# CHAPTER 2
# RESEARCH METHODOLOGY

This chapter addresses methodology used in the research work which consists of geophysical data acquisition, geophysical data processing as follows;

## 2.1. Equipment

### 2.1.1. Electrical resistivity data acquisition

1. Measuring tapes and two rolls of string for assigning positions of electrodes.
2. Hammers used for forcing current and potential electrodes into ground.
3. A Resistivity meter, ABEM Terrameter SAS 1000, for measuring ground resistivity (Figure 2.1).
4. GPS Garmin, model Extrex for determining locations of sounding points.
5. Four rolls of electrical cables for connecting current and potential electrodes with resistivity meter (SAS 1000).
6. Car battery (12V-20A) for a direct current power supply of the resistivity meter (SAS 1000).
7. Two steel electrodes for injecting current into ground and two potential electrodes for measuring voltage difference at the ground surface.
8. The topographic map of Xaithani district in scale of 1: 60,000 for planning sounding points.


*Figure 2.1* Resistivity meter, ABEM Terrameter SAS 1000

### 2.1.2. Gravity data acquisition

1. Hammers, concrete nails, pieces of cloths and lids of drinking water bottles for marking gravity measuring points.
2. The topographic map and the geological map of Vientiane capital in a scale 1: 200,000 for planning gravity surveys.
3. Gravimeter plate for horizontal leveling gravimeter.
4. Lacoste & Romberg gravimeter model G-565 with an accuracy of 0.01 g.u. (Figure 2.2) for measuring gravity in Vientiane basin.

*Figure 2.2* Lacoste & Romberg gravimeter model G-565

5. An American Paulin Altimeter (AMP) model MDM-5 (Figure 2.3 (a)) for determining elevation of gravity points.
6. A watch for recording time of gravity and elevation measurements.
7. A thermometer for measuring temperature of ambient air.
8. A Trimble GPS model Basic Pathfinder for determining locations of gravity points (Figure 2.3 (b)).

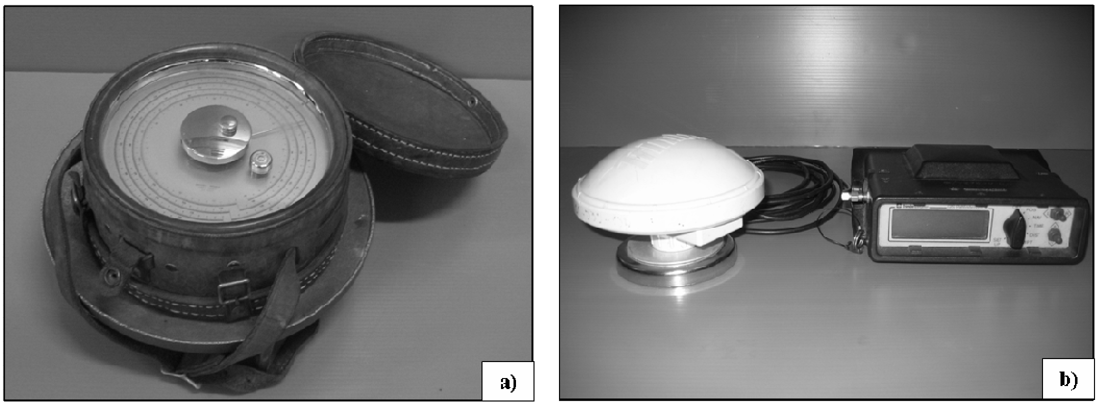


*Figure 2.3* (a) AMP altimeter model MDM-5, (b) Trimble GPS model Basic Pathfinder

### 2.1.3. Density of rock determination

1. An electronics balance model PB 3002-S with a weighing range of 0.5 to 3100 g.
2. Water and water container for weight of rock sample in water.

### 2.1.4. Other equipment and materials

1. A personal computer
2. Surfer program, Grapher program, MapInfo program and Photoshop program for geophysical data processing and analyzing.
3. Computer materials; CD, diskette and handy driver for transferring and storing data system.

## 2.2. Geophysical principles

Geophysics applies the principle of physics to the study the earth. Geophysical investigations of the interior of the earth involve taking measurements near earth surface that are determined by the internal distribution of physical properties (Kearey *et al.*, 2002). In this research project, gravity and resistivity methods were selected for determining regional subsurface geological structures in Vientiane basin and areas of potential groundwater in Xaithni district.

### 2.2.1. Electrical resistivity method

The purpose of electrical survey is to determine the subsurface resistivity distribution by conducting measurement on the ground surface. Resistivity of rocks depends on porosity, saturation, content of clay and resistivity of pore water. Rocks are usually porous and pores are filled with fluids, mainly water (Reynolds, 1997). Rock resistivity of clean sand, saturated aquifer was explained by Archie's law:

$$\rho_r = a\rho_w\phi^{-m}$$

Where: $\rho_r$ , $\rho_w$ are resistivities of rock and water respectively

$a$ is the saturation coefficient

$m$ is the cementation factor

$\phi$ is fractional porosity.

