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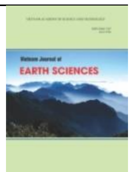

Combination of 2D-Electrical Resistivity Imaging and Seismic Refraction Tomography methods for groundwater potential assessments: A case study of Khammouane Province, Laos

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ABSTRACT

2D Electrical Resistivity Imaging (2D-ERI) and Seismic Refraction Tomography (SRT) are non-destructive techniques widely used for numerous geophysical investigations, namely, structural geology mapping, archaeological, engineering, and groundwater investigations. The present study aims to define potential groundwater zones in the Thakhek district of Khammouane Province, Laos, by 2D-ERI and SRT methods; due to the limitation of groundwater potential information, monitoring and evaluation activities regarding groundwater quantity and quality have not been conducted in this study area. The 2D-ERI measurement is based on the Wenner configuration with an electrode spacing of 10-160 m. In contrast, SRT uses a 6.5 kg sledgehammer for a seismic source with a 4 m geophone interval. The results indicate moderate resistivity values ranging from 18.8-71 Ohm.m, and seismic velocities ranging from 1220-2140 m/s were found at 12-30 m in the study region, illustrating the existence of a groundwater/aquifer at this depth. These results correlate well with drilling results from the borehole measurements in the Thakhek district, where the water levels were found at a depth of 12 m for borehole 1 and 15 m for borehole 2. The present study also demonstrates the correlation between 2D-ERI and SRT techniques. The adopted methods favor groundwater identification in the study region and other areas with similar geology formations.

Keywords: Electrical Resistivity Imaging, Seismic Refraction Tomography, groundwater, geophysical investigation, Laos.

1. Introduction

Groundwater is one of the major sources of drinking water in both urban and rural areas in Laos, with only 60% of the cities and 51% of the rural population having direct access to water sources in 1998. Groundwater consumption has increased food security in central Laos. At the same time, groundwater data has limited understanding and management in the study region. Monitoring and evaluation activities regarding the

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quantity and quality of groundwater resources have not been undertaken significantly (JICA, 2000). Groundwater is an alternative source for people who live far from surface water sources, such as irrigation, agriculture, industry, households, and drinking water in some places in Laos. Laos often uses hand-dug shallow wells at depths of less than 10 m, which are biologically unsafe and tend to become arid during the dry season. Poor groundwater quality is caused by the infiltration of domestic waste and from farm animals (Takayanagi, 1993). Limited water availability is still a big problem in many areas. This includes selected research areas for the economy and growing population. This is associated with increasing water demand and a lack of mechanisms for collecting, storing groundwater, and verifying groundwater. Therefore, it is necessary to conduct these geophysical surveys to determine the location of the potential groundwater zones and guide future drilling operations in the study areas.

The 2D Electrical Resistivity Imaging (2D-ERI) method is widely used for earth subsurface mapping, including groundwater investigations. The 2D-ERI method can determine the depth and thickness of the Earth's subsurface and the groundwater or aquifer levels based on the observed Earth resistivity. However, there is some ambiguity in the interpretation of earth resistivity values. Low resistivity values can either indicate higher clay content or higher water content. At the same time, the seismic refraction method can identify water tables or aquifers by seismic velocity analysis (Ronczka et al., 2017; Saad et al., 2013).

The seismic refraction method (SRT) is commonly applied to determine the depth of subsurface structures such as water tables or basement structures in engineering and construction sites. Application of ERI and SRT methods for geotechnical problems (landslide, groundwater exploration, mineral exploration, etc.) are explained by recent publications such as studies on the effect of porosity in water-saturated areas (Himi et al., 2022; Matthew et al., 2018; Uyanik O, 2019).

This method has been extensively used for a variety of purposes in various geological information in many countries around the world to map structural geology, including groundwater and other studies" (Sander, 1978; Stümpel et al., 1984; Uyanık and Ulugergerli., 2008; Uyanık et al., 2013). The results of Seismic Refraction Tomography (SRT) in terms of seismic velocity models may reduce the ambiguity between clay content and water level (Knudsenet et al., 2004). Thus, it is necessary to use geophysical exploration methods such as 2D-ERI and SRT methods to assess the potential of groundwater in the selected study area. Groundwater exploration using geophysical methods has been widely applied in large research areas in various geological situations in many regions of the world (Dahlin et al., 2002., Kafadar, 2020, 2021; Vu et al., 2021). Applying these geophysical methods for groundwater investigation is still limited to central Laos (Perttu et al., 2011a, b). Therefore, this work aims to determine the location of the water table or aquifer and the aquifer thickness using 2D-ERI and SRT techniques in the study areas. The results of the two geophysical methods matched with drilling results from both wells, including soil sample data in these boreholes.

