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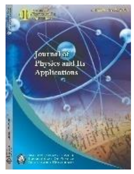

Study of Potential Land Subsidence in East Aceh Region Based on Sediment Characterization Using Logging Data

Tarmizi[1*], Layna Miska[1], Muhammad Syukri[2], Zahratul Maghfirah[1], Tika Hapsari[3], Dian Darisma[1], and Ikhlas[4]

[1]Department of Geophysical Engineering, Faculty of Engineering, Universitas Syiah Kuala, Aceh, Indonesia
[2]Department of Physics, Faculty of Mathematics and Natural Sciences, Universitas Syiah Kuala, Aceh, Indonesia
[3]Department of Geological Engineering, Faculty of Engineering, Universitas Syiah Kuala, Aceh, Indonesia
[4]Aceh Energy and Mineral Resources Service, Aceh, Indonesia

**Corresponding author: tarmizi_hasyem@usk.ac.id*

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Observations to determine subsidence potential were conducted in East Aceh, based on sediment characterization using logging data. The study encompassed 9 measurement sites representing 9 villages from 9 sub-districts. The data used obtained from the Aceh Energy and Mineral Resources Service (ESDM). This data is processed to obtain the resistivity value of the subsurface sediment layer. The measurement results were then depicted in 1D profile illustrating the cross-section of subsurface lithology for each measurement point. Subsequently, several measurement points were correlated to generate a 2D bottom image representing two regions, referred to as cross-section A-A' and cross-section B-B'. The correlation outcomes revealed that cross-sectional area A-A', spanning approximately ±50 km from east to west through Cot Geulumpang Village, Java Village, Kuala Lawah Village, Bukit Seroja Village, and Rantau Panjang Village, shows a shallow surface layer consisting mostly of sand and sandy clay soil. The sand layer in this area exhibited a medium to fine size with a configuration of round-shaped particles containing quartz and shell minerals, forming a soft sediment layer. The structure and type of sediment in this area indicate the potential for land subsidence.

1. Introduction

with the high level of exploitation of underground resources, land subsidence has become a hot issue. Land subsidence can occur suddenly or gradually due to the movement of materials on the earth's surface [1]. This phenomenon can cause losses in the form of infrastructure damage, flooding, and other social and economic impacts for the community [2]. Land subsidence can occur naturally or as a side effect of human activities. Factors causing land subsidence include excessive water exploitation, mining, building loads, tectonic activity, geological cycles, and sedimentation [3]. Land subsidence can occur when porous rocks lose cement such as clay that fills the pores or the groundwater level drops close to a pumping well due to excessive groundwater pumping [4]. Land subsidence can occur from several indications, such as wider expansion of (coastal) flooding areas, cracking of buildings and infrastructure, and increased seawater intrusion into the inland [5]. The common occurrence of pumping-induced ground subsidence is supported by various conditions such as arid climate, decrease in groundwater level due to long-term pumping, large thickness and variable distribution of compressible layer, variation of compression index value of granular material, and the presence of structural weak zones such as faults that allow stress accumulation [6]. Regarding land subsidence linked to ground deformation caused by pumping, an essential factor that requires attention is the modulus of incompressibility, known as bulk modulus (K), which signifies the material's resistance to volume changes due to pore pressure or fluid loss within the pores. The connection between this parameter and deformation is that a high modulus of incompressibility signifies greater soil compaction, with no deformation occurring [7]. Numerous researchers used a strategy for hydrogeological investigation by applying electromagnetic, resistivity, and other geophysical methods [8][9][10]. One way to determine the possibility of land subsidence in an area is by characterizing the sediments in the region. The research area is adjacent to the coast, which is quite vulnerable to land subsidence, because coastal areas are very vulnerable to environmental pressures, both from the land and from the sea [11]. Land subsidence has occurred in East Aceh district, more precisely the subsidence of infrastructure on the Peureulak-Lokop-Border of Gayo Lues road segment l on January 2022 [12].

