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# Identification of soil porosity using geophysical and geotechnical observation for agricultural application

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**Abstract** Results indicated that sand dominated the soil structure of the soil, and the degree of sand domination varied among locations. Both apparent soil electrical resistivity and soil porosity declined with the increasing soil depth. A positive linear relationship between those soil characteristics was found for all locations with the largest increment in predicted soil porosity along with the increase in apparent soil electrical resistivity. The findings of this study imply that soil porosity can be predicted by measuring its apparent electrical resistivity using a geo-electrical method and, therefore, they can be used for managing irrigation during crop production.

**Keywords:** Apparent resistivity, Georesistivimeter, Porosity, Sandy soil, Schlumberger

## Introduction

Soil plays an important role in agroecosystems, providing essential nutrients, water, oxygen, root support, and all the elements that promote crop growth and development. It would mean that the crop production's success to a large extent depends on the quality of the soil where the crop is grown. In good quality soil, nutrients are available at rates high enough to supply plant needs, but low enough to leach excess nutrients into groundwater, balanced water holding capacity, aeration, and drainage is maintained (Usharani *et al.*, 2019), the available pores space allows the plant root to penetrate at depth (Strock *et al.*, 2022), and a diverse community of beneficial microorganisms is supported (Parr *et al.*, 1994).

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Recognizing the quality of soil is critical when considering soil management for crop production, and identification of the main issues affecting soil quality is the first step in managing it to become more sustainable. Johannes *et al.* (2019) noted that most soil functions are strongly dependent on soil structure quality. Soil structure is important for water and nutrient flow, aeration of plants and microorganisms, and resistance to soil erosion and compaction (Rathoure, 2019). A well-structured soil has enough pore space to allow it to drain well while still having good water retention and nutrient capacity (Rabot *et al.*, 2018). For this reason, soil porosity is widely regarded as the best indicator of soil structural quality, and quantification of pore space in terms of shape, size, continuity, orientation, and arrangement of pores in soils allows us to define the complexity of soil structure (Pagliai and Vignozzi, 2002).

The major drawbacks of direct measurement of soil porosity are that it is tedious, time-consuming, expensive, and destructive (Eluozo and Oba (2018). Alternatively, the quantitative relationship between soil porosity and soil electrical resistivity can be employed as a convenient and non-destructive method for determining soil porosity (Islam and Chik, 2013). Archie's law postulates that the soil electrical resistivity of fully water-saturated soil is inversely proportional to its porosity (Glover, 2016). Based on such a relationship, the geoelectrical resistivity approach is widely adopted in soil porosity exploration. Nevertheless, Friedman (2005) suggested that an empirical relationship needs to be established for each site between soil electrical resistivity and soil porosity as these relationships may be site-specific.

The advancement of geoelectrical resistivity imaging has been facilitating geophysical surveys for mapping and assessing the subsurface lithology along with its electrical resistivity and the soil quality, including soil porosity (Aizebeokhai and Oyeyemi, 2015; Anuar and Nordiana, 2018). Corwin and Lesch (2005) have shown that geoelectrical resistivity mapping can provide spatial information for soil quality assessment and the delineation of site-specific management. This study was performed to measure the soil electrical resistivity of the coastal area of Bengkulu City, Indonesia, to a depth of 7.5 m using geoelectrical resistivity imaging and to assess their porosity to a depth of 3 m along with their implication on the agricultural land management.

## Materials and methods

### *Study area*

This study was conducted in Bengkulu City, Indonesia, by collecting samples at three locations, representing all the city's tree geological units, Bintunan Formation ($Q_{Tb}$), Alluvium ($Q_a$), and Alluvium Terraces ($Q_{at}$) (Key *et al.*, 2016), as depicted in Figure 1. The surveyed sites are indicated by the black-yellow triangle and named P-1, P-2, and P-3, located in Bengkulu City's coastline area (5 m asl), plantation land (20 m asl), and woodland (40 m asl), and each was represented by paddy field, oil palm plantation, and forest areas, respectively.