2. Geological setting

The Khammouane and Savannakhet Basins are considered to be similar to the expansion of the Sakon Nakhon Basin in the northeast region of Thailand. While East Vietnam Sea appears between longitude 106-115°E in the easten part of Laos (Fig. 1). The Phu Phan Mountains divide the Korat Plateau into two basins such as the southern Korat Basin and the northern Sakon Nakhon Basin. These basins cover a wide area of approximately 36×10^3 km^2 and 21×10^3 km^2, respectively (Hite et al., 1979; El Tabakh et al., 1999;

Keith et al., 2005; Zhang et al., 2013). The primary Potash deposits can be found in two areas, namely the Vientiane and Khammouane sub-basins, considered extensions of potash deposits in Thailand. They serve ~50 million tons with grades up to 15% of K_2O at a depth varying from 25-200 m and a thickness of up to ~100 m (Inthavong, 2005).

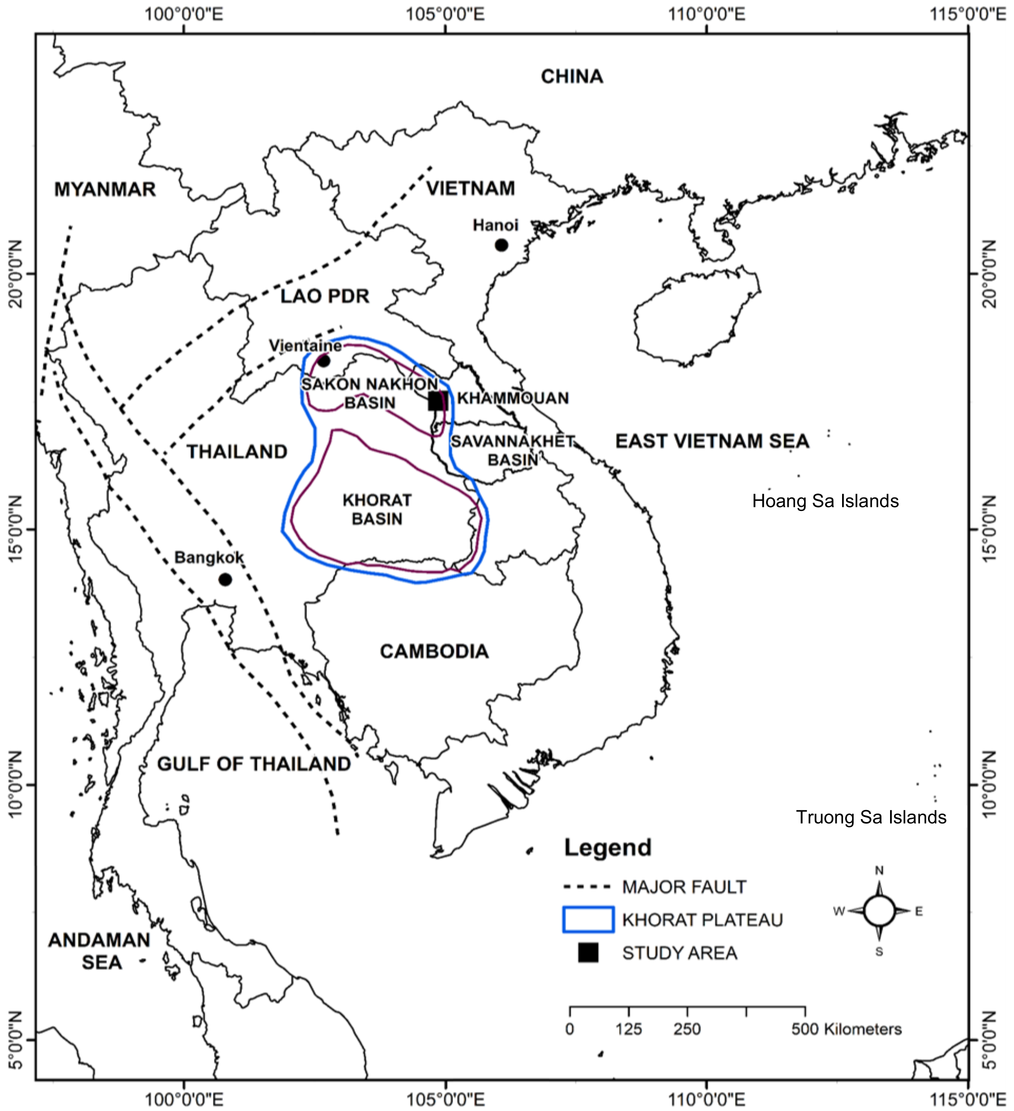

Figure 1. The general geology and tectonic settings describing the extension of the Khorat Plateau. The locations of different basins and the study region's location in Khammouan province are also shown in the figure (modified after El Tabakh et al., 1999)

The geology of the Khammouane basin comprises carbonate rocks of limestone, dolomitic limestone, or dolomite lithology, which are complex, compact, and pure. The Khammouane Formation is underlain by the sandstones of the early Carboniferous Boualapha Formation (Fig. 2). During the Mesozoic Era, the Khammouane Formation was covered unconformably by continental red beds of the early to middle Jurassic Ban