Sedimentation is the process of settling suspended material due to gravity. Sedimentation can occur directly or indirectly causing the change of sediments into sedimentary rocks. Sedimentation activities can occur through physical, chemical and biological processes. Sediments come from fragments of rock fragments, minerals, and organic materials that settle in sedimentation basins which in a long time will experience rocking [13]. The deposition process is assisted by wind, water, gravity, and so on. The sedimentation process that occurs continuously forms layers on the earth's surface [14].

The process of transporting sediment-forming materials can occur in three ways, namely suspension, bed load, and saltation. Suspension occurs due to the flow of water and wind that transports sedimentary material with a very small size. Bed load occurs because the force acting exceeds the moment of inertia of the material, causing the flow or movement of the material. While saltation is the fall of material due to the force of gravity [15].

The final destination for the transportation of sedimentation material is called a basin. The basin is lower than the surrounding area and is the place where deposition or sedimentation occurs. The process of sedimentation that occurs continuously results in differences in the subsurface structure or crust of the Earth. Each region has a different subsurface structure or formation depending on the sedimentation process that takes place over millions of years. This sedimentation process determines the subsurface characteristics of an area. Determination of subsurface characteristics can be done using the Electrical Well Logging method. Both geophysical and geological methods that have been integrated by this researcher as a spatial analysis with an approach to sedimentation and groundwater studies i.e in Krueng Aceh was done by [16].

Electrical well logging is a geophysical method to determine subsurface structures by utilizing the physical properties of rocks. The physical properties referred to here are the conductivity and electrical potential of rocks. Each type of rock has a different type of resistance or resistivity that causes different electrical conductivity [17]. The resistivity value of a rock depends on the effective porosity, permeability, salinity, and hydrocarbons in the rock pores. The same type of rock does not necessarily have the same resistivity value but is in a certain range of values. The following is an example of material classification based on the range of resistivity values.

The electrical well logging method can provide an overview of the vertical subsurface structure so that characterization of each subsurface sediment layer can be done. Measurements are made by flowing electric current into the subsurface through 2 electrodes [18].

Table 1: Resistivity Value of Rocks and Minerals [19].

Material	Resistivity (Ωm)
Sandstone	500 – 10000
Sand	20 - 2000
Clay	1 – 1000
Ground water	0,5 - 300
Sea water	0,2
Dry gravel	600 - 10000
Alluvium	10 – 800
Gravel	100 - 600

According to [20][21], East Aceh area was formed by the quaternary and pre-quaternary rock, recognized as alluvium deposited along the coast of East Aceh which includes the area Peureulak, Idi Rayeuk, Idi, and parts of Simpang Ulim sediments. Westward from the coast, the study area is located in the Idi and Julu Rayeu formations. The alluvium deposited consists of gravels, sands, and clays. The Idi formation is distinguished by limestone and semi-consolidated sands, then the Julu Rayeu formation consists of rhytmic sandstones, lignitic clays, and mudstones.

2. Methods

The data acquisition process was carried out with 9 borehole sites in several sub-districts in East Aceh District as shown in Fig 1. Table 2 provides information on the borehole sites and the areas that were traversed.

Table 2: List of borehole points in the study area

Drill Point	District	Village	Depth Wells (m)
TB01	Peureulak	Cot Geulumpang	130
TB02	Idi	Jawa	124
TB03	Idi Rayeuk	Kuala Lawah	100
TB04	Julok	Bukit Seroja	102
TB05	Pantai Bidari	Rantau Panjang	123
TB06	Rantau Peureulak	Pulo Blang	108
TB07	Darul Ihsan	Pantaiyan Timur	111
TB08	Nurul Salam	Beurandang	121
TB09	Indra Makmur	Alue Hitam	83

The data used in this research is borehole data, where cutting of material fragments from the well wall eroded by the drill bit is carried out as supporting data in determining the type of rock. The data acquisition process was carried out by the Aceh Energy and Mineral Resources Service (ESDM). Drilling was carried out at a depth of 0 to 135 m, and resistivity measurements using the Naniura ND 112 P instrument. The data processing begins with inputting electrical well logging data in the form of resistivity logs, SP logs, and cutting data using Logplot 2007 software so that the results are obtained in the form of cross sections and lithology descriptions as well as resistivity curves and SP (Spontaneous Potential) curves.