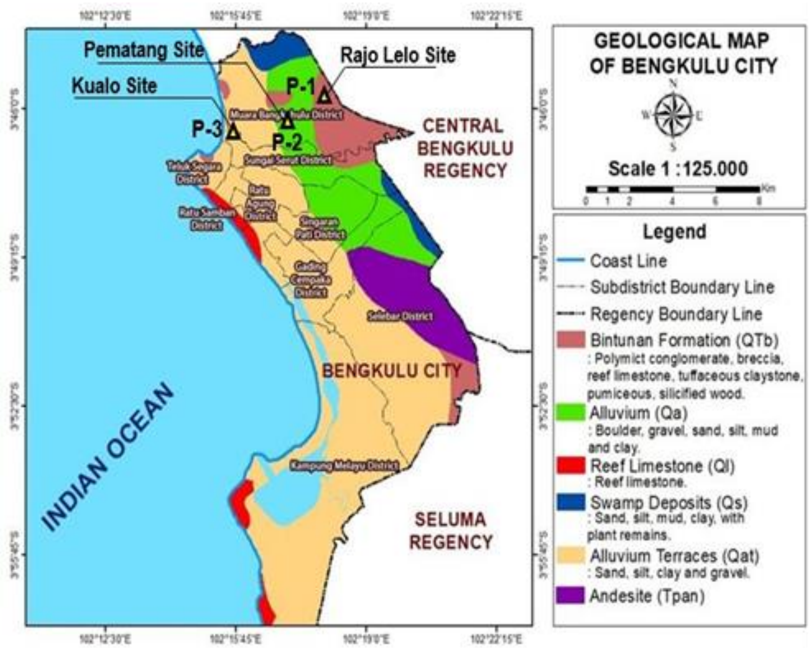



**Figure 1.** Bengkulu City's geological map (Mase, 2020) with the three surveyed sites (coastline area, plantation land, and woodland)

### *Data collection and processing*

A multi-channel georesistivimeter of MAE X612-EM with 48 electrodes arranged 10 m apart and 7.5 m deep in a 480 m long path according to the Schlumberger electrode configuration was used to acquire data for the strong current (I) and the potential difference ($v$) of between the electrodes in each area (Figure 2).

The acquired data were, then, used to measure the apparent resistivity using the following equation (Loke *et al.*, 2020).

$$\rho_a = k\frac{\Delta v}{I}$$

where $\rho_a$ is the apparent resistivity (Ohm.m), $k$ is the geometric factor, $\Delta v$ is the potential difference (volt), and $I$ is the applied current (Ampere). The resulting ρa data were used as input in the process of inversion using RES2DINV software for interpolating and interpreting the field data of electrical geophysical prospecting (2D sounding) in the form of a 2D electrical resistivity distribution profile.

Soil physical properties for each interval of 0.5 m to a depth of 3 m were determined at the Civil Engineering Department Geotechnical Laboratory, University of Bengkulu based on soil samples taken by hand auger from each site. The data were collected for moisture content (*w*), bulk density (*γ*), specific gravity (Gs), porosity (*n*), and void ratio (e).

Both soil porosity and soil electrical resistivity data were subjected to regression analysis to elucidate the relationship between the two measurements. The data analysis was performed using IBM SPSS Statistics version 20.

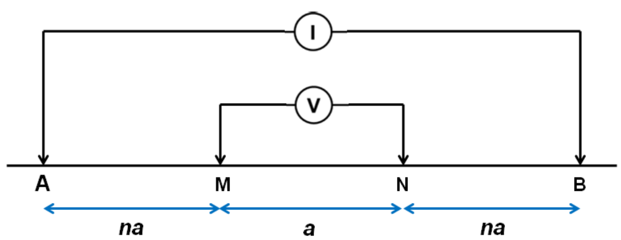



**Figure 2**. Schlumberger electrode configuration. A and B, are current electrodes, while M and N are potential electrodes

## Results

### *Soil physical properties*

Result showed a summary of the resulting soil physical properties for each site to indicate that soils in the study area are generally categorized as poorly graded sand (SP), based on the Unified Soil Classification System (USCS) as seen in Table 1. A closer inspection reveals that the porosity and void ratios varied with the soil depth and generally tended to be larger at a shallower layer. However as laid in a humid tropics area, Bengkulu City receives high precipitation throughout the year and it is not surprising when the moisture content tended to be relatively higher at shallower depths, indicating the soil surface was relatively wetter than it was at the greater depths. Similarly, The existence of aquifers found in each site suggests groundwater migration to depth is impeded by the indurated sand layer.