Lao Formation, which in turn was covered by the red beds of the late Jurassic Nam Phouan and early Cretaceous Nam Xot formations. Additionally, Khammouane Basin was covered by the rock formations named Ban Lao, Nam Phuoan, Nam Xot, Nam Noy, and Nong Boua formations are the Jurassic-Cretaceous redbeds (Tran et al., 2000a, b). The geology of this area is complicated, with various faults and fractures. The Thakek-Sepon active fault zone is considered an extension fault zone from Laos into Vietnam and is more significant than 550 km. The fault zone is composed mainly of three main faults running nearly NW-SE in Laos. The fault zone partly runs along the Mekong River at the Thai-Laos border (Thom et al., 2015; Zhang et al., 2017).

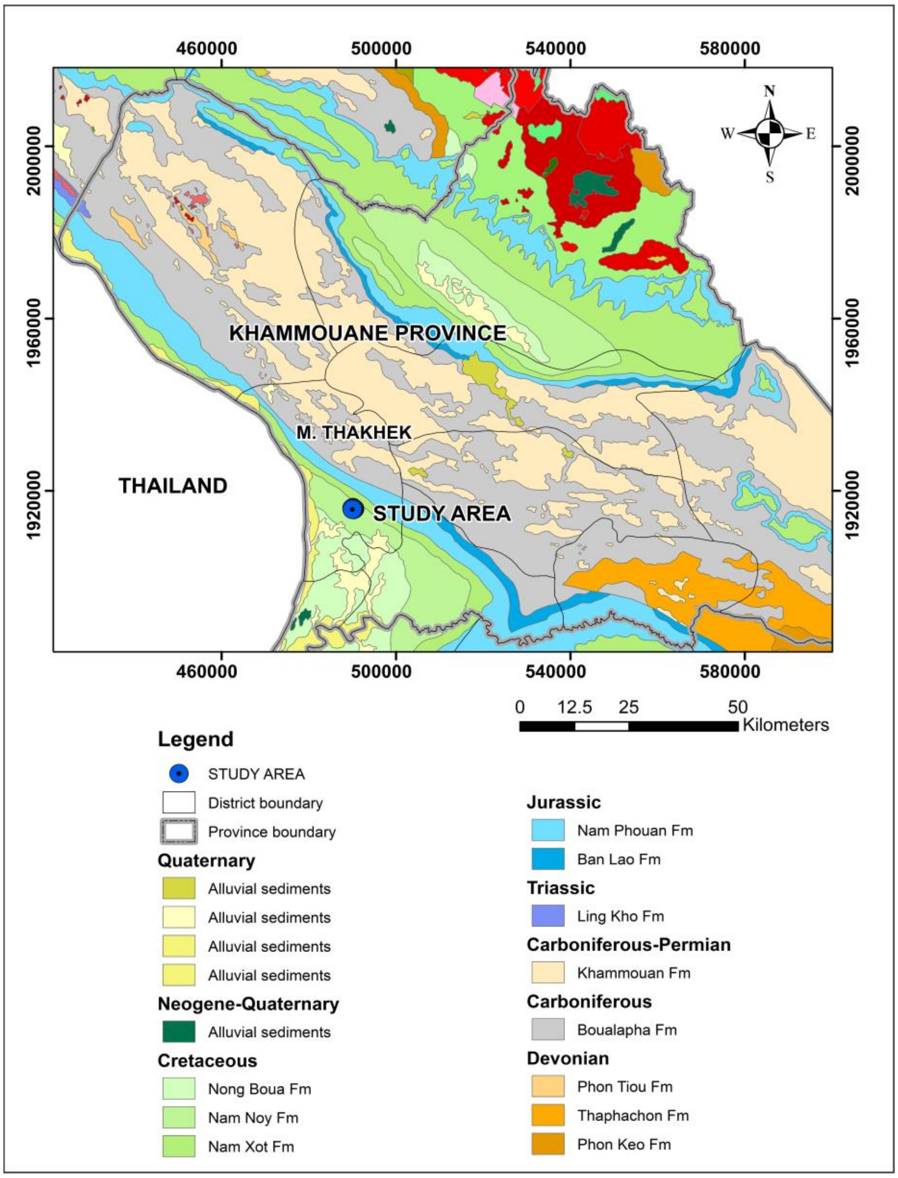

Figure 2. Detailed geology of the study region in Khammouan Province overlaid with the boundaries of the province and districts (Tran et al., 2000a, b)

The stratigraphic gap of the unconformity between the Paleozoic carbonates and Mesozoic red beds reaches up to 60 Ma in central Laos. This gap in the sedimentary record indicates a long erosion period favorable to karst formation before burial by the Mesozoic continental red beds created a paleokarst (Vote et al., 2015). Geology in the Thakhek District of Khammouane Basin consists of limestone covered with Permian limestone. It is a carbonic group composed of thick-bottomed limestone interspersed with hard rock and shale. Limestone forms cliffs and steep mountains Carboniferous due to the high hardness in deep groundwater. The study area was selected in the Thakhek district of Khammouane province, far from 350 kilometers south of Vientiane's capital, with a population of ~85,000 people, located across the Mekong River from the Nakhon Phanom province, Thailand. Thakhek district covers an area of about 980 km², with the Mekong River to the west and mountains to the east. The average annual rainfall from 2007 to 2011 was 2,350 mm, and the average temperature was 26.7°C (JICA, 2013).