Based on geologic map of this research area, those borehole wells include several formations such as unnamed superficial deposits (Qh), Idi Formation (Qpi), Julurayeu Formation (QTjr), Seureula Formation (Tps) and Keutapang Formation (Tuk) [20][21]. The ages of these formations and deposits ranges from Late Miocene to Holocene and there was a tectonic setting geological event at the time of the compression force associated with the Sumatra fault [22]. Deposits of Qh consists lithologies deposited in the coastal and fluviatile. The lithology of Idi formation consists of semi-consolidated gravels, sands, limestone and clays. In Julurayeu Formation consists of fluviatile tuffaceous sandstones, lignitic clays and mudstones. In Seureula Formation consists of sublitoral volcaniclastic sandstones and calcareous mudstones. Then, in Keutapang Formation consists of sublitoral and fluvio-deltaic volcaniclastic sandstones. The Keutapang formation is the orifin of deltaic deposition in this basin.

The principle of log SP is to measure the electrical potential between the depth in the drill hole and the ground voltage at the surface [23]. Numerous research applications on log SP have been applied to groundwater investigation [24][25][26][27]. Furthermore, logging and cutting data in the form of 1D rock layer cross sections are analyzed so that the charac-

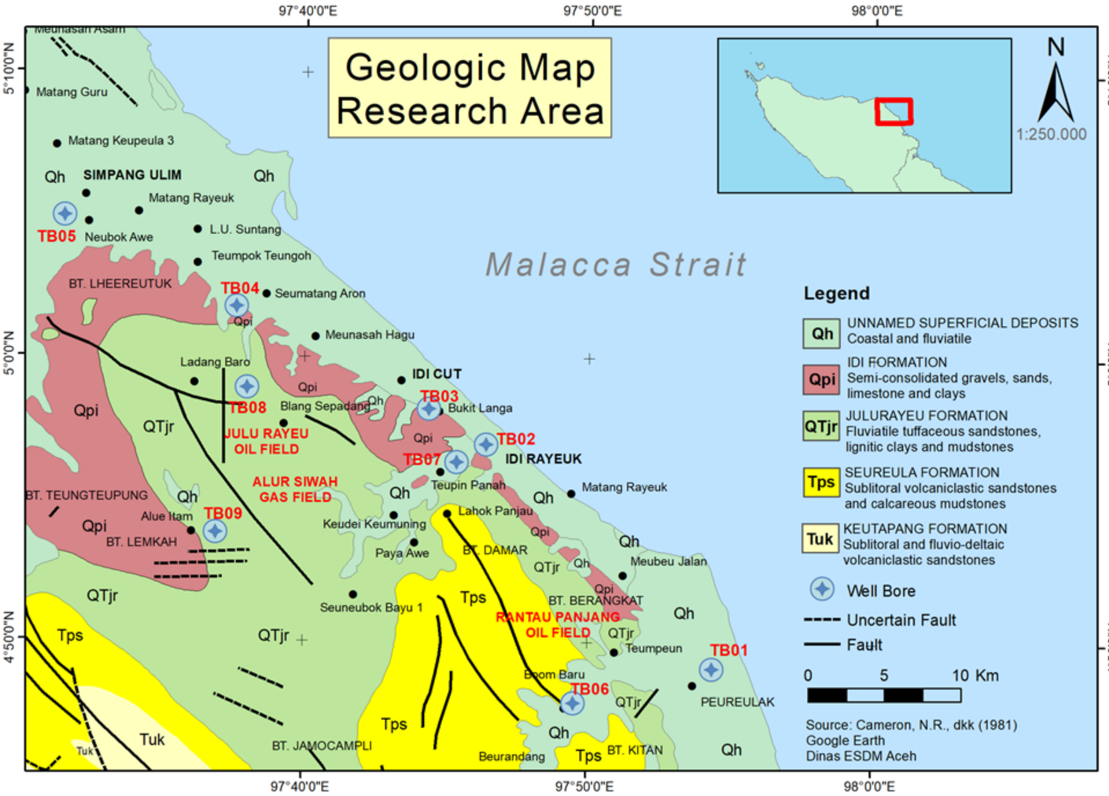


Fig 1: Borehole sites map.

ter of the sedimentary deposits of the study area can be determined. While the permeability of the layer is reviewed by analyzing the response of the resistivity log curve and SP log.