Table 2.1: Resistivities of some common rocks and other materials (modified from Loke, 1999 and Reynolds, 1997)

| Materials | Resistivity (ohm-m) |
|---|---|
| Igneous and metamorphic rocks | |
| Granite | $5x10^3$-$10^6$ |
| Basalt | $1x10^3$-$10^6$ |
| Slate | $6x10^2$-$4x10^7$ |
| Marble | $1x10^2$-$2.5x10^8$ |
| Quartzite | $1x10^2$-$2x10^8$ |
| Sedimentary rocks | |
| Sandstones | 8-$4x10^3$ |
| Shale | 20-$2x10^3$ |
| Limestone | 50-$4x10^7$ |
| Rock salt | 30-$1x10^{13}$ |
| Gravel(dry) | 14 $x10^2$ |
| Gravel(saturated) | 1 $x10^2$ |
| Soils and water | |
| Clay | 1-$1x10^2$ |
| Alluvium | 10-8 $x10^2$ |
| Groundwater | 0.5-3 $x10^2$ |
| Groundwater(fresh) | 10-1 $x10^2$ |
| Sea water | 0.2 |

Electrical resistivity measurements are normally made by injecting current into the ground through two current electrodes ($C_1$ and $C_2$), and measure resulting voltage difference at two potential electrodes ($P_1$ and $P_2$). From the current (I) and voltage (V) values, an apparent resistivity $(\rho_a)$ values is calculated by

$$\rho_a = k\frac{V}{I} \tag{2.1}$$

Where: k is the geometric factor, depends on the arrangement of the four electrodes.

Wenner, Schlumberger and Dipole-Dipole configurations are commonly used in electrical resistivity surveys. Wenner and Dipole-Dipole configurations are usually applied for environmental problem, archeological problem or landfill problem, whereas Schlumberger configuration is commonly used in groundwater exploration (Telford *et al.*, 1990).

In this work, electrical resistivity sounding with Schlumberger electrode configuration (Figure 2.4) was carried out in Xaithani district for determining groundwater layer. The apparent resistivity $(\rho_a)$ of the Schlumberger configuration is determined from the following equations;

$$\rho_a = \frac{\pi\left(L^2 - l^2\right)}{2l}\left(\frac{V}{I}\right) \tag{2.2}$$

Where $2l$ is spacing between potential electrodes, $2L$ is a spacing between current electrodes and $(V/I)$ is reading taking from resistivity meter.

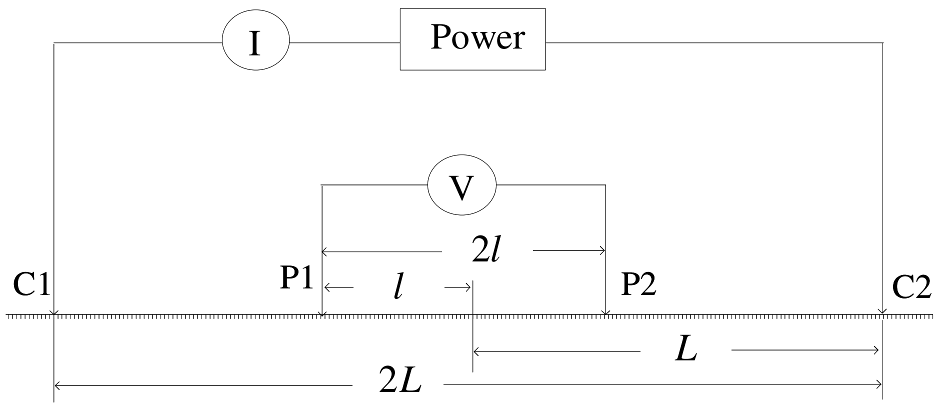


*Figure 2.4* Schlumberger electrodes configuration

### 2.2.2. Gravity method

The gravity method involves measuring the earth's gravitational field on the earth's surface for delineating subsurface geological structures due to difference in density. The gravity method was employed when the subsurface target is greater or lesser in density than the surrounding rocks. The density of the rock depends on both its mineral composition and porosity. The variation in porosity mainly controls the density of sedimentary rocks (Table 2.2). In addition, density of rock increases with depth due to compression, cementation and age (Kearey *et al*., 2002).

Table 2.2: Densities of some common rock types (Telford *et al*., 1990)

| Rock type | Density range ($g/cm^3$) | Average density ($g/cm^3$) |
|---|---|---|
| Sediments and sedimentary rocks (wet) | | |
| Clay | 1.63-2.60 | 2.21 |
| Gravel | 1.70-2.40 | 2.00 |
| Silt | 1.80-2.20 | 1.93 |
| Soil | 1.20-2.40 | 1.92 |
| Sand | 1.70-2.30 | 2.00 |
| Sandstone | 1.61-2.76 | 2.35 |
| Shale | 1.77-3.20 | 2.40 |
| Limestone | 1.93-2.90 | 2.55 |
| Dolomite | 2.28-2.90 | 2.70 |
| Rock salt | 2.10-2.60 | 2.22 |
| Gypsum | 2.20-2.60 | 2.35 |
| Anhydrite | 2.29-3.00 | 2.93 |
| Igneous rocks | | |
| Andesite | 2.40-2.80 | 2.61 |
| Granite | 2.50-2.81 | 2.64 |
| Quartz diorite | 2.62-2.96 | 2.79 |
| Basalt | 2.70-3.30 | 2.99 |
| Metamorphic rocks | | |
| Quartzite | 2.50-2.70 | 2.60 |
| Marble | 2.60-2.90 | 2.75 |
| Gneiss | 2.59-3.00 | 2.80 |

## 2.3. Data acquisition

### 2.3.1. Electrical resistivity data acquisition

An electrical resistivity measurement was conducted at 30 sounding points with ABEM Terrameter SAS 1000 in Xaithani district during 29th May to 9th June 2006. The Schlumberger electrode configuration was employed in the measurement with the half current electrode spacing of 1.5, 2, 3, 4.5, 7, 10, 15, 20, 30, 45, 60, 90, 150, 225, 350 and 500 meters in the following steps;

1. Determine locations of resistivity sounding stations by using topographic map of Xaithani district of scale 1: 60,000.
2. Select line of measurement and placing four electrodes on the ground surface along the straight line. Connecting electrodes to the resistivity meter SAS 1000 via electric cables as shown in Figure 2.4.
3. Start the measurement and reading the resistance value of R.
4. Increase spacing between current electrodes and repeat step (3). In case that the reading value of R is too low, spacing between potential electrodes should be increased by keeping $l \leq L/3$.
5. Repeat steps (3) and (4) until $L = 500m$.
6. Record name of sounding station name, location of sounding point by GPS in a data sheet as shown in Table 2.3. The fieldwork activities are shown Figure 2.5.
7. Move to next sounding station and repeat steps (2), (3), (4), (5) and (6).
8. All together 30 sounding points were measured in Xaithani district. The locations of these sounding points are shown in Figure 2.9.
9. Measure TDS value of water samples of 35 water wells in Xaithani district.

