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Application of VLF-EM Method for Archaeological Mapping on an Ancient Graveyard in Banda Aceh

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Abstract. Gampong Pande is an ancient village from the first millennium, the area is known as zero km of Banda Aceh Municipality today. Many cultural heritages are found around the area including a complex of ancient graveyards known as diwai by Acehnese. Physically the structure has been destroyed and buried by aging and natural hazards processes, archaeological investigation is needed for conservation. Before archaeological excavation, a geophysical survey of the very low frequency electromagnetic (VLF-EM) method has been applied to image subsurface structures of the ancient graveyard. The VLF-EM data were measured using the GEM-systems console, namely, GSM-19 T. Data measurement was carried out on 20 profiles with a 1 m distance between stations. The length of each profile is 45 meters so that the measurement covered the graveyard area. Magnetic fields in terms of in-phase and out-phase data were measured with frequencies 19.8 kHz and 21.4 kHz propagated by VLF radio transmitters. Based on the data, the area with the graveyard structure is shown by lower in-phase and out-phase values than the area outside the structure. The first derivative of VLF-EM data (i.e., Fraser filter) analysis indicated some elongated buried structures in the subsurface. The structures were further clarified by 2D modeling of the Karous Hjelt filter as the wall of the graveyard was 1 meter to 4 meters.

INTRODUCTION

Banda Aceh is one of the oldest cities in South East Asia which was founded in 1205 [1]. Since the 14th century, Banda Aceh has been developing and is still the capital of Aceh Province. In the early days of the establishment of the Kingdom of Aceh Darussalam, the center of the kingdom was in the coastal area which is still known as Gampong Jawa, Gampong Pande, Merduati, Kandang, and Kedah [2]. In this area, many remains of old building foundations and graveyards were found, including several tombs of sultans, clerics, and royal families. However, this area has now been damaged especially after the earthquake and tsunami in 2004. One of the famous sites that have been damaged is the *diwai* structure located in Gampong Pande, Kutaraja District, Banda Aceh Municipality. The word "*diwai*" itself is an absorption term from Persian. *Diwai* in ancient Acehnese society was known as a cemetery complex surrounded by buildings in the form of rectangular walls with an east-west orientation. Therefore, in terms of geometry and building materials, the distinctive *diwai* shape is very promising to be mapped using a geophysical survey, even though the building has been buried beneath the surface.

Several geophysical methods are often used for mapping archaeological sites which are generally buried at relatively shallow depths, including seismic, geoelectric [3], magnetic [4], [5], gravity [6], [7], Ground Penetrating Radar (GPR) [3] and Very Low Frequency Electromagnetic (VLF-EM) methods [8]. The seismic method is based on the propagation of seismic waves below the surface. The gravity and magnetic methods are carried out by utilizing the earth's gravitational and magnetic potential fields. While the GPR and VLF-EM methods are based on the concept of propagation of electromagnetic waves on the ground. The VLF-EM

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method works by utilizing electromagnetic waves emitted by radio transmitters with a frequency of around 15-30 kHz [9]. These radio communication transmitter sources are available in various parts of the world, therefore the VLF-EM method is often used for geophysical investigation. For the Aceh region, some VLF frequencies can also be captured well. Broadly, in Aceh, this method has been applied for various purposes, including fault investigation [10], paleochannel delineation [11], and archaeological studies [12]. From the successes of these methods, this paper also presents the advantages of the VLF-EM method for investigating the *diwai* archaeological site in Gampong Pande, Banda Aceh.

The success of the exploration of archaeological sites buried beneath the surface using geophysical methods is highly dependent on knowledge of the physical properties of the target being sought. In the VLF-EM method, the magnetic and electrical properties of the material are the main properties that can indicate the presence of the target being sought. Most of the archaeological sites sought are buried less than 10 meters below the surface. The covering material above the target is generally alluvium, colluviums, peat, sand, earth, or silt. This condition presents its challenges in exploration using the VLF-EM concept.