3. Material and Methods

3.1. Resistivity measurement

The resistivity of the layers of the Earth largely depends on different rock types, such as igneous, metamorphic, and sedimentary rocks, as well as the amount of fluid or water added to cracks or voids in the pores. The 2D-ERI technique measures the resistivity of the Earth's subsurface. In general, sedimentary rocks have lower resistance than igneous and metamorphic rocks because they are more porous and richer in water. Commonly, the resistivity of the clay layer is lower than that of the sand layer. On the other hand, the disparity in the Earth's resistivity values of different types of rocks complicates the resistivity values for aquifers or clay layers (Loke, 2015). The electrical resistivity of rocks depends on porosity, permeability, water content, and pore-dissolved solids in the Earth's subsurface layers (Table 1). Therefore, the resistivity technique is widely used for geology mapping and potential groundwater assessment (Reynold, 2011).

Table 1. Resistivity of various earth materials (Reynold., 2011)

Materials	Resistivity (Ohm.m)
Clay	1-100
Clayey sand	30-215
Gravel	100-5000
Sand	60-1000
Sandstone	8-4000
Shale	20-2000
Sand and gravel saturated with fresh water	15-600
Groundwater	10-800
Fresh groundwater	20-160
Sediments with salt water	<10
Saltwater	0.25

In general, resistivity measurements are performed by a current injected into the Earth's subsurface using a pair of current electrodes. The potential difference is measured between two other potential electrodes. The apparent resistivity is the average bulk resistivity of the Earth's subsurface affecting the electric current. The apparent resistivity can be calculated by dividing the measured potential difference and the input current and multiplying by a specific geometric factor for the applied layout and electrode spacing (Loke, 2015). In this work, the Wenner configuration was chosen to collect 2D-ERI data (Fig. 3). The 2D-ERI data were carried out manually and automatically with the ABEM Terrameter SAS 1000 instrument.

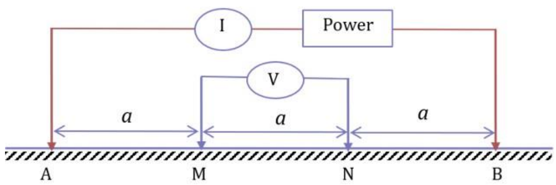

Figure 3. Schematic diagram representing the Wenner electrode configuration with a line of four equally spaced electrodes

3.2. Seismic refraction method

The seismic method uses seismic energy that returns to the surface after traveling through the Earth's subsurface along a horizon as a refracted ray path. The first seismic arrival is detected by seismic receivers or geophones arranged along the ground surface from seismic sources commonly known as direct or refracted waves (Fig. 4). Seismic waves travel in seismic velocity contrast when they travel through interfaces between different horizons. The thickness and seismic velocity between two different Earth layers can be determined by calculating the arrival time for direct and refracted waves from the time relative to the distance graph or seismic section (Kearey et al., 2002). The seismic velocity depends on rock type, water content, lithology, porous, density, and modules of rocks and soils (Table 2). Seismic refraction methods are widely used for subsurface mapping, including groundwater investigations (Hasselstroem, 1969; Grelle et al., 2009; Anomohanran, 2012; Gabr, 2012; Bery, 2013; Thomas et al., 2013; Osumeje et al., 2014; Adewoyin et al., 2016). In this work, the ERT data is processed by EarthImager software to produce cross-sections of resistivity distribution, which is used to estimate the actual structures. The mean depth investigation was approximately 0.52 times the electrode spacing for the Wenner configuration (Loke, 2015). On the other hand, the SeisImager software was used for processing and analyzing seismic refraction data for real-earth layer mapping. This software uses the inverse time to generate seismic velocity models regarding earth thickness and corresponding seismic velocity values under seismic profile (Akingboye, 2009).