To obtain a comprehensive picture of the subsurface conditions of the study area, correlation between measurement points was carried out using Rockwork 16 software to obtain a 2D model of the lithology of the study area.

3. Results and discussions

Based on the results of data processing using Logplot 7 software, a lithology cross-section of 9 measurement sites is obtained as shown in the Fig 2.

Well TB-01 (a)

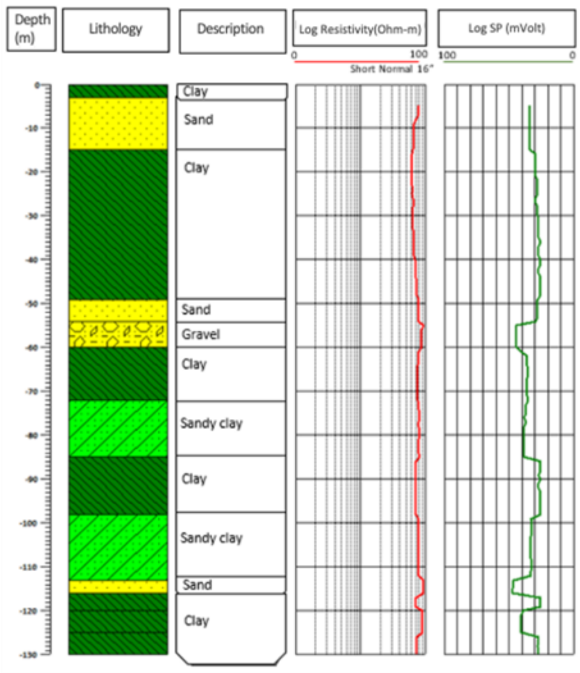
Resistivity logs and SP logs start to be recorded at a depth of 5 m, represented as a curve. From the analysis of the resistivity log and SP log, various lithologies including clay, sand, gravel, and sandy clay were identified. At a depth of 55 m, a notable leftward deflection up to 60 m suggests a lithological change within the permeable layer, specifically gravel, showing SP log values of -45 mV and 80 -92 Ωm. High resistivity values indicate rock formations significant porosity, like gravel, which is believed to contain fresh water.

Well TB-02 (b)

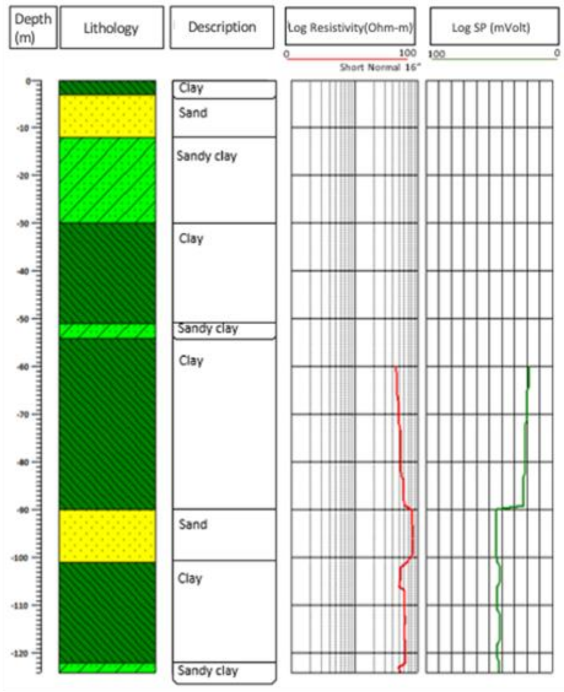
The log SP value began to be measured at a depth of 60 m, where it showed a sharp negative deflection (left direction) at a depth of 90 m with a value of -45 mV. The negative deflection of the SP log is also in line with the resistivity log, which shows a curve shift to the right at that depth with a value of 66 – 83 Ωm. The SP log can distinguish between permeable and non-permeable layers. In this well, there is a sharp shift curve, indicating a lithologic boundary that has a contrasting electric potential difference.