HISTORICAL AND GEOLOGICAL STUDY

Geographically, Gampong Pande is located in the coastal area of Banda Aceh with an area of 242.20 ha and an average height of 3 meters above mean sea level. Therefore, Gampong Pande area is very vulnerable to hydrogeological hazards such as tidal flooding, tides, and tsunamis. Gampong Pande is one of the ancient toponyms in Banda Aceh City. The existence of this village has existed since the beginning Banda Aceh was founded. Therefore, in this place, there are still many traces of settlements in the past. Gampong Pande is adjacent to the Krueng Aceh estuary on the east and the Malacca Strait on the north side, so its location was very strategic at that time (Figure 1). Until the 19th century AD, Gampong Pande area was under the direct supervision and government of the Aceh Sultanate, especially during the reign of Sultan Mansyur Syah or Tuanku Ibrahim in the period 1846-1870 [13]

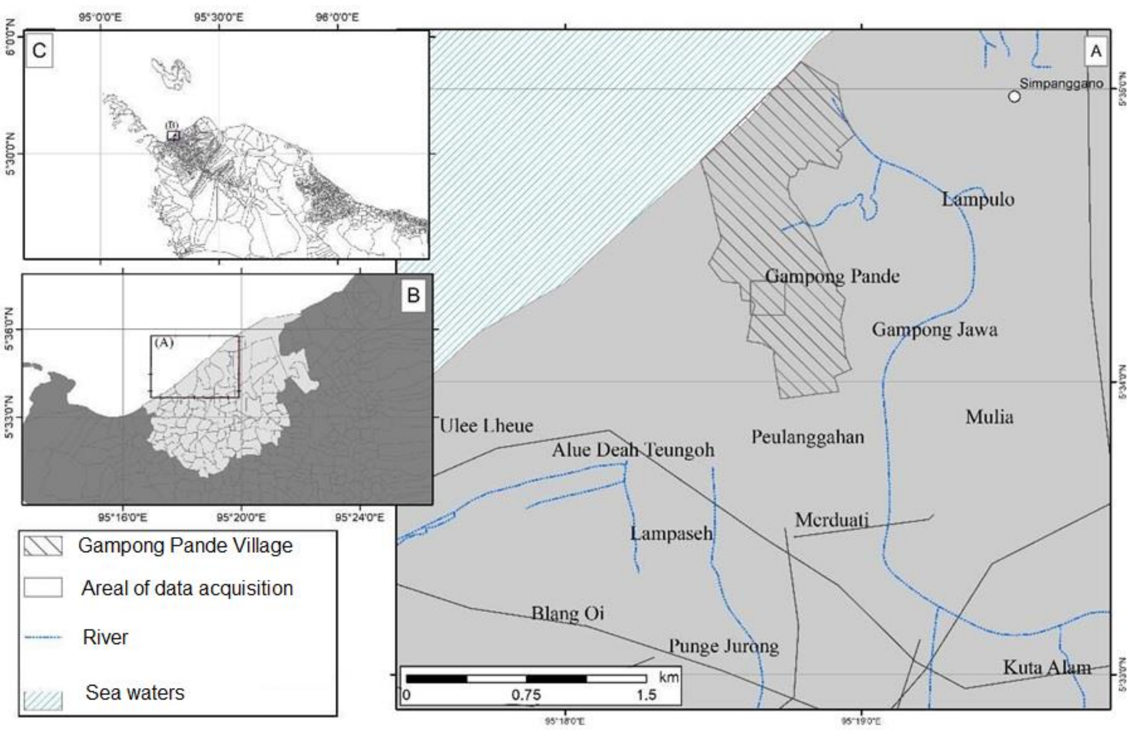

FIGURE 1. (A) Map of Banda Aceh, Gampong Pande Village and its surroundings (modified from Bennett et al., 1981). (B) and (C) are the location of Banda Aceh Municipality on the tip of Sumatra Island in the Northwest.

Besides Gampong Pande, the special areas also include Merduati, Keudah, Gampong Jawa, Peulanggahan, and Kandang. Regarding van Langen [13], in Gampong Pande there was a workshop that produces various war equipment.

