of the granular materials. The volume measurements were used together with the specific gravity of the materials to come up with the bulk density and the void ratio of each lift of the material deposited in the test tank. Temperature corrected electrical conductivity measurements were also recorded at each CCM sensor elevation. By making use of the data points emerging from different sand profiles, the electrical conductivity measurements were converted to void ratios. Fig. 14 illustrates the conversion of electrical conductivity measurements to porosity for all sands tested. In Fig. 14, a porosity range of less than 0.5 (or a void ratio of less than unity) was considered as a relevant upper limit for sand materials. This limit was deliberately determined to avoid the suspension state of the materials used and to stay within the maximum void ratios of the materials as outlined in Table 1. In addition to the back-calculated void ratio values, Fig. 14 also illustrates the void ratio measurements taken from the dense portion (Lift-1) of each soil profile via a cylindrical sampler. The reason for sampling only the dense layer was the difficulty in extracting intact or coherent samples from other layers which were considerably looser. The sampling for density was undertaken in line with ISO 17892-2:2014 [16]. These data points are highlighted with a triangular marker to differentiate them from the rest of the back-calculated data points. The density related data points are plotted by way of utilizing the conductivity measurement of the nearest CCM pair and the porosity value of the retrieved ring sample. Overall, there seems to be a good agreement between the back-calculated values and values obtained via density sampling method. The coefficient of determination of the data points excluding the data points acquired via the ring sampler is 0.957 which indicates a good correlation between the electrical conductivity measurements and the void ratio of the sand matrix. It should be noted that the data points stemming from the electrical conductivity measurements are averaged for each lift within the sand layers tested. A porosity profile representation of the sands are given in Fig. 15 where the distribution of the porosity values for different sands can be seen. Fig. 15 utilizes the trendline acquired for all measurements in Fig. 14 and uses it as a transfer function to convert CCM readings into porosity. It should be noted that the linear relationship observed in this study hold true for clean sands and electrical conductivity – porosity relationship may not be of linear nature in other types of media [30].

#### 4.3. Formation factor and comparison with existing literature

The concept of formation factor postulated above by Archie [3] can be interpreted as a relationship describing the void ratio or the porosity of a granular matrix with additional terms for correcting for the so-called cementation effects (exponent  $m$  in Eq. (2)). There are numerous studies investigating the relationship between the porosity natural clean sands and the formation factor. Garba et al. [13] have investigated the characteristic formation factor versus porosity relationships for natural sands acquired from two different beaches, namely Scarborough and Cottesloe, sourced from Perth Basin, Western Australia. Moreover, Koch et al. [20] carried out electrical measurement on industrial-grade granular quartz samples over a very broad range of average grain diameters from fine sand to fine gravel to quantify the influence of pore space characteristics on the hydraulic conductivity of these materials. The values used herein from the study of Koch et al. [20] are reported in [33]. Lastly, Jackson et al. [17] investigated the resistivity-porosity-particle shape relationships for eight different marine sands. As for the formation factor calculated for the present experimental program, the very last measurement taken in each experiment is used irrespective of

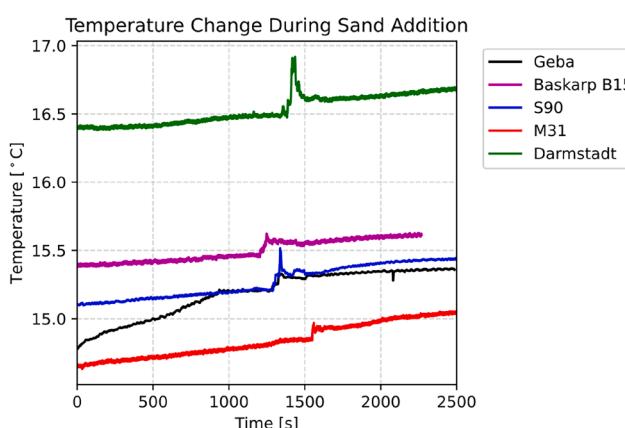


Fig. 9. Measured temperatures during the sand addition tests.