### 2.3.2. Gravity data acquisition

Gravity measurements were conducted at 132 stations in Vientiane basin along available roads and tracks in the study area. The gravity was measured with Lacoste & Romberg gravimeter model G-565 covering an area of about 4,000 square kilometers during May 2-12, 2007. The station spacing of 4 kilometers was designed for gravity surveys in the study area. The measurement was conducted in the following steps;

1. Begin the measurement by planning locations of gravity points on topographic map of Vientiane capital of scale 1 : 200,000
2. Go to the assigned base station, the very first gravity station of this gravity campaign.
3. Measure its gravity value and table name of gravity station, gravity reading and time of measurement in data sheet as shown in Table 2.4.
4. Measure altitude of the gravity station with AMP altimeter and temperature of ambient air with a thermometer. Table their values in a data sheet as also shown in Table 2.4.
5. Determine the UTM coordinates of the gravity station with a GPS, average elevation of topography on zones B to E of Hammer chart around the gravity station and table these data in a data sheet as shown in Table 2.5
6. Move to next gravity station and repeat measurement steps (3) to (6).

*Figure 2.5* Electrical resistivity surveys in Xaithani district

Table 2.3: Example of data sheet for resistivity sounding measurement

| Survey no. 1 | | Location: E= 0265636; N=1998917 | | | | | Date: May 29, 2006 | |
|---|---|---|---|---|---|---|---|---|
| Line no.1 | | Operator: Mr. Viengthong Xayavong | | | | | Time: 13:00 | |
| Electrode spacing (m) | | TERRMETR reading in ohms | | k | Calculated apparent Resistivity in ohm-m | | | Co |
| C1C2/2 | P1P2/2 | $R_1$ | $R_2$ | | $\rho_1$ | $\rho_2$ | $\overline{\rho}$ | |
| 1.5 | 0.5 | 33.8450 | 33.8530 | 6.3 | 213.22 | 213.27 | 213.25 | |
| 2.0 | 0.5 | 19.3210 | 19.3230 | 11.8 | 227.99 | 228.01 | 228.00 | |
| 3.0 | 0.5 | 6.9309 | 6.9299 | 27.5 | 190.60 | 190.57 | 190.59 | |
| 4.5 | 0.5 | 1.2948 | 1.2955 | 62.8 | 81.31 | 81.36 | 81.34 | |
| 7.0 | 0.5 | 0.1585 | 0.1587 | 153.2 | 24.28 | 24.31 | 24.30 | |
| 7.0 | 2.0 | 0.8742 | 0.8737 | 35.3 | 30.86 | 30.84 | 30.85 | |
| 10.0 | 0.5 | 0.0326 | 0.0325 | 313.4 | 10.22 | 10.17 | 10.20 | |
| 10.0 | 2.0 | 0.1601 | 0.1590 | 75.4 | 12.07 | 11.99 | 12.03 | |
| 15.0 | 2.0 | 0.0432 | 0.0433 | 173.6 | 7.50 | 7.52 | 7.51 | |
| 20.0 | 2.0 | 0.0278 | 0.0276 | 311.0 | 8.64 | 8.57 | 8.61 | |
| 20.0 | 6.0 | 0.1071 | 0.1075 | 95.3 | 10.20 | 10.25 | 10.22 | |
| 30.0 | 6.0 | 0.0502 | 0.0501 | 226.2 | 11.35 | 11.34 | 11.35 | |
| 45.0 | 6.0 | 0.0247 | 0.0247 | 520.7 | 12.87 | 12.86 | 12.87 | |
| 45.0 | 10.0 | 0.0341 | 0.0340 | 302.4 | 12.93 | 12.73 | 12.83 | |
| 60.0 | 10.0 | 0.0210 | 0.0209 | 549.8 | 14.86 | 14.67 | 14.77 | |
| 60.0 | 20.0 | 0.0475 | 0.0468 | 251.3 | 14.26 | 13.58 | 13.92 | |
| 90.0 | 20.0 | 0.0222 | 0.0022 | 604.8 | 14.61 | 14.62 | 14.62 | |
| 90.0 | 30.0 | 0.0344 | 0.0339 | 377.0 | 14.67 | 14.37 | 14.52 | |
| 150.0 | 30.0 | 0.0132 | 0.0131 | 1131.0 | 14.28 | 14.22 | 14.25 | |
| 150.0 | 50.0 | 0.0233 | 0.0234 | 628.3 | 15.57 | 14.98 | 15.27 | |
| 225.0 | 50.0 | 0.0102 | 0.0103 | 1511.9 | 15.25 | 15.27 | 15.26 | |
| 225.0 | 30.0 | 0.0066 | 0.0065 | 2603.6 | 15.88 | 14.91 | 15.40 | |
| 350.0 | 50.0 | 0.0048 | 0.0042 | 3769.9 | 15.60 | 14.91 | 15.25 | |
| 500.0 | 50.0 | 0.0019 | 0.0021 | 7775.4 | 50.66 | 44.94 | 47.80 | |