As an important area at that time, until now in the area still can be found fragments of ancient ceramics, building foundations, as well as the Putroe Ijo graveyard, the tombs of the kings of Gampong Pande, and the tomb of Teungku di Kandang. The three tombs are located only 10 to 20 meters apart and are under the supervision of the Archaeological Heritage Preservation Center of Banda Aceh. It is estimated that there are hundreds of ancient tombstones with unique and beautiful carvings there. Meanwhile, the *diwai* structure which is the object of this research is still in the initial investigation stage to be proposed as a cultural heritage site.

BASIC THEORY OF THE VLF-EM METHOD

The very low frequency electromagnetic (VLF-EM) method is one of the electromagnetic methods to delineate near-surface conducting structures. The method is considered a passive method that utilizes radiation from ground-based military radio transmitters operating in the VLF band (15–30 kHz) as the primary EM field. The VLF radio signal is recorded by a receiver antenna in terms of the total magnetic field (H_R) from the primary field (H_P) that propagates through the air. The secondary magnetic field (Hs) is the magnetic field induced by the conductor beneath the surface. The magnitude of Hs and H_R is a variation of space, time, and frequency [14], [15]. The primary and secondary electromagnetic field measured at the receiver with frequency $f = (\omega/2\pi)$ will have a different phase (φ) as shown in Eq. 1;

$$H_R = \left|H_p\right|e^{iwt} + |H_s|e^{i(wt-\varphi)} \tag{1}$$

The components of the magnetic field can be presented in form of vectors as shown in Eq. 2

$$\begin{pmatrix} 0 \\ H_{RY} \\ H_{RZ} \end{pmatrix} = \begin{pmatrix} 0 \\ H_{PY} \\ 0 \end{pmatrix} + \begin{pmatrix} 0 \\ H_{SY} \\ H_{SZ} \end{pmatrix} \tag{2}$$

In practice, the parameters measured on the surface are in terms of in-phase and quadrature, which is the ratio of $\boldsymbol{H_{RZ}/H_{RY}}$ and reflect the variation of resistivity beneath it. Most VLF-EM data acquisition is based on a 2D conductivity structure assumption with a presumed geological strike in the *x*-axis as well as the direction of the VLF transmitter. By this assumption, the data collection is measured along a profile in the *y*-axis. The VLF-EM instrument measures the vertical (Hz) and horizontal (Hy) components of the magnetic field. The scalar tipper transfer B can be calculated by using a simple formulation of $Hz = B\ Hy$. The difference in polarity of the two components may provide information on the conductive and resistive medium beneath the surface. In a resistive medium, the horizontal and vertical components have a similar polarity, while in a conductive medium, they will have different phases [16]. During the data collection, the magnetic field will be influenced in the in-phase mode that causes attenuation of the electromagnetic wave. The ability of the electromagnetic wave to penetrate to deeper part can be determined by the skin depth formula as shown below [17]

$$\delta = 503.3\sqrt{\frac{\rho}{f}} \tag{3}$$

Standard filtering of Fraser and Karous Hjelt filter was also applied to the data for qualitative analysis of VLF-EM data. The Fraser filter is the first derivative of the data [18]. It replaces the point of in-phase and out-of-phase data into a maximum response with a shift angle of 90 degrees. By this method, nodes between both data show the target bodies as a maximum response. This filter can remove the direct current effect, which can decrease noises between stations resulting from the VLF component of sharp irregular responses. The Fraser filter gets rid of the noises from long waves to enhance the resolution of local anomalies. In-phase or out-of-phase data were used from four stations by subtracting the data from the 3rd and 4th to the 1st and 2nd stations as represented by *H3* and *H4* to *H1* and *H2*, respectively. The distance between data refers to the distance between measurement stations in the field, *e.g*, a 1-meter distance has been used in this study.