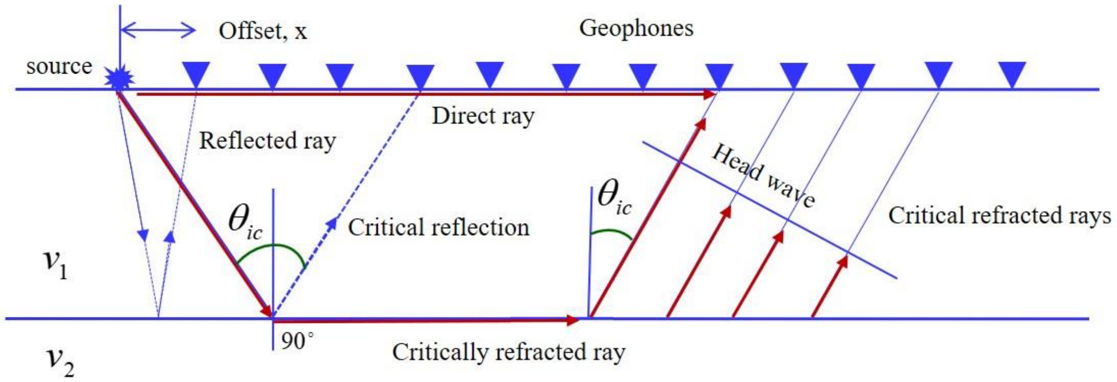

Figure 4. Schematic diagram representing the seismic ray path of direct, reflection, and refraction waves

Table 2. The seismic velocity (primary waves) of common materials (Kearey et al., 2002)

Common materials	Seismic velocity (m/s)
Air	331
Dry silt and sand	200-800
Gypsum	2000-3500
Water	1400-1500
Gravel and sand below the water table	800-2300
Dry sand	200-1000
Sand (water-saturated)	1500-2000
Clay	1000- 2500

3.3. Survey profiles

Four 2D-ERI and SRT profiles were conducted in selected research areas in the Thakhek District of Khammouane province. Three 2D-ERI profiles are placed in the direction of NW-SE, while another profile is located in the direction of NE-SW, with the intersection of profiles 1, 2, and 3 at 50 m, 200, and 300 m, respectively. The maximum length of the profile is 480 m (Fig. 5). The

Wenner electrode configuration is used in the present study with an electrode spacing of 10-160 m. 2D-ERI data is recorded manually and automatically in the Terrameter ABEM SAS 1000 (Made in Sweden). Three seismic refractive profiles were performed at selected 2D-ERI profiles using SmartSeis ST with a 12-channel seismograph. Three seismic refractive profiles (1, 2, and 3) were arranged in overlaps in three selected 2D-ERI profiles (1, 2, and 4) at the research site (Fig. 5), with a profile length of 352 m. The relevant parameters of seismic data acquisition include a geophone interval of 4 m, sample interval of 0.125 ms, and record length of 0.04s. This measurement's seismic spread consists of 12 geophones arranged along a straight line. This work was performed using a 6.5 kg sled hammer into a steel plate that was set at seven shot points for each seismic spread (Fig. 6). In the first spread, the first geophone is located at 0 m, and the 12th geophone is at 44 m; while in the second spread, the first geophone 1 is at 44 m and the 12th one is placed at 88 m. Then we moved to the next spread to the first geophone of the last spread at 308 m and the 12th geophone at 352 m. To compare the results, two boreholes were drilled in the survey area to match and demonstrate the obtained results of a combination of 2D-ERI and SRT methods.