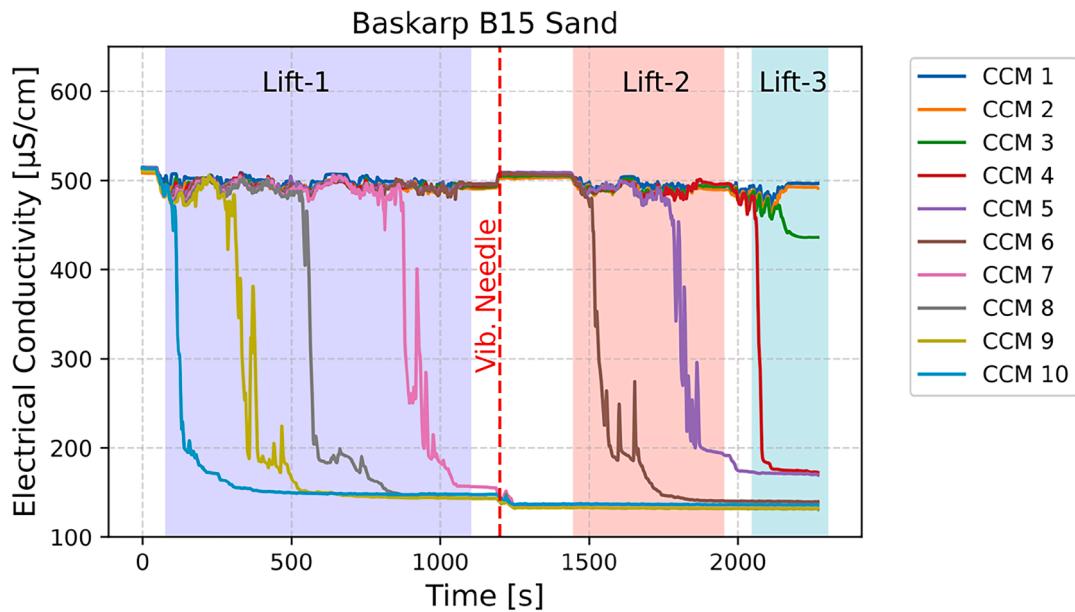


Fig. 10. Electrical conductivity time-history for Baskarp B15 sand.

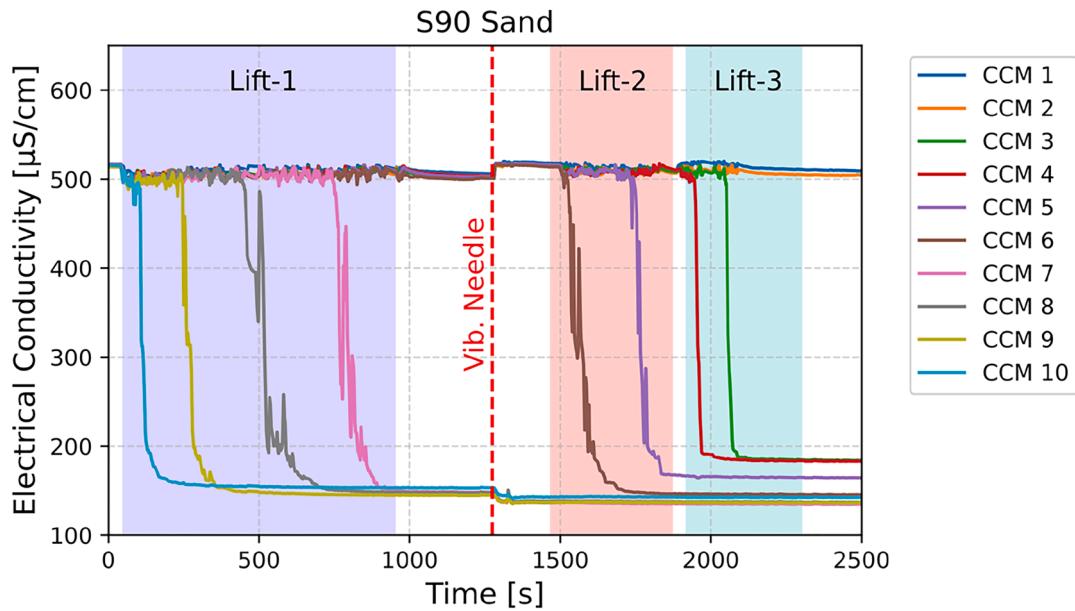


Fig. 11. Electrical conductivity time-history for S90 sand.

the increases in pore water electrical conductivity. The reason for this is the formation factor by definition removes the effect of pore-fluid conductivity as it is present throughout the media and grains themselves can be regarded as insulators according to many studies [17,26]. Fig. 16 illustrates a comparison of the formation factors calculated from the present experimental investigation with the above-mentioned studies in the literature (the value of  $a$  is equal to unity in all curves).