$$F_{2,3} = (H3 + H4) - (H1 + H2) \tag{4}$$

Where the result is gained between *H2* and *H3* from in-phase or out-of-phase stations. On the other hand, Geonic Inc [19] announced a relative conductivity filter that can be used to show subsurface anomalies based on conductivity parameters. The filter operated by converting magnetic data from the in-phase components into relative conductivity in milli-Siemens (mS/m). The relative conductivity data is in agreement with the electrical conductivity EM – 34 and EM – 31 methods. Karous-Hjelt is a VLF filter is constructed based on the Biot-Savart law. The filter will be able to explain the vertical component of magnetic fields related to electric currents. The Karous-Hjelt filter produces a depth profile of the electric density in each station by using the following equation:

$$\left(\frac{\Delta z}{2\pi}\right) I_a \left(\frac{\Delta x}{2}\right) = -\ 0.205\ H_{-2} + 0.323\mathrm{H}_{-1} - 1.446H_0 + 1446H_1 - 0.323H_2 + 0.205\ H_3\ I_a(x/2) \qquad (5)$$

Parameters Δz is the presumed thickness for the cross-sectional area of charge density and Δx is the spacing between stations that represents depth in a layer. Values of *H2* to *H3* are the vertical magnetic field (*Hz*/*Hy*) in the six measurement data. The electric current depth is caused by conductive geological structures such as faults, cracks, or fracture zones. The qualitative analysis of VLF-EM data was carried out using the Karous-Hjelt filter proposed by Pirttijärvi, while the PrepVLF was used for relative conductivity developed by Monteiro Santos [20].

METHODOLOGY

Measurement of VLF-EM data was carried out at the *diwai* site of Gampong Pande Village, Kutaraja District, Banda Aceh. The geometry of the measurement stations can be seen in Figure (2). Data acquisition is made in the form of profiles with a total of 20 parallel profiles so that it covers the entire area of *diwai*. In each profile, there are 45 stations with a distance of 1 meter between stations. Data acquisition was performed using GEM-systems Console equipment, GSM-19 T. The measured data are in-phase and out-phase data. The data is measured using tilt angle mode. Tilt mode is the ratio of the intensity of the vertical magnetic field and the horizontal magnetic field. Data were measured at a frequency of 19.8 kHz from Australia and 21.4 kHz transmitted from Hawaii. These two signals were chosen because they have good signal quality when used at the research site. The in-phase and out-of-phase data obtained from the measurement were processed by several corrections so that they could be interpreted. Only data with a good signal-to-noise ratio were collected during the measurement. The processing applied to the data includes moving average, Fraser, and Karous-Hjelt filters.