Well TB-03 (c)

The SP log and resistivity log readings begin at a depth of 40 m. In this well, a substantially high SP log value was noted, suggesting the presence of clean sand, which typically lacks clay minerals. At a depth of 60 m, there is a sharp shift curve which is interpreted as clay with SP log values ranging from -84 to -70 mV and resistivity log values approximately 70 Ωm. This shift curve reflects a transition in lithology marked by a contrast boundary, interpreted as clay due to the significant shift in the resistivity log, believed to indicate high water content or conductive dissolved ions within the clay structure. This explanation is further corroborated by the rightward shift of the SP log, signifying a rise in clay minerals.



(a)



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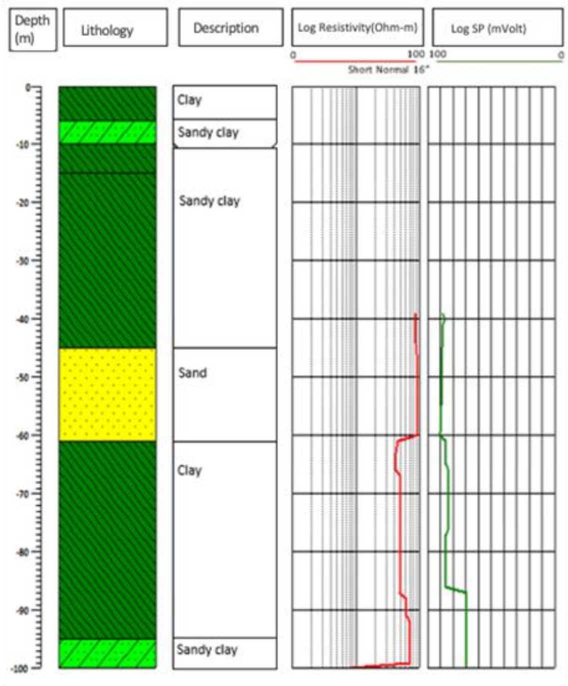
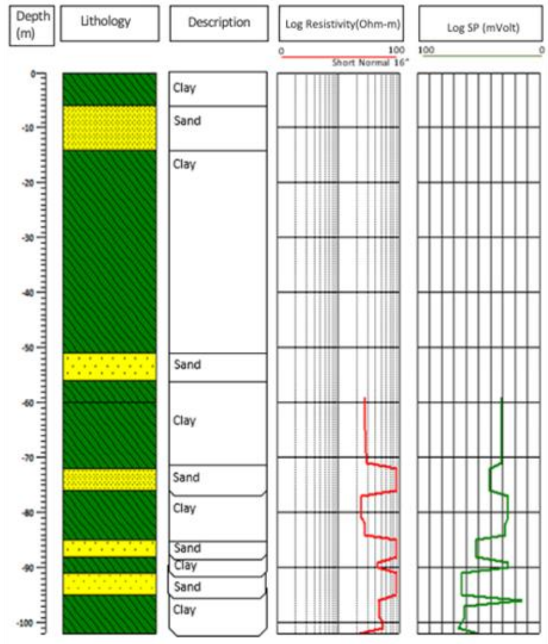