In Fig. 16a, a comparison of the available data in the literature is presented for the natural sands used in this study. Since the dataset from the study conducted by Jackson et al. [17] is only partially available, only two sands were used in the comparison. Overall, the dataset presented from the literature contains a wide range of porosities which happens to fall within the bounds of the empirical relationship proposed by Archie [3] where upper and lower-bound  $m$  factors of 1.7 and 1.2 are

considered. It should be noted that Archie [3] recommended 1.3 as the value of  $m$  for clean unconsolidated sands which seems to encapsulate a vast majority of the measurements done in this study utilizing natural sands. As for the Cottesloe and Scarborough sands [13], the lower porosities materials in general makes the comparison difficult although at porosities around 0.35, the results were similar to that of the Darmstadt sand used in this study. Although the material gradation limits were similar in both the present study and the work of Garba et al. [13], the formation factor-porosity relationship is somewhat different. One of the reasons for the disparity between the results might be explained by the sand mix design made by Garba et al. [13] whereby all the samples were composed of quartz and carbonate in 80%/20% (volume) proportion. The values reported by Koch et al. [20] tended to show closer agreement with the measurements made and the likely reason for that might be the

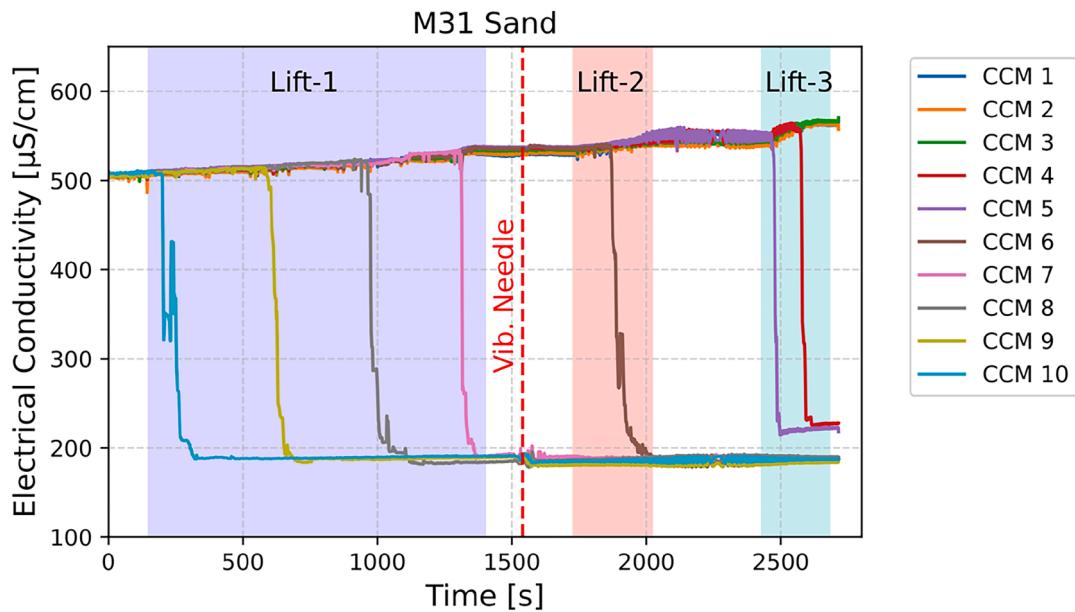


Fig. 12. Electrical conductivity time-history for M31 sand.