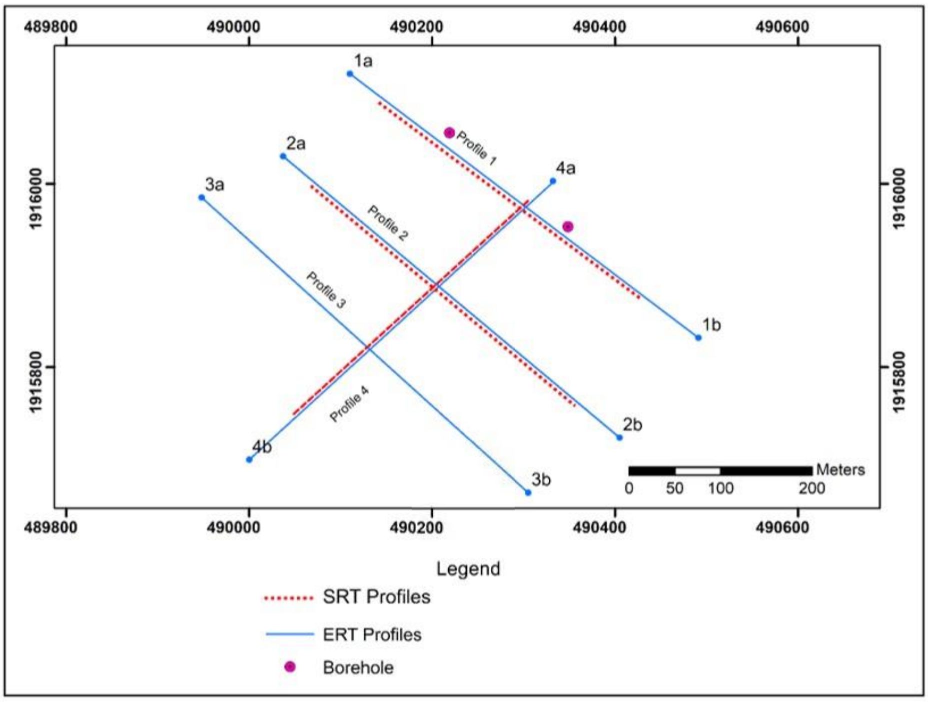

Figure 5. Maps showing the orientation of the 2D-ERI and SRT profiles

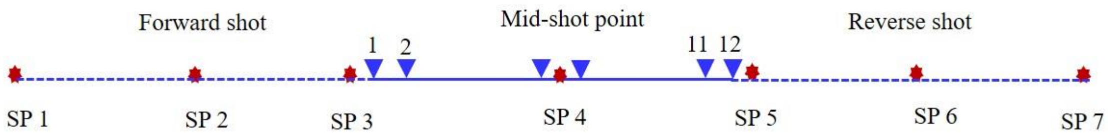

Figure 6. A typical seismic refraction data acquisition layout and location of shot points for seismic refraction survey profile

4. Results

Three parallel NW-SE oriented profiles (1, 2, and 3) at the study site showed near similar results (Fig. 7). A resistivity region higher than 100 Ohm.m was observed at shallow depths of approximately 10 m, some zones at depths between 40 and 80 m with fuzzy thicknesses are considered as sandy clay topsoil layers for shallow depths and sandstone bedrocks layers for more profound depths. A relatively low resistivity region is lower than 10 Ohm.m, which appears to be some zones of unclear thickness and is interpreted as a thick clay layer beneath each profile. However, a moderate resistivity range from 18.8-71 Ohm.m was observed at 12-30 m depth along these profiles are considered an appropriate water table. To link the location of the subsurface layers beneath the survey area, a fourth profile is extracted, crossing the three parallel profiles (1, 2, and 3) in the NE-SW direction with the intersection of profiles 1, 2, and 3 at 50 m, 200 and 300 m, respectively (Fig. 8). Several relatively low-resistivity regions (less than 10 Ohm.m) in some zones with the unclear thickness are inferred to show the presence of a thick clay region, while another zone at approximately 12 to 30 m deep is interpreted as an appropriate groundwater potential zone or aquifer in this profile.