**Table 1.** A summary of the study area's soil physical properties

| Locations | Latitude and Longitude | Geotechnical Parameters | Symbol/Ref | Depth (m) | | | | | | Unit |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | 0.50 | 1.00 | 1.50 | 2.00 | 2.50 | 3.00 | |
| P-1 | 3.73695 °S and 101.31726 °E | Specific Gravity | $G_s$ | 2.47 | 2.31 | 2.51 | 2.08 | 2.40 | 2.55 | - |
| | | Moisture Content | $w$ | 85.66 | 97.73 | 83.50 | 72.80 | 73.46 | 45.30 | % |
| | | Void Ratio | $e$ | 2.57 | 2.25 | 2.03 | 1.86 | 1.44 | 1.31 | - |
| | | Porosity | $n$ | 0.72 | 0.69 | 0.67 | 0.65 | 0.59 | 0.57 | - |
| | | Bulk Density | $g_b$ | 1.28 | 1.40 | 1.52 | 1.26 | 1.71 | 1.61 | $g/cm^3$ |
| | | Dry Density | $g_d$ | 0.69 | 0.71 | 0.83 | 0.73 | 0.99 | 1.10 | $g/cm^3$ |
| | | Soil Type | USCS | SP | SP | SP | SP | SP | SP | - |
| P-2 | 3.75576 °S and 102.28872 °E | Specific Gravity | $G_s$ | 2.31 | 2.42 | 2.58 | 2.68 | 2.66 | 2.59 | - |
| | | Moisture Content | $w$ | 44.94 | 47.28 | 49.09 | 34.02 | 37.43 | 35.43 | % |
| | | Void Ratio | $e$ | 1.38 | 1.08 | 1.08 | 1.04 | 0.92 | 0.89 | - |
| | | Porosity | $n$ | 0.58 | 0.52 | 0.52 | 0.51 | 0.48 | 0.47 | - |
| | | Bulk Density | $g_b$ | 1.41 | 1.71 | 1.84 | 1.76 | 1.90 | 1.86 | $g/cm^3$ |
| | | Dry Density | $g_d$ | 0.97 | 1.16 | 1.24 | 1.31 | 1.38 | 1.37 | $g/cm^3$ |
| | | Soil Type | USCS | SP | SP | SP | SP | SP | MH | - |
| P-3 | 3.77999 °S and 102.25937 °E | Specific Gravity | $G_s$ | 2.99 | 2.95 | 2.81 | 2.78 | 2.72 | 2.73 | - |
| | | Moisture Content | $w$ | 35.62 | 33.84 | 31.54 | 28.79 | 27.13 | 26.14 | % |
| | | Void Ratio | $e$ | 0.96 | 0.82 | 0.67 | 0.52 | 0.32 | 0.27 | - |
| | | Porosity | $n$ | 0.49 | 0.45 | 0.40 | 0.34 | 0.24 | 0.21 | - |
| | | Bulk Density | $g_b$ | 2.07 | 2.17 | 2.22 | 2.36 | 2.63 | 2.72 | $g/cm^3$ |
| | | Dry Density | $g_d$ | 1.53 | 1.62 | 1.69 | 1.83 | 2.07 | 2.16 | $g/cm^3$ |
| | | Soil Type | USCS | SP | SP | SP | SP | SP | SP | - |

*Soil electrical resistivity*

The 2D electrical resistivity distribution profile to a depth of 7.5 m at each site was shown in] Figure 2. For the coastline area, sand and boulders dominated the soil to a depth of 2.5 m with an average electrical resistivity of more than 88.3 Ohm.m (Figure 3a). However, as the soil depth increased, the amount of sand and boulders declined, and, thus, the electrical resistivity was weakened accordingly. For plantation land, sand was the predominant soil material down to depths of up to 6.5 m with an electrical resistivity of over 240 Ohms.m (Figure 3b). The domination of sand and boulders with high electrical resistivity (> 996 Ohm.m) was also observed in woodland, but it occurred only to the depth of 2.5 m and was declined as the soil material changed in the deeper layers (Figure 3c).