7. When gravity measurement has been carried out for a period of about 3 hour, the base station must be re-visited and new gravity reading at the base station must be re-taken in order to close the first loop of measurement. This step was carried out in order to monitor a drift in gravity reading of the loop.
8. Start a new loop of the gravity measurement by assigning a gravity station in the first loop as the starting base station of the new loop and repeat steps (3) to (6).
9. When gravity measurement in this new loop has been carried out for a period of about 3 hour, any gravity station in the previous loop, a finishing base station, must be re-visited and new gravity reading at this base station must be re-taken in order to close the loop of measurement. This step was carried out in order to monitor a drift in gravity reading of the loop.
10. Repeat steps (8) and (9) until the study area was covered by gravity stations as planned. The diagram of loop measurement is shown in Figure 2.6, whereas field gravity survey and locations of gravity stations are shown in Figures 2.7 and 2.8 respectively.
11. 38 rock samples of Cretaceous sandstone were collected from 11 sites within and outside the study area. Density of these rock samples was determined in a laboratory and was later used as a constraint in gravity modeling.
12. Gather geological log information of deep wells available in the study area and use them as constraints of geophysical interpretation. The log information was taken from Department of Geology and Mines of Laos.

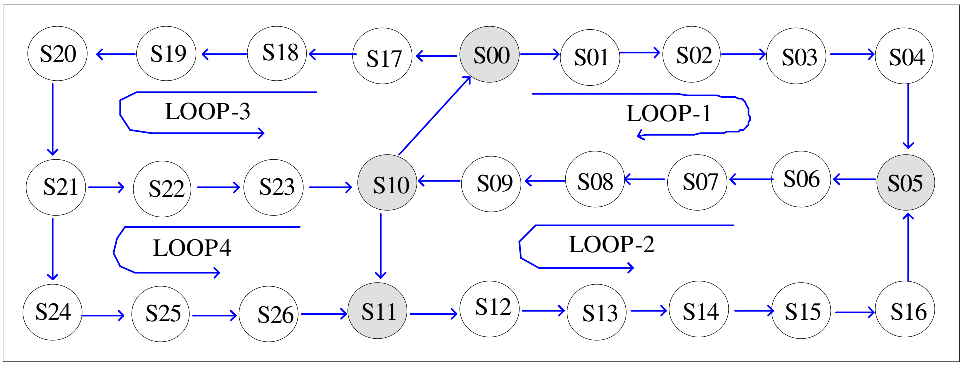


*Figure 2.6* Example of the diagram for loop gravity measurement. The grey stations are base stations.

*Figure 2.7* Gravity surveys and geological sites surveys in Vientiane basin

Table 2.4 Example of data sheet for gravity measurement

| Station | E | N | Time (hr: min) | Reading | Altitude (m) | Temp. ($^{o}C$) |
|---|---|---|---|---|---|---|
| VT001.B* | 251446 | 1995291 | 13:05 | 2014.965 | 199.5 | 33.3 |
| VT002 | 253680 | 1998084 | 13:35 | 2016.096 | 208.0 | 35.0 |
| VT003 | 257417 | 1999146 | 13:50 | 2015.160 | 214.0 | 33.3 |
| VT004 | 261120 | 1999934 | 14:07 | 2012.280 | 223.0 | 34.4 |
| VT005 | 264907 | 1998844 | 14:23 | 2009.469 | 219.5 | 35.6 |
| VT006 | 268671 | 1997983 | 14:36 | 2007.385 | 221.0 | 34.4 |
| VT007 | 272536 | 1997237 | 14:48 | 2003.566 | 228.5 | 35.0 |
| VT008 | 276280 | 1997049 | 15:03 | 2002.442 | 223.5 | 34.4 |
| VT009 | 279058 | 1999822 | 15:16 | 2003.632 | 230.0 | 36.1 |
| VT010 | 282885 | 2000007 | 15:29 | 2001.730 | 229.0 | 37.2 |
| VT001.B* | 251446 | 1995291 | 16:14 | 2015.150 | 227.0 | 31.1 |