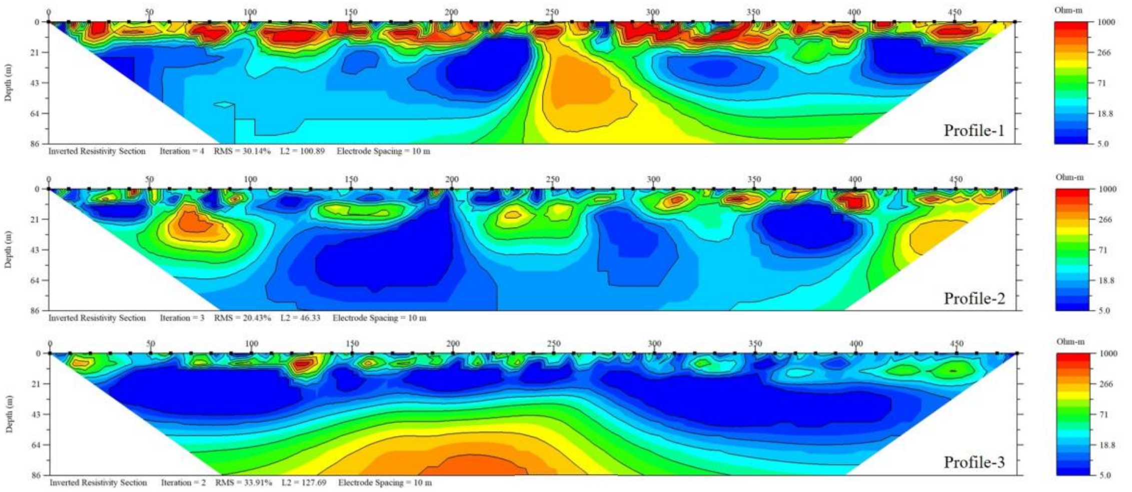

Figure 7. 2D-ERI cross sections at profiles 1, 2 and 3

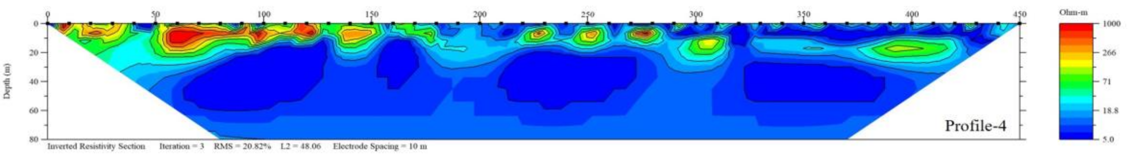

Figure 8. 2D-ERI cross section at profile 4

Additionally, two similar SRT profiles (1 and 2) were superimposed on selected 2D-ERI profiles (1 and 2). The beginning of the seismic profile was 44 m from the 2D-ERI profile, while the end of the profile was located at 352 m of the 2D-ERI profile (Fig. 9). The results of the two SRT profiles (1 and 2) correlated well with the 2D-ERI cross-sections of profiles 1 and 2. These two geophysical results show a moderate resistivity of 18.8-71 Ohm.m and a seismic velocity range from 1220-2140 m/s. This is considered water level at a depth from 12-30 m. On the other hand, a third seismic profile was conducted at the fourth 2D-ERI profile (Fig. 10). A moderate resistivity region of 18.8-71 Ohm.m and seismic velocity varying from 1220-2140 m/s at depth from 12-30 m along this profile are interpreted as groundwater potential zones or aquifers. The integrated results of ERT and SRT methods indicated that potential potential groundwater zones or aquifers found at depth from 12-30 m responded well to moderate resistivity and seismic velocity regions of 18.8-71 Ohm.m and 1220-2140 m/s respectively. However, there limitation depth of investigation for seismic refraction methods due to the use of striking a 6.5 kg sledgehammer into a steel plate is not sufficient seismic energy enough for more profound depths. On the basic is the decision of groundwater depth based on resistivity values of resistivity cross-sections. To be accurate for water tables or aquifers, drilling results were used only for comparison with geophysical data processing results.

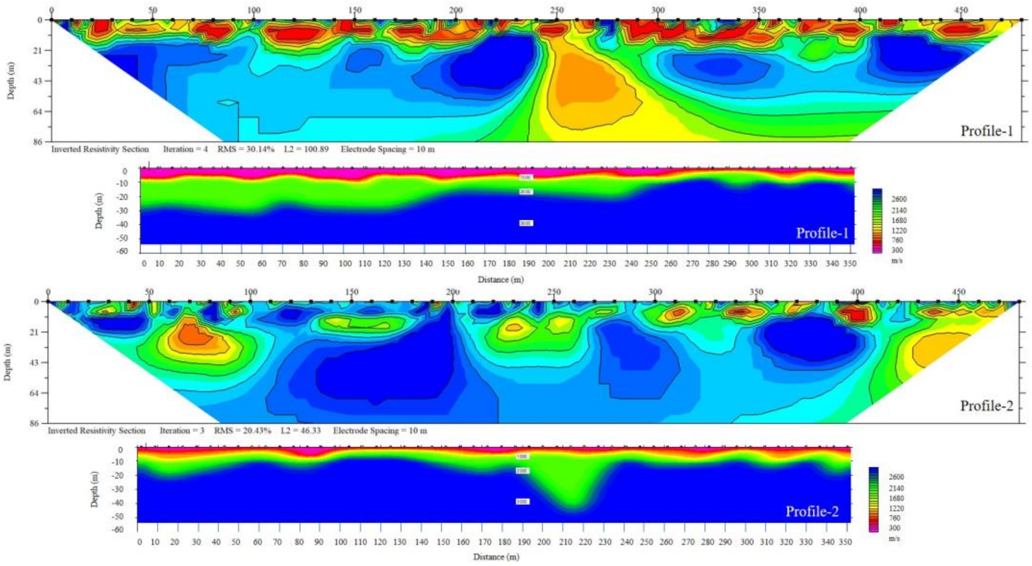

Figure 9. 2D-ERI and SRT cross sections at profiles 1 and 2

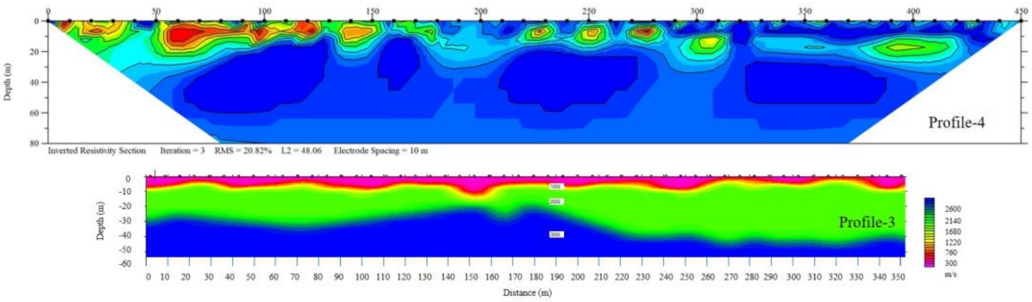

Figure 10. 2D-ERI and SRT cross sections at profile 4 and profile 3, respectively