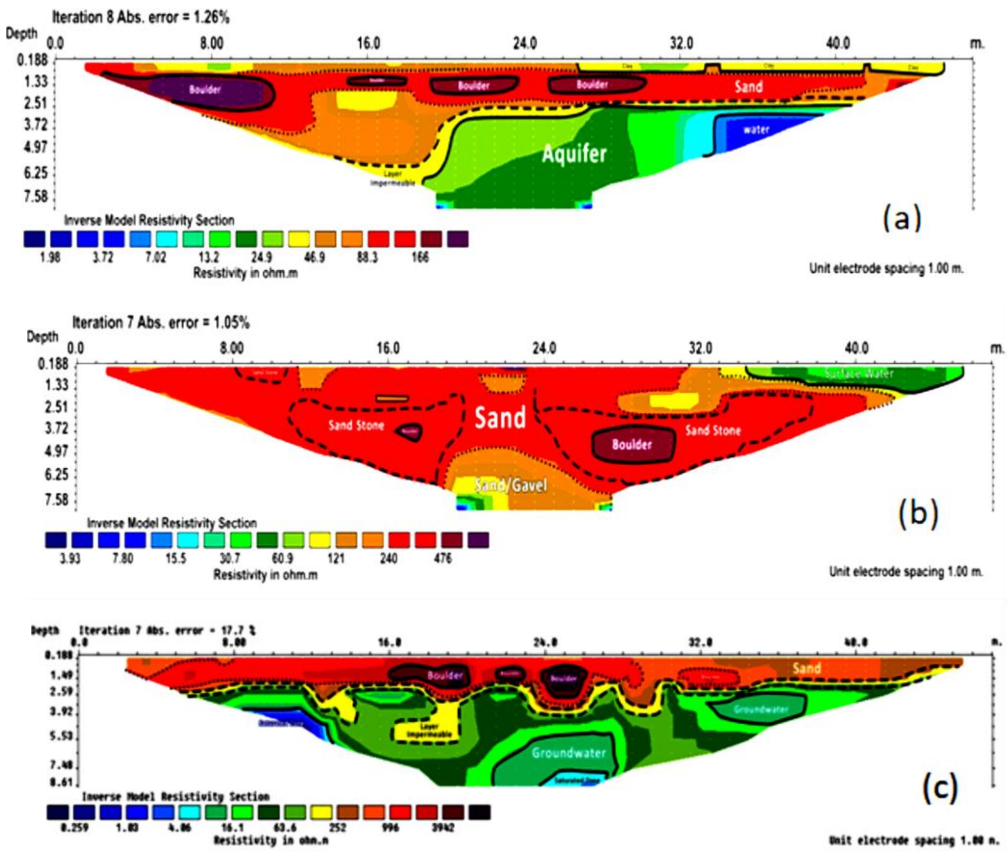
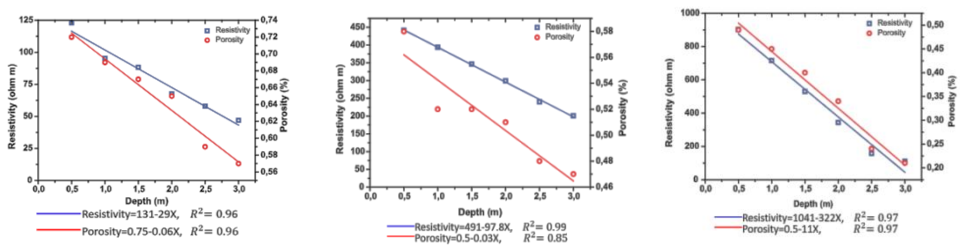



**Figure 3**. Resistivity values of soil layers at various depths up to 7.5 meters, at (**a)** coastline area, (**b**) plantation land, and (**c**) woodland

The pattern of changes in porosity and electrical resistivity for the increment of soil depth of 0.5 m up to 5 m in each site are depicted in Figure 4. Both porosity and electrical resistivity decreased linearly as the soil got deeper. However, the rate of changes was found to be varied among sites. For coastal areas, the decreases in porosity and electrical resistivity were recorded as much as 0.06% and 29 Ohm.m, respectively, for each 0.5 m deeper soil. Sharper decreases in both measurements were found on plantation land with the reduction of porosity and electrical resistivity as much as 0,03% and 97,8 Ohm.m, respectively. Moreover, the highest reductions along with the increasing soil depth were observed in woodland with porosity and electrical resistivity as much as 11% and 323 Ohm.m.