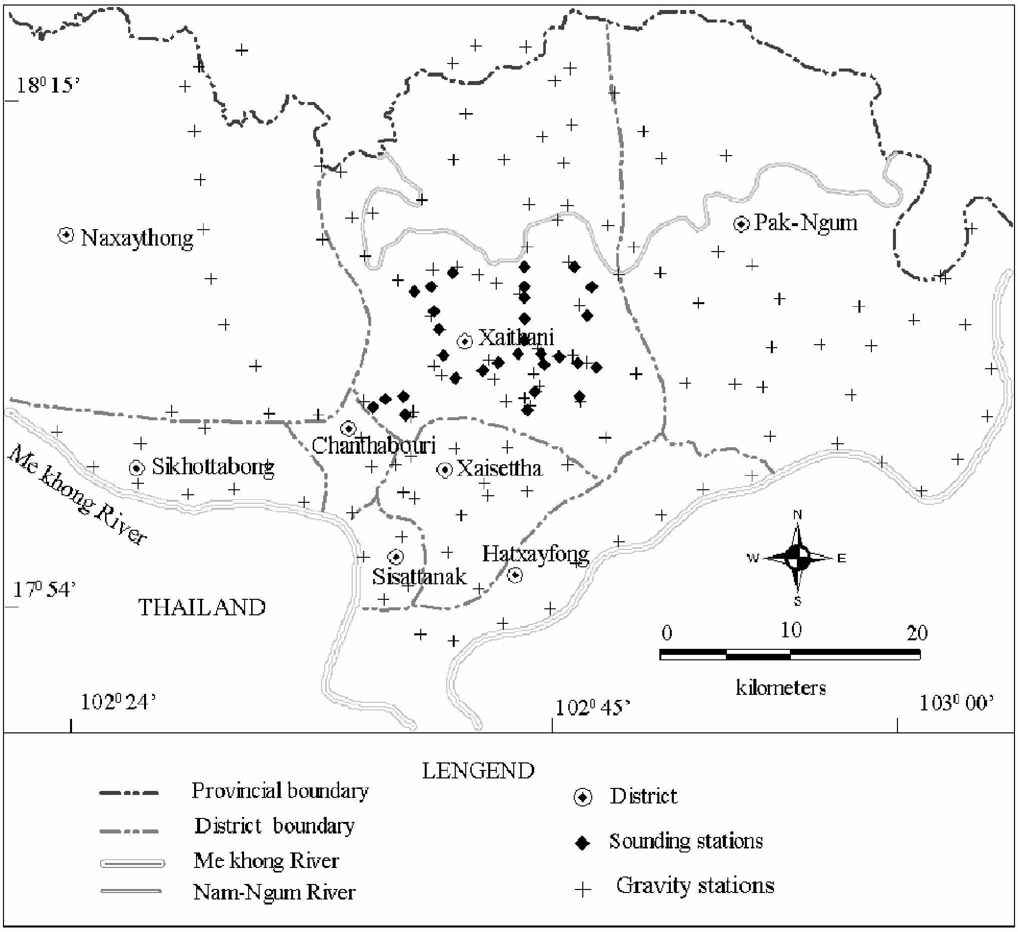


*Figure 2.8* Locations of gravity and sounding stations

Table 2.5: Example of data sheet for average elevation of topography around the gravity station on zones B to E

| STATION: VT 001……..ALTITUDE: 199.5 m ……TOTAL CORRECTION | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| COMPARTMENT | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | |
| ZONE | | | | | | | | | | |
| A | | | | | | | | | | |
| B | ALT. | | | | | | | | | |
| | DIF. | 0 | 0 | 0 | 0 | | | | | |
| | COR. | | | | | | | | | |
| C | ALT. | | | | | | | | | |
| | DIF. | -0.5 | 0 | 0 | 0 | 0 | 0 | | | |
| | COR. | | | | | | | | | |
| D | ALT. | | | | | | | | | |
| | DIF. | -0.5 | -0.5 | -0.5 | 0 | -1 | -1 | | | |
| | COR. | | | | | | | | | |
| E | ALT. | | | | | | | | | |
| | DIF. | -0.5 | -0.5 | -0.5 | 0 | 0 | -1 | -1 | 0 | |
| | COR. | | | | | | | | | |

## 2.4. Data processing

### 2.4.1. Electrical resistivity data processing and interpretation

Electrical resistivity data were processed and interpreted by using a personal computer and RESIST-87 program. The aim of this processing and interpretation is to determine a resistivity model of the ground beneath a sounding point, e.g. number of ground layer, their resistivity and thicknesses. The procedures are as follows:

1. Input observed resistivity data and their corresponding half current electrode spacing of a sounding point into the RESIST-87 modeling program.
2. Display resistivity curve of apparent resistivity versus half current electrode spacing in log-log graph. This procedure will allow us to guess an initial resistivity model of the ground, e.g. number of ground layer, resistivity and thickness of each ground layer.
3. Input this initial resistivity model into the RESIST-87 program and let the program compute a calculated resistivity curve.
4. Compare this calculated resistivity curve with the observed resistivity curve. If they are mismatched, modify the resistivity model until they are matched

to each other. The final resistivity model which gives a good match between the calculated and the observed resistivity curves will represent the ground structure at that sounding point.

5. Plot contour maps of apparent resistivity at half current electrode spacing of 1.5, 10, 20, 30, 45, 60, 90, 150, 225, and 350 m in order to monitor horizontal and vertical changes in apparent resistivity of ground.
6. Plot contour maps of true ground resistivity at depths of 0, 5, 10, 15, 20, 40, 60, 80, 100, and 150 m in order to monitor horizontal and vertical changes in true ground resistivity.
7. Correlate the resistivity model of some sounding points with geological log of nearby deep wells in order to determine resistivity of each lithological layer.
8. Plot a contour map of TDS values of water samples obtained from water wells in the study area in order to monitor spatial distribution of groundwater quality in the study area.
9. Delineate area of good quality groundwater in Xaithani district from the above resistivity results.

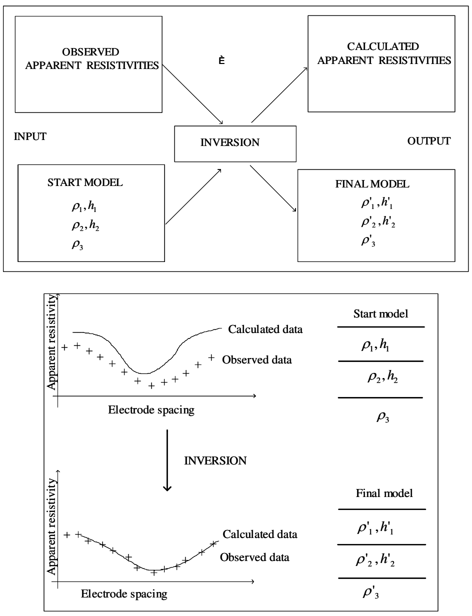


*Figure 2 9* Resistivity curve matching technique for determining resistivity model of the ground at each sounding point

### 2.4.2. Altimeter data processing

Since a barometric altimeter is used for reading the elevation of a gravity point, its reading changes with ambient temperature. Therefore a correction for temperature effect is applied on reading values in order to determine the true altitude of gravity points. The correction is carried out as follows;

1) The corrected elevation difference between n$^{th}$ and $(n+1)^{th}$ gravity stations in a loop of measurement is calculated by the following equation:

$$\Delta H_{n+1}^{TEMP} = \left(h_{n+1} - h_n\right) \times \left\{1 + 0.0036\left[\left(\frac{T_{n+1} + T_n}{2}\right) - 10\right]\right\} \qquad (2.3)$$

Where: $n = 1,2,3,...$

$h_n, h_{n+1}$ are reading elevations of $n^{th}$ and $(n+1)^{th}$ stations in meters

$T_n, T_{n+1}$ are ambient temperatures at $n^{th}$ and $(n+1)^{th}$ stations in degree Celsius.