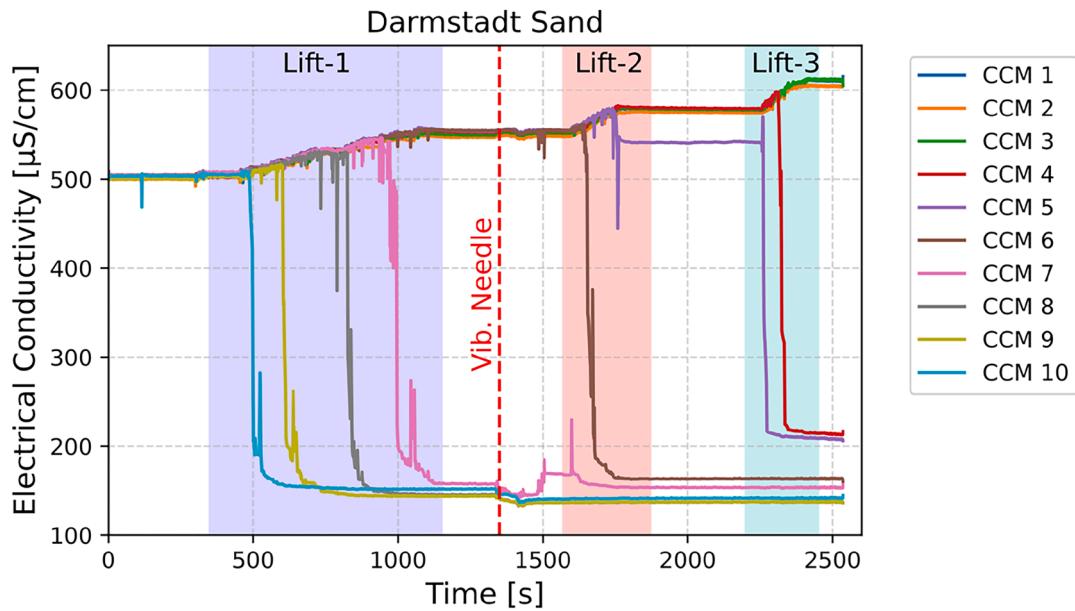


Fig. 13. Electrical conductivity time-history for Darmstadt sand.

use of quartz sands. The study also included compacted and uncompacted sand samples which explains the larger porosity values. Similarly, the data taken from Jackson et al. [17] pertained to two different quartz sands retrieved from marine environment with gravel and sea shells with the sample designations 74/5/6 and 74/4/27. It is seen that the gravel mixed sample more closely fits with the present dataset. For further details of the literature data, interested readers are referred to cited resources. Lastly, based on the experimental data on the glass beads' formation factor versus porosity relationship Wyllie and Gregory [55], Friedman [11], and [12] have proposed  $m$  values of 1.38, 1.2, and 1.35, respectively. For the present study this value is in the order of 1.3 which coincides with the value proposed Archie [3] in his early studies. It should be noted that the  $a$  factor is equal to unity in all the above-mentioned cases.

## 5. Conclusions

Electrical conductivity measurements within the realm of geotechnical engineering is mostly confined to water content and salinity measurements. However, in different branches of geo-sciences and other disciplines, the electrical conductivity is used to infer the porosity or void ratio of granular matrices. In this study, electrical conductivity measurements utilizing Conductivity-type Concentration Meter (CCM) sensors were employed to investigate the measure the porosity of granular materials deposited in a glass-tank. The porosity was varied by employing compactive efforts on different lifts of the same material and the CCM method was used to predict the porosity and formation factor (FF) of granular matrices utilizing both silica sands and glass beads. As a consequence of the above prescribed experiments, the following