5. Discussions

For comparing the results of 2D-ERI and SRT, two boreholes were drilled at profile 1 to match the location of the water level or aquifer (Fig. 11 a, b, c, and d). The obtained results from both boreholes 1 and 2 (KBH-1 and KBH-2) provided water tables at a depth of approximately 12 m for KBH-1 and a depth of 15 m for KBH-2 in the first 2D-ERI and SRT (profile 1). Soil samples collected from the two boreholes were classified as sand and gravel at aquifers (Fig. 11 c, d), which responded well to a resistivity region of 18.8-71 Ohm.m and a seismic velocity region between 1220-2140 m/s specified for groundwater potential zones (Fig. 11 a, b). The combination of ERT and SRT methods complement each other to obtain the most accurate analysis results possible. The integrated geophysical methods defined the thickness of aquifers and groundwater potential and identified the soil and rock layers in the study area. The electrical resistivity and seismic refraction data analysis results indicated that the water table is about 12-15 m deep. This result is consistent with results from the drilling test at boreholes 1 and 2 along Profile 1.

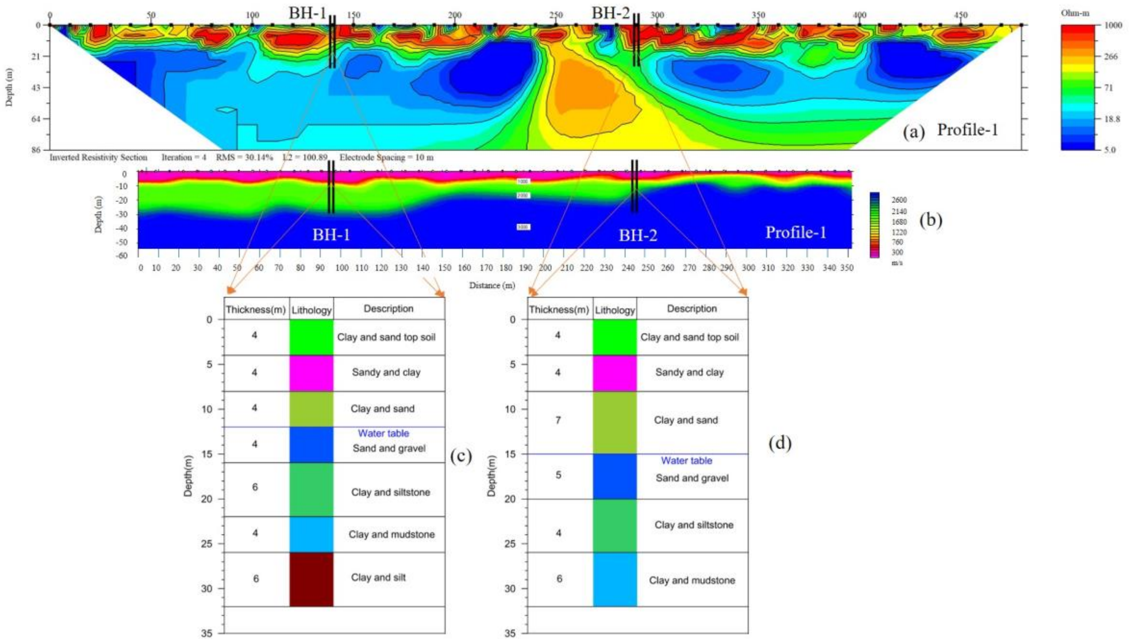

Figure 11. (a) 2D-ERI cross-section at profile 1; (b) SRT cross-section at profile 1;
(c) Vertical geological cross-section of KBH-1 at 140 m at 2D-ERI profile 1 and 96 m at SRT profile 1;
(d) Vertical geological cross-section of KBH-2 at 290 m at 2D-ERI profile 1 and 246 m at SRT profile 1

5. Conclusions

2D-ERI and SRT techniques have been proven in Earth subsurface mapping research areas in the Thakhek district of Khammouane province, Laos. The results of 2D-ERI and SRT models showed that regions of relatively low resistivity below 10 Ohm.m and seismic velocity regions of 760-1220 m/s are considered thick clay layers. At the same time, areas of high resistivity greater than 100 Ohm.m and seismic velocities of 300-760 m/s are found at shallow depths of about 10 m along these profiles with fuzzy thickness considered as the sandy clay topsoil. A moderate resistivity area of 18.8-71 Ohm.m and a seismic velocity range of 1220-2140 m/s at a depth of 12-30 m are considered possible water tables. This indicated a water table with an excellent correlation to the groundwater table from the obtained results from boreholes 1 and 2 (KBH-1 and KBH-2). The results provided a water table at approximately 12 m for borehole 1 and 15 m for borehole 2 in the first

2D-ERI and SRT profiles. The results illustrated that combining 2D-2D-ERI and SRT methods to identify the potential of groundwater zones in selected research areas was feasible and practical. The results of this study will help assess aquifers and groundwater in the study area, and these two geophysical methods can be used to assess the potential of groundwater in other areas with similar geology formations.

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