$\Delta H_{n+1}^{TEMP}$ is relative elevation of $(n+1)^{th}$ station with respect to n$^{th}$ station

2) Temperature corrected elevation of (n+1)$^{th}$ gravity station is then determined from the following equation;

$$H_{n+1}^{TEMP} = \Delta H_{n+1}^{TEMP} + H_n^{TEMP} \qquad (2.4)$$

Where: $n = 1, 2, 3,...$

$H_n^{TEMP}, H_{n+1}^{TEMP}$ are temperature corrected elevation of $n^{th}$ and $(n+1)^{th}$ stations in the loop.

3) In case there is a drift in temperature corrected elevation, a drift correction should be applied as follows;

First determine a drift rate from the temperature corrected elevation of bases at the beginning and the end of a loop with the following equation;

$$Drift = \frac{H_E^{TEMP} - H_B^{TEMP} - (H_E - H_B)}{(t_f - t_i)} \qquad (2.5)$$

Where: $H_B^{TEMP}$ is temperature corrected elevation of station B at the beginning of the elevation measurement loop.

$H_E^{TEMP}$ is temperature corrected elevation of station E at the end of the elevation measurement loop.

$(t_f - t_i)$ is the lapse time of the loop.

$(H_E - H_B)$ is real difference in elevation between stations E and B.

4) The true elevation above mean sea level of n$^{th}$ station in the study area can then be calculated by adding an elevation of 170 m to the drift corrected elevation of n$^{th}$ station as follows;

$$H_n = \left[H_n^{TEMP} - Drift \times (t_n - t_i)\right] + 170\,m \qquad (2.6)$$

Where: $H_n^{TEMP}$ is the temperature corrected elevation of n$^{th}$ station

$t_i$ is the beginning time of the loop

$t_n$ is measuring time of the n$^{th}$ station

$H_n$ is the elevation of the n$^{th}$ station after applying drift correction.

Table 2.6: Example of temperature and drift corrections on elevation data

| Station | Time (hrs) | Reading (m) | $\Delta H_{n+1}^{TEMP}$ (m) | $H_n^{TEMP}$ (m) | $H_n$ (m) |
|---|---|---|---|---|---|
| VT001.B* | 13.05 | 199.5 | 0 | 0 | 170 |
| VT002 | 13.35 | 208.0 | 9 | 4 | 174 |
| VT003 | 13.50 | 214.0 | 16 | 9 | 179 |
| VT004 | 14.07 | 223.0 | 26 | 16 | 186 |
| VT005 | 14.23 | 219.5 | 22 | 9 | 179 |
| VT006 | 14.36 | 221.0 | 23 | 9 | 179 |
| VT007 | 14.48 | 228.5 | 32 | 15 | 185 |
| VT008 | 15.03 | 223.5 | 26 | 7 | 177 |
| VT009 | 15.16 | 230.0 | 33 | 12 | 182 |
| VT010 | 15.29 | 229.0 | 32 | 9 | 179 |
| VT001.B* | 16.14 | 227.0 | 30 | 0 | 170 |

### 2.4.3. Gravity data processing

In general, gravity readings are affected by tides, latitude and elevation of gravity stations, topography of terrain in vicinity of gravity stations, and density variations in the subsurface. Therefore, in order to determine density variation of subsurface structure, effects of tides, latitude and elevation of gravity stations and surrounding terrain should be removed from the observed gravity value (Telford *et al*., 1990) as follows;

1) Convert gravimeter reading of each gravity station into observed gravity in milligals with the following equation;

$$g_{mgal} = C + (R - A) \times B \tag{2.7}$$

Where: R is gravimeter reading.

$g_{mgal}$ is observed gravity in milligals.

A, B and C are constants corresponding with gravimeter reading range as shown in Table 2.7.

Table 2.7: Conversion constants for Lacoste & Romberg gravimeter model G-565

| Gravimeter reading range | A | B | C |
|---|---|---|---|
| 1900 to 1999.999 | 1900 | 1.01891 | 1934.71 |
| 2000 to 2099.999 | 2000 | 1.01901 | 2036.61 |
| 2100 to 2199.999 | 2100 | 1.01910 | 2138.51 |

2) Calculate drift rate of observed gravity in every loop of gravity by the following equation;

$$Drift = \frac{g_E^f - g_B^i - (g_E - g_B)}{(t_f - t_i)} \tag{2.8}$$

Where:

$g_B^i$ is observed gravity of station B at the beginning of the gravity measurement loop.

$g_E^f$ is observed gravity of station E at the end of the gravity measurement loop.

$(t_f - t_i)$ is the lapse time of the loop.

$(g_E - g_B)$ is real difference in gravity value between stations E and B.

3) Calculate drift corrected gravity value of every gravity station within a loop of gravity measurement by following equation. An example of drift correction is shown in Table 2.5 and Appendix A1.

$$g_n^{drift} = g_n - Drift \times (t_n - t_i) \tag{2.9}$$

Where:

$g_n$ is observed gravity value at n$^{th}$ station.

$t_i$ is beginning time of a gravity loop.

$t_n$ is measuring time at the n$^{th}$ station.