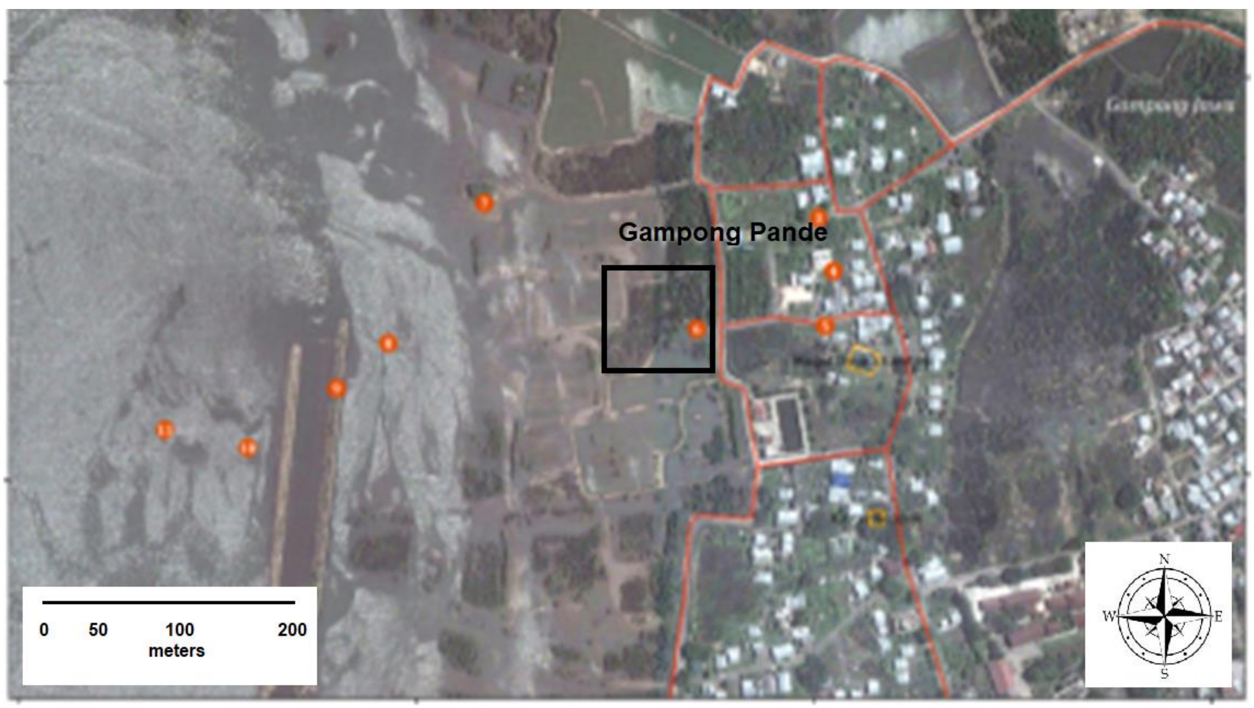

FIGURE 2. Aerial photo of the studied area. The *diwai* site is indicated by rectangular) surrounded by sea waters, mangrove forests, and fishponds. The orange circles show the distribution of archaeological objects.

RESULT AND DISCUSSION

In tilt mode measurement data, the horizontal magnetic strength ratio is expressed in percentage units (%). The tilt value obtained from the VLF-EM measurement is related to the magnitude of the conductivity that affects the secondary field.

Therefore the data tilt can be interpreted as a manifestation of conductors [8]. Figure 4 shows the Fraser data at frequencies of 19.8 kHz and 21.4 kHz. For instance, Fraser values above 0 indicate the presence of a conductive zone, while resistive zones are below 0. Here the presence of resistive objects is indicated by the red color of Fraser values.