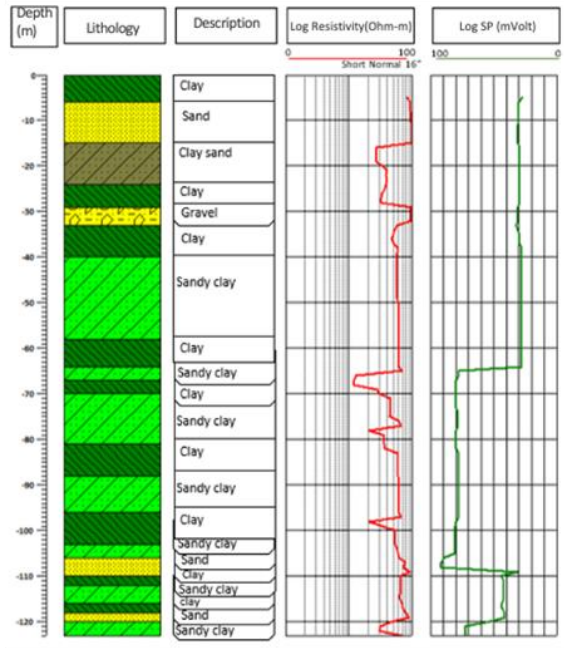
(c)

Well TB-04 (d)

The log reading started at a depth of 60 m, where in this well, the curve's direction and deflection changed. This well is interpreted to have a mixture of clay and sand. This is similarly evident in the curves where the deflection corresponds between both logs. The direction of bending between the both logs at a specific depth is reversed. Consequently, it can be inferred that when the SP log shows a positive deflection, the resistivity log reflects a low value. On the other hand, a negative deflection in the SP log leads to an increase in the resistivity value, suggesting the existence of fresh water. At a depth of 72 – 76 m, the sand layer is shown with a log SP value of -41 mV and a log resistivity of 90 Ωm. Resistivity logs help identify the fluid type and salinity concentration within the layer.



(d)



(e)

Fig 2. Lithologic cross-section of 9 measurement points

Well TB-05 (e)

This well effectively characterized different lithologies including clay, sand, clayey sand, gravel, and sandy clay. The response on the SP log resembles a dense layer that can be identified above the shala baseline (highest positive value), characterized by a sudden negative deflection beginning at a depth of 66 m, which can be interpreted as sand extending to a depth of 110 m. The resistivity log curve shows a fluctuating deflection of the thickness, allowing it to be understood as sand. The resistivity log curve shows a fluctuating deflection, indicating a variation in the layers thickness. The shale baseline in the SP log response is -30 mV, while the sand baseline ranges from -80 to -90 mV. The resistivity log between 66 - 68 m depth displays a low resistivity reading associated with sandy clay lithology, subsequently the curve shifts to the right, reflecting an increase in resistivity 80 to 85 Ωm, potentially signaling a reduction in electrically conductive fluid within the clay layer.

Well TB-06 (f)

In this well, the SP log response is fairly linear and did not deviate much, therefore it serves as a shale baseline. Essentially, the SP log bends when the salinity of the formation water exceeds that of the drilling mud. The Log SP value fluctuates between 38 – 45 mV, with a negative deflection at a depth of 24 m indicating it is sand possessing a maximum (high) resistivity value. Between 34 m and 84 m depths, it is understood to be clay where the resistivity value shifts further to the left or toward lower resistivity values. A low resistivity value suggests the presence of ions in conductive clay. The resistivity measurement in this layer varies between 17 and 89 Ωm.

Well TB-07 (g)

Resistivity logs and SP logs began to be read at a depth of 20 m. The SP log response in this well exhibits a diverse curve deflection. In this well, SP logs and resistivity logs indicate the presence of sand, clay, and sandy clay lithologies. At a depth of 24 m, the SP and resistivity log curves start to deviate, specifically a negative deflection in the SP log measuring -69 mV and a rightward deviation in the resistivity log ranging from 87 to 98 Ωm. In this well, the shale baseline at -23 mV while the sand baseline is at -69 mV. At depths ranging from 57 m to 69 m, the resistivity log shows a sudden deviation, believed to represent a conductive layer that suggests the existence of saline water. This layer is understood as clay.

Well TB-08 (h)

Both logs in this well started recording at a depth of 60 m. The SP and resistivity log measurements indicated no variation in deflection. The SP log readings range from -24 mV to -32 mV. This well is composed of clay, sand, and sandy clay materials. The resistivity log readings range from 15 to 97 Ωm. At a depth of 104 – 108 m, it is classified as sandy clay, indicated by low resistivity values that imply saline water is present in the pore spaces.