$g_n^{drift}$ is drifted corrected gravity value at the n$^{th}$ station

Table 2.8: Examples of drift correction of observed gravity data

| Station | Time (hrs) | Reading | $g_n$ (mgal) | $g_n^{drift}$ (mgal) |
|---|---|---|---|---|
| VT001.Base | 13.05 | 2014.965 | 2051.86 | 2051.86 |
| VT002 | 13.35 | 2016.096 | 2053.01 | 2052.98 |
| VT003 | 13.50 | 2015.160 | 2052.06 | 2052.01 |
| VT004 | 14.07 | 2012.280 | 2049.12 | 2049.06 |
| VT005 | 14.23 | 2009.469 | 2046.26 | 2046.18 |
| VT006 | 14.36 | 2007.385 | 2044.14 | 2044.04 |
| VT007 | 14.48 | 2003.566 | 2040.24 | 2040.14 |
| VT008 | 15.03 | 2002.442 | 2039.10 | 2038.98 |
| VT009 | 15.16 | 2003.632 | 2040.31 | 2040.18 |
| VT010 | 15.29 | 2001.730 | 2038.37 | 2038.23 |
| VT001.Base | 16.14 | 2015.150 | 2052.05 | 2051.86 |

4) Latitude correction

Because the best approximation in the shape of the earth is an ellipsoid of revolution with an equatorial radius (6378 km) which is about 20 km greater than the polar radius, therefore gravity on the earth surface increases with latitude. The variation of gravity with latitude over the surface of an ellipsoidal earth can be expressed in the form (Griffiths and King, 1981)

$$g = g_0(1 + C_1 \sin^2\phi - C_2 \sin^2 2\phi) \tag{2.10}$$

Where: $g_0$= 9.780318 m/s$^2$ is the value of gravity on the equator

$\phi$ is latitude in degree

$C_1 = 0.0053024$ , $C_2 = 0.0000058$

At latitude $\phi$, the latitude correction in north-south direction is

$$\Delta g = 0.081 \sin(2\phi) \quad \text{g.u./10 m} \tag{2.11}$$

This correction should be subtracted from the observed gravity if the gravity station is to the north of a reference station or a fixed base station and vice versa.

5) Elevation correction

5.1 Free-air correction:

Since gravity varies inversely with the square of distance, a difference in observed gravity between any two stations of different elevations partly attributes to difference in their observed gravity value. A correction called free-air correction will be applied to the observed gravity in order to reduce its value to a value at a datum plane, often the sea level. The free-air correction does not account for materials between the station and datum plane (Telford *et al.*, 1990). The free-air correction is calculated from the following equation;

$$FAC = 3.072 \times h \quad \text{(Parasnis, 1997)} \tag{2.12}$$

$h$ is the elevation of the gravity station above the datum plane. This correction is added to the observed gravity when the station is above the datum plane and vice versa.

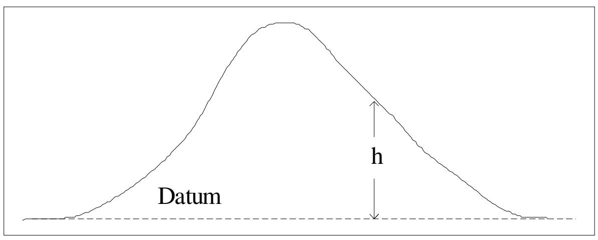


*Figure 2.10* The free-air correction for an observation at a height ($h$) above datum (modified from Kearey *et al.*, 2002)

5.2. Bouguer correction:

Bouguer correction accounts for the attraction of material between the station and datum plane that was ignored in the free-air calculation (Telford *et al.*, 1990). The Bouguer correction (Parasnis, 1997) is calculated by the following equation;

$$BC = 0.0004191 \times \rho \times h \tag{2.13}$$

$\rho$ is the average density of the rocks underlying the survey area. This correction is subtracted from the observed gravity when the gravity station is above the datum plane and vice versa.

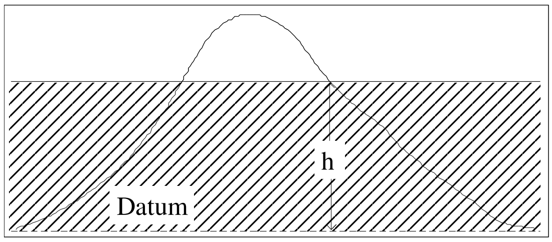


*Figure 2.11* The Bouguer correction. The shaded region corresponds to an infinity rock slab of thickness $h$ (modified from Kearey *et al.*, 2002)

6) Terrain correction.

Terrain correction accounts for gravity effects of topography in vicinity of gravity stations. The terrain correction is positive regardless of whether the surrounding topography is a mountain or a valley (Kearey *et al*, 1981). In terrain correction, the surrounding area of a gravity station is divided into zones and compartments. A zone is an area bounded by two circles of which common center of circles are at a gravity station and a zone consists of many compartments, says n. The parameters of a zone are shown in Table 2.9 and the terrain correction of each compartment is then calculated from the following equation;

$$TC = 0.0004191 \times \left(\frac{\rho}{n}\right) \times \left\{ r_2 - r_1 + \left(\sqrt{r_1^{\ 2} + z^2}\right) - \left(\sqrt{r_2^{\ 2} + z^2}\right) \right\} \tag{2.14}$$

$TC$ is terrain correction in g.u. of each compartment. $\rho$ is density of rock in kg/m$^3$. $n$ is the number of compartments in a zone. $r_1$ *and* $r_2$ are inner and outer radii of circles which bound a zone in m. z is a difference between elevation of gravity station and an average elevation of a compartment in meters.