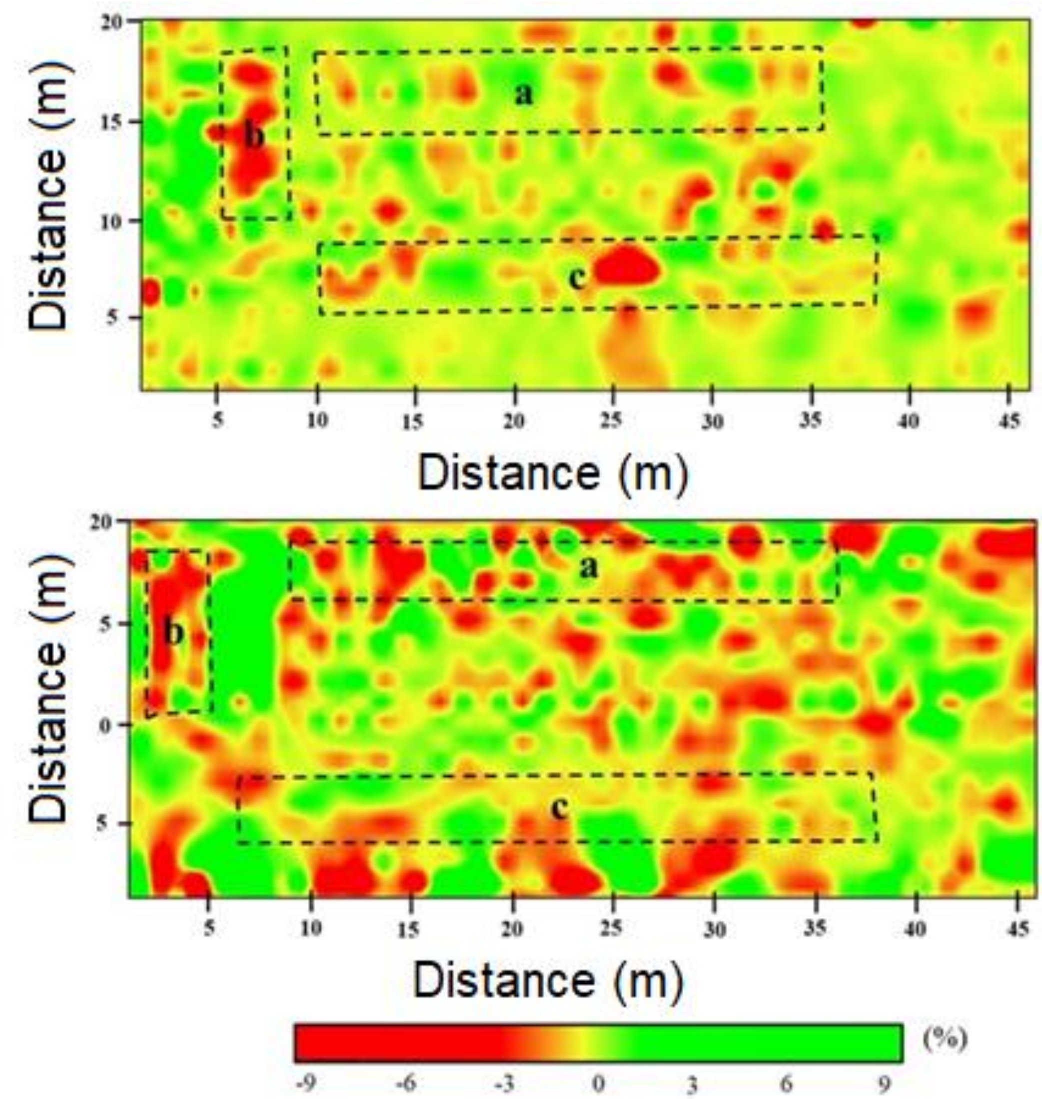

FIGURE 3. Fraser contour map measured at frequencies 19.8 kHz (top) and 21.4 kHz (bottom).

The archaeological targets sought in this study are tombstones made of sandstone and concrete structures of *diwai* composed of cemented limestone. Both materials are more resistive compared to the uppermost layer of sandy clay found at the surface. Thus, archaeological objects are characterized by a negative Fraser value. The dashed lines a, b, and c in Figure 3 correspond to the presence of archaeological targets. Fraser contour maps at both frequencies show almost the same pattern of negative Fraser values, although there is a slight shift in position. This can be caused by the difference in the azimuth position of the two transmitters to the measured profile. The remains of a *diwai*-like structure are to the east. While the remains of ancient tombs are in the west. Some of the former ancient tombs are separated from the *diwai* structures. From the two frequencies used, it can be seen that the Fraser data at a frequency of 21.4 kHz are more detailed both in terms of location and in terms of the quality of the resulting data. Therefore, only data at frequency 21.4 are presented in the following discussion. Figure 4 presents a Fraser data map at a frequency of 21.4 kHz which is overlaid with the outcrop of the *diwai* structure and several tombstones. All of these outcrops correspond to the position of negative Fraser values. This shows that the *diwai* structure composed of limestone and tombstones made of sandy clay is more resistive than the surrounding topsoil layer. Figure 4.a shows the presence of tombstones and Figure 4.b shows the outcrop of *diwai* structures that are still intact.