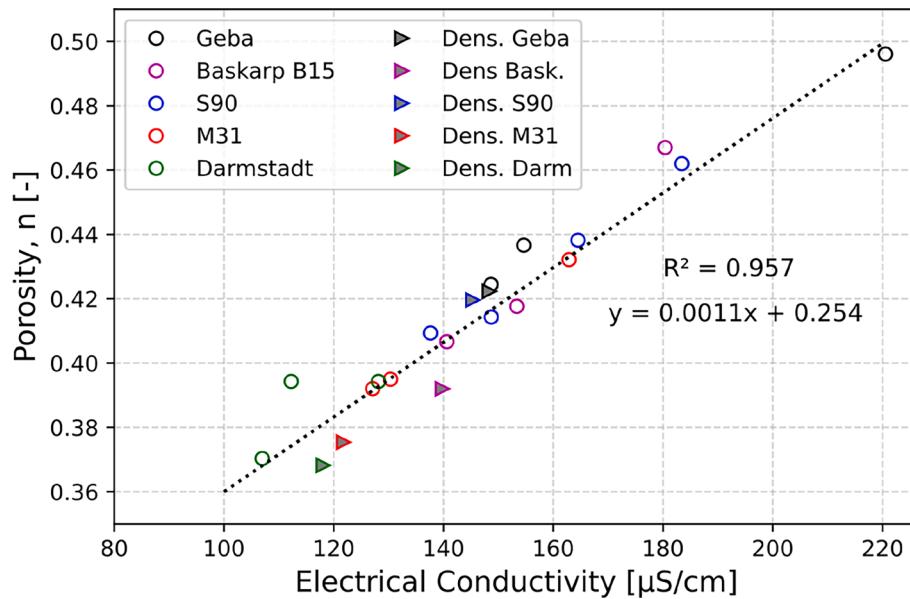


Fig. 14. Relation between measured electrical conductivity and porosity values.

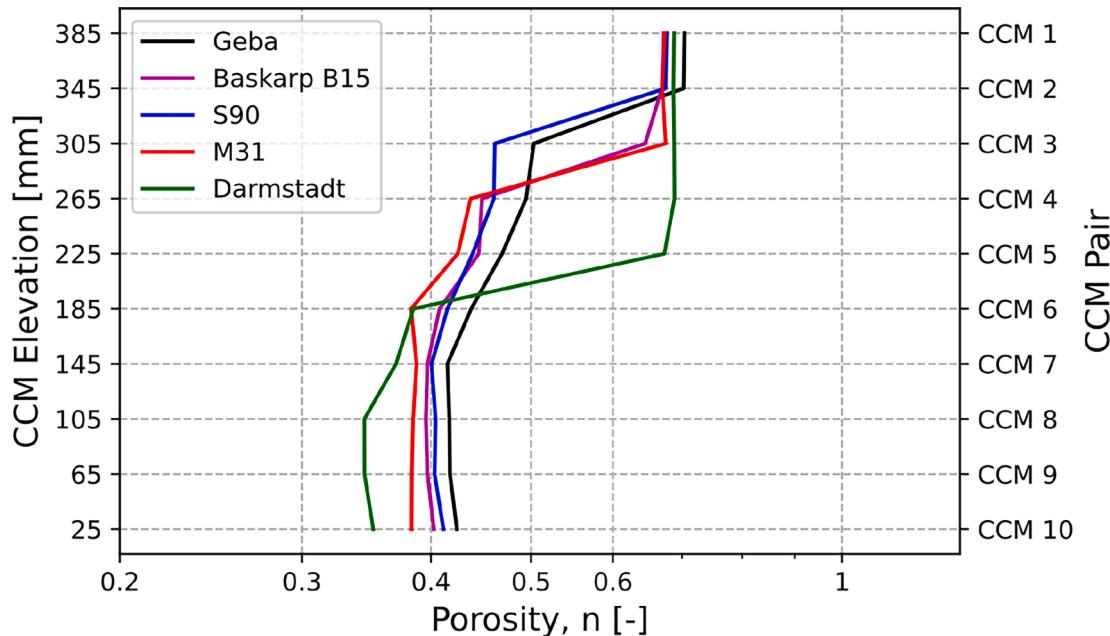
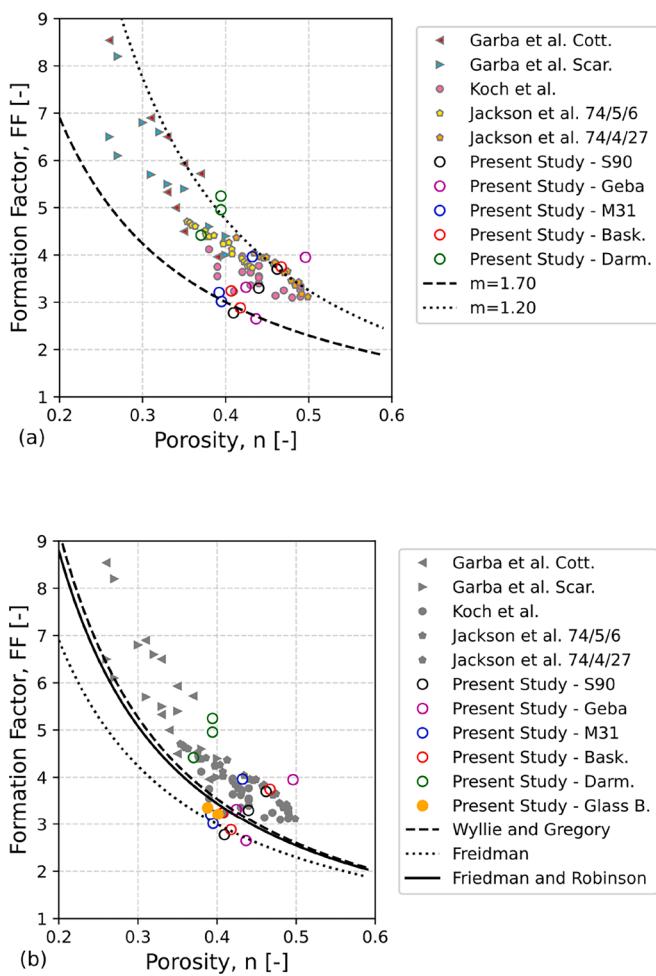