Well TB-09 (i)

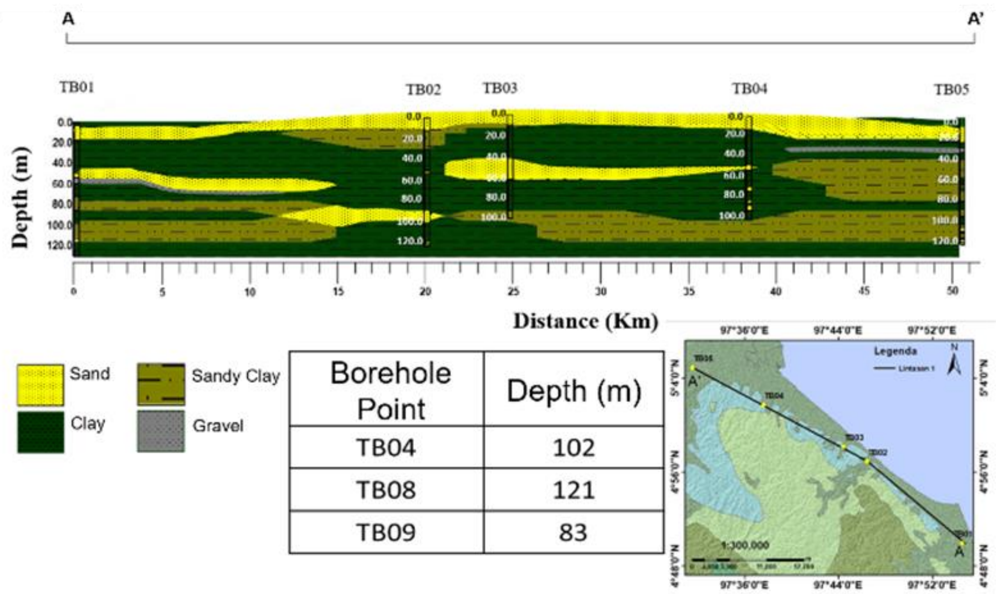
In this well, the readings of the logs started at a depth of 40 m. The deflection of this well shows little variation as well. The SP log measurements in this well vary between -52 mV and -60 mV, while the resistivity log measurements range from 12 to 74 Ωm. Both logs at depths of 42 – 45 m showed a deflection where the resistivity value rose, indicating fresh water's presence within the non-conductive sand layer.

This lithology analysis relies on the cutting outcomes acquired as secondary data, which corroborate the readings and interpretation of the SP log and resistivity log responses. It can be inferred that a lithology consisting of sand and clay is present in the research area.

These interpretations rely on the analysis of log responses with validation through cutting as secondary data. However, this interpretation considered the geological map that indicated which formation the site points were associated with. For example, it is true that in wells TB-01 (a) and TB-05 (e), there are gravels that represent fluviatile deposition.

Based on the response of log resistivity and log SP curves, the type of subsurface layer of the research area is obtained as shown in Fig 2. The subsurface sedimentary structure of the East Aceh Regency area is a mixture dominated by a clay layer. The clay layer has a high resistivity value because it traps water.

Correlation between measurement points was carried out and a lithological cross-section of 2 passes was obtained as follows: (1) Cross-section A-A'. This cross-section is the result of correlation forming a ± 50 km long track that stretches from east to west through Cot Geulumpang Village, Java Village, Kuala Lawah Village, Bukit Seroja Village and Rantau Panjang Village. This track covers 5 sub-districts which in this study are called points TB01 to TB05. The 2D cross-section of the correlation results is presented in Fig 3 as follows.



Borehole Point	Depth (m)
TB04	102
TB08	121
TB09	83

Fig 3: Lithology cross section A-A'

Fig. 3 shows that the sedimentary structure of cross-section A-A' consists of a mixture of clay, sandy clay, and sand layers. The ground surface to a depth of ±18 m along this area is dominated by sand. In some areas, the sand layer is on the surface while in other areas the surface layer is in the form of passive clay and the sand layer inserts underneath. Sand layers are also visible at a depth of 85 m to 100 m with a thickness of about 15 m stretching between points TB01 and TB02 along 9 km.