To obtain depth information on archaeological objects, the Karous-Hjelt filter was also calculated. A low value of charge density is a resistive region. In archaeological studies, resistive areas are thought to be buried anomalous objects [8]. Figure 6 shows the profile of the Karous-Hjelt filter value on one of the paths that intersect the measurement area. The value is plotted on a color scale that is easy to see so that the contrast between the conductivity and resistivity of an object is visible. The conductive zone in Figure 5 is indicated by the letters A and E with a charge density of 15 – 45 mA/cm^2 at a depth of 1-4 meters. The resistive zones are indicated by the letters B, C, and D which are assumed to be anomalies of the *diwai* structure. The results of the observers at the measurement site also showed that along this path debris from the remaining *diwai* structures was still found. The presence of the anomaly is estimated at a depth of 3 meters.

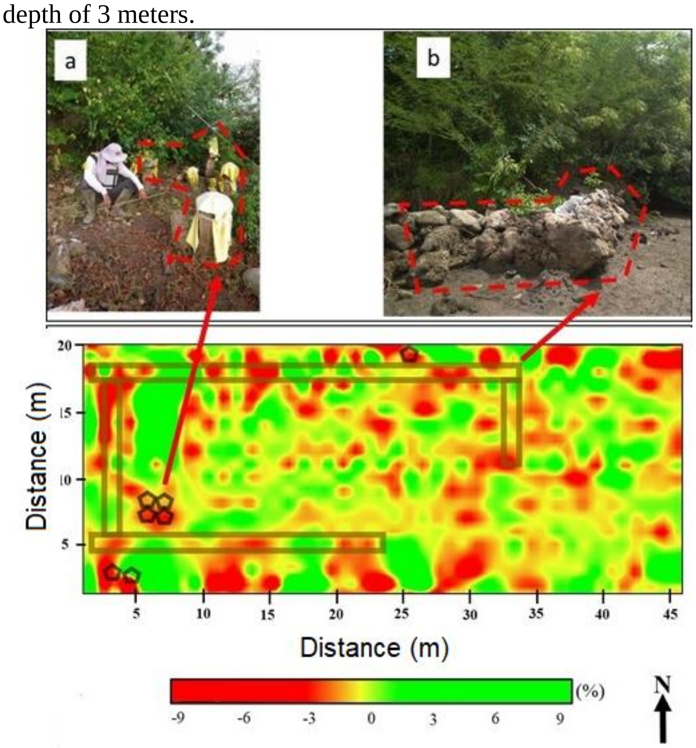

FIGURE 4. Overlaying the position of the tombstone outcrop and the intact *diwai* structure with the Fraser value map at a frequency of 21.4 kHz.

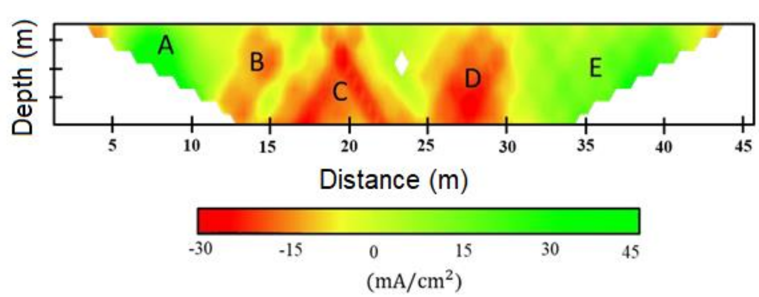

FIGURE 5. The current density in profile 17 with a frequency of 21.4 kHz

Karous-Hjelt filter calculations were also performed for six profiles, however, the figures are not shown here. The results show models of the profiles agree. In general, it can be said that the charge density value which is just above the *diwai* structure is resistive with a value of -30 to -15 (mA/cm^2). While the uppermost layer formed by sandy clay is characterized by positive charge density values between 0 to 45 (mA/cm^2).

CONCLUSION

Based on the results of this study, some conclusions can be drawn as follows. Measurement of VLF-EM data shows lower in-phase and out-of-phase data on archaeological objects compared to higher ambient conditions. Fraser's analysis shows the anomalous distribution of archaeological traces in the form of outcrops as well as a buried objects beneath the surface. The results of 2D modeling using the Karous Hjelt filter show that the *diwai* structure is found at a depth of 1 to 4 meters, with current strength values of -30 to -15 mA/cm^2.

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