Fig. 15. Height versus porosity profiles for different sands.

conclusions were drawn:

- Formation factor and porosity measurements conducted with CCM sensors have been compared against physical measurements of porosity via a series of density cup measurements and the results indicate a good fit. Beyond the comparisons done within the framework of the present study, it has been shown that the CCM measurements fit well with the available data in the literature and empirical relationships.
- CCM measurements are affected by the temperature changes and the correction for temperature fluctuations should be carried out during the measurement period. While the correction is needed to gather reliable data, the correction itself is straightforward and can be done with ease.

- CCM measurements are also influenced by the presence and addition of ions in the mixture whereby the increase of ionic concentrations leads to an increased electrical conductivity. Within the limits of the studied materials, while some sands such as Baskarp B15 and S90 sands and glass beads were found to be inert in terms of free ions added to the aqueous solution. While the use of other sands, namely, Geba, M31, and Darmstadt, has influenced the electrical conductivity measurements taken by CCM sensors. In the present study these changes are dealt with a baseline correction to compensate for the drift in the measured values. Overall, the use of the technique might be impacted in environments where ionic concentrations are expected to vary over time. It is advisable to track the electrical conductivity characteristics of the aqueous part of the mixture to have a continuous benchmark for corrections.



**Fig. 16.** Comparison of the formation factor (FF) versus porosity values for (a) natural sands and (b) glass beads.

4. The relationship between the porosity of the soil with the formation factor was investigated by way of comparing the experimental findings with the empirical relationships and the available data in the literature. It can be said that the values generated by CCM method falls in close agreement with both experimental data stemming from a range of tests and empirical formulations.
5. Overall, the electrical conductivity technique for geotechnical laboratory use is a promising alternative to determine the porosity of the granular materials. Since the technique does not rely on wave propagation characteristics, it is less likely to be affected by a 'noisy' background and the relative ease of use and simplistic electronics required might make this method desirable for geotechnical laboratory applications. Furthermore, the non-destructive nature of the method also complements its use in geotechnical applications.

#### CRediT authorship contribution statement

**Cihan Cengiz:** Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Maria Konstantinou:** Writing – review & editing, Supervision, Funding acquisition. **Marien Harkes:** Writing – review & editing, Resources, Methodology. **Danko Boonstra:** Software, Resources. **Alba Rodríguez Piedrabuena:** Investigation. **Arno Talmon:** Conceptualization.

#### Declaration of competing interest

The authors declare that they have no known competing financial

interests or personal relationships that could have appeared to influence the work reported in this paper.

#### Data availability

Data will be made available on request.

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