The sand layer of this area is relatively medium to fine in size with a rounded particle arrangement containing quartz and shell minerals. The characteristics of the sand layer in this area indicate that these sediments originated from the marine sedimentation process, forming soft deposits and sediments. This soft sediment character allows for subsidence.

Clay layers are underlain at depths of 18m - 43m, 80m - 100m, and 120m -125m with thicknesses of 25m, 20m, and 5m respectively.

(2) Cross- section B-B'. This cross-section is the result of correlation with a ±15 km long track through Bukit Seroja Village, Beurandang Village, and Alue Hitam Village which in this study are called points TB04, TB08, and TB09. The lithological cross-section of this area is shown in Fig 4 as follows:

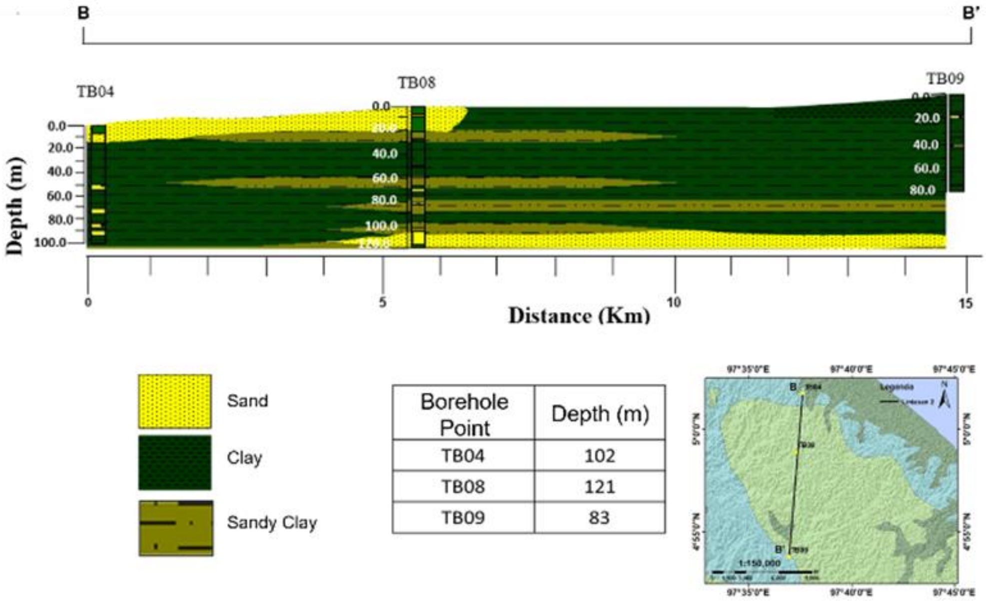


Fig 4: Lithology cross-section B-B'.

Fig. 4 shows that the sedimentary layer structure representing these 3 sub-districts is similar to cross-section A-A' which is composed of a mixture of clay, sandy clay, and sand layers. However, part of the surface of this area consists of sand layers and the other part is clay. The sand layer of this area is also identified as the result of marine sedimentation with relatively coarse to fine particle sizes and contains quartz and shell minerals.

The subsurface layer of the area is entirely dominated by clay with a thickness of up to 70m. These characteristics indicate low or almost no potential for subsidence. A layer of passive clay inserts into the subsurface sedimentary structure of the area with an average thickness of 5m.

4. Conclusion

The results showed the potential for land subsidence in part of the study area. The potential for land subsidence is seen in the A-A' cross-section area which includes Cot Geulumpang Village, Jawa Village, Kuala Lawah Village, Bukit Seroja Village, and Rantau Panjang Village with the surface layer dominated by medium to fine-grained sand that forms soft sediments. Cross section B-B' extends for ±15 km through Bukit Seroja Village, Beurandang Village, and Alue Hitam Village, dominated by a clay layer with a thickness of up to 70 m. These sedimentary characteristics make the B-B' cross-section area minimal or even no potential for land subsidence.

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