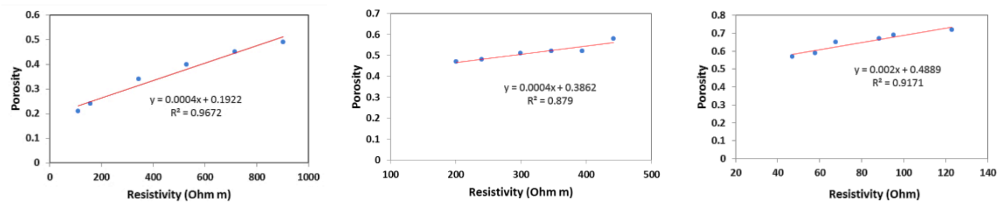



(a) (b) (c)

**Figure 4.** Porosity and resistivity corresponding to depth as observed at (**a)** coastline area, (**b**) plantation land, and (**c**) woodland

***Soil electrical resistivity and porosity relationship***

The regression analysis resulted in a linear relationship between apparent soil electrical resistivity and laboratory soil porosity for all surveyed sites with a coefficient of determination > 90%. The patterns of relationship between the two measurements in the soil layer to a depth of 3 m are shown in Figure 5. Referring to obtained relationship, it can be deduced that soil porosity increases with increasing soil electrical resistivity. However, the rate of increment varied among the sites. In both coastal areas and plantation areas, an increase of about 4% in soil porosity can be expected with an increase in the apparent electrical resistivity of the soil by 100 Ohm.m. However, on timber land, a sharper increase in soil porosity was seen in line with an increase in apparent soil electrical resistivity, namely a 2% increase in soil porosity with an increase in apparent soil electrical resistivity of 10 Ohm.m.




(a) (b) (c)

**Figure 5.** Relationship between porosity and resistivity observed at (**a**) coastline area, (**b**) plantation land, and (**c**) woodland

## Discussion

The current study indicates that the three surveyed sites exhibit sandy soils with significant spatial variations. These results are in accordance with those of previous studies, indicating that Bengkulu City soil is dominated by sandy soils (Mase, 2020; Mase and Anggraini, 2021). Soils with sandy textures are characterized by large pore spaces (macro pores) and high permeability, which result in high infiltration rates and good drainage. Such features, accompanied by high rainfall, can serve as a good medium for plants to develop deeper and stronger rooting systems.

The georesistivimeter employed in this study has helped to generate multi-depth electrical resistivity maps and provide information on the variation of soil structure in the study areas, including aquifers that potentially serve as a water source for irrigation when the rainfall is not sufficient to supply the plant water need (Kwoyiga and Stefan, 2018; Quintana-Ashwell and Gholson, 2022). In fact, a soil electrical resistivity map with limited depth but thorough coverage is an emerging tool for profiling variations in physicochemical soil characteristics for precision agriculture (e.g. Unal *et al.*, 2020; Roy and George, 2020).

The estimate of apparent soil electrical resistivity and the laboratory soil porosity measurement to the depth of 3 m indicated that both parameters declined with increasing soil depth. The decrease in apparent electrical can be attributed to an increase in water content because it coincides with the groundwater table (Dahlin *et al.*, 2014). The decrease in porosity, on the other hand, is due to the physical forces of compaction (Fu *et al.*, 2019) and the decreased organic matter content (in the deeper soil layers (Franzluebbers, 2011).

A positive linear relationship between apparent soil electrical resistivity and laboratory soil porosity in the three surveyed sites is in line with those reported by Hakamada *et al.* (2007). At a glance, these findings are contradictory with Archie's law where soil electrical resistivity is inversely related to soil porosity. However, it should be noted that the porosity was measured in the laboratory on unsaturated soil samples and, consequently, Archie's law equation is inversed to indicate that the increase in porosity will lead to an increase in the electrical resistivity (Reynolds, 2011). From a practical standpoint, these results demonstrate that soil porosity can be predicted by measuring its resistivity and can be used to assist farmers in determining where and when irrigation is required or where it may be postponed, lowering costs and raising production.

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