Table 2.9: Terrain correction values of zone B to E

| Zone | Inner radius (m) | Outer radius (m) | Number of sector |
|---|---|---|---|
| B | 2.0 | 16.6 | 4 |
| C | 16.6 | 53.3 | 6 |
| D | 53.3 | 170.1 | 6 |
| E | 170.1 | 390.1 | 8 |

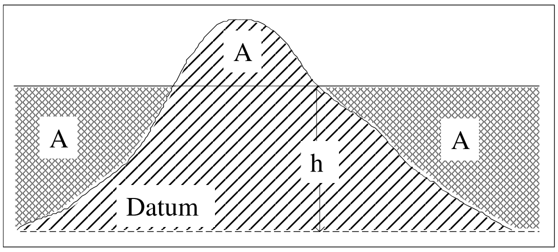


*Figure 2.12* The Terrain correction (modified from Kearey *et al.*, 2002)

The terrain correction of a zone will be the sum of terrain correction of compartments within that zone and the total terrain correction for a gravity station will be equal to the sum of terrain corrections of every zone around the gravity station as shown in the following equation and in Table 2.10.

$$TC = TC_B + TC_C + TC_D + TC_E \qquad (2.15)$$

$TC$ is total terrain correction of a gravity station. $TC_B, TC_C, TC_D, TC_E$ are terrain corrections of zone B, C, D, and E respectively.

7) Bouguer anomaly

All known gravitational effects which do not related to the subsurface density variations will be removed from the observed gravity. The remaining is called Bouguer anomaly representing gravity anomaly (Griffiths and King, 1981). Its calculation is shown in the following equation and Table 2.11.

$$BA = g_{obs} - \Delta g_L + FAC - BC + TC \qquad (2.16)$$

$g_{obs}$ is observed gravity, $\Delta g_L$ is latitude correction, $FAC$ is free-air correction, $BC$ is Bouguer correction and $TC$ is terrain correction.

Table 2.10: Example of gravity values due to elevation of topography

| STATION:VT 001, ALTITUDE: 199.5 m…TOTAL CORRECTION: 0.003 | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Compartment | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | |
| ZONE | | | | | | | | | | |
| A | | | | | | | | | | |
| B | ALT. | | | | | | | | | |
| | DIF. | 0 | 0 | 0 | 0 | | | | | |
| | COR. | 0 | 0 | 0 | 0 | | | | | 0 |
| C | ALT. | | | | | | | | | |
| | DIF. | -0.50 | 0 | 0 | 0 | 0 | 0 | | | |
| | COR. | 0.001 | 0 | 0 | 0 | 0 | 0 | | | 0.001 |
| D | ALT. | | | | | | | | | |
| | DIF. | -0.50 | -0.5 | -0.5 | 0 | -1 | -1 | | | |
| | COR. | 0.00 | 0.0 | 0.00 | 0 | 0.001 | 0.001 | | | 0.002 |
| E | ALT. | | | | | | | | | |
| | DIF. | -0.50 | -0.5 | -0.5 | 0 | 0 | -1 | -1 | 0 | |
| | COR. | 0.00 | 0.0 | 0.00 | 0 | 0 | 0.000 | 0.00 | 0 | 0.000 |

Table 2.11: Examples of Absolute Bouguer gravity anomaly

| Station | $g_{obs}$ (g.u) | $\Delta g_L$ (g.u) | FAC (g.u) | BC (g.u) | TC (g.u | BA (g.u) |
|---|---|---|---|---|---|---|
| VT001 | 0.0 | 0.0 | 522.2 | 178.1 | 0.2 | 344 |
| VT002 | 11.5 | 15.9 | 536.0 | 182.8 | 0.0 | 349 |
| VT003 | 2.0 | 21.2 | 548.8 | 187.2 | 0.0 | 342 |
| VT004 | -27.4 | 21.2 | 570.6 | 194.6 | 0.0 | 327 |
| VT005 | -56.0 | 21.2 | 551.1 | 187.9 | 0.0 | 286 |
| VT006 | -77.3 | 15.9 | 549.8 | 187.5 | 0.1 | 269 |
| VT007 | -116.2 | 10.6 | 569.0 | 194.1 | 0.1 | 248 |
| VT008 | -127.6 | 10.6 | 545.0 | 185.9 | 0.1 | 221 |
| VT009 | -115.5 | 26.6 | 560.5 | 191.2 | 0.0 | 227 |
| VT010 | -134.9 | 26.6 | 522.2 | 178.1 | 0.2 | 202 |

8) Plot Bouguer contour map of the study area with the Surfer program using the following parameters; 1,000 meters grid spacing and kriging gridding technique.

9) Select five west-east gravity profiles, namely; AA' ($17^{o}58'$N and $102^{o}21'$E to$103^{o}00'$E), BB' ($18^{o}02'$N and $102^{o}21'$E to$103^{o}00'$E), CC' ($18^{o}07'$ N and $102^{o}21'$E to$103^{o}00'$E), DD' ($18^{o}12'$ N and $102^{o}21'$E to$103^{o}00'$E), and EE' ($18^{o}16'$N and $102^{o}21'$E to$103^{o}00'$E) for gravity modeling.
10) The gravity modeling of Vientiane basin was carried out with GeoVista AB-Gravity and Magnetic modeling program (GMM) version 1.31. This is a program which calculates a gravity response of 2.5D model body of polygonal cross-section.

## 2.5. Density of rock samples determination

The classic method of density determination involves the principle of Archimedes, namely that, the loss in the weight of the body when it is totally immersed in a liquid is equal to the weight of the liquid displaced by the body.

If $W_{air}$ and $W_{water}$ are the weights in the air and water, the loss of weight is $W_{air} - W_{water} = V \cdot \rho_{water}$. V is the volume of the body and the density of water ($\rho_{water}$) is equal to 1.

The procedure of determination density of rock sample was performed in laboratory, as follows:

1) The rock sample is prepared and its weight is not more than 3.1 kg. The sample must be clear from loosening parts.
2) Place a scale on a stable table and adjust its leveling. Place a plastic bowl on the scale and zero the reading. Put a rock sample in the bowl and record the reading of the scale. This reading is the weight of the rock sample in the air, $W_{air}$.
3) Tie a net with the bottom hook of the scale and zero the scale reading. Put the rock sample in the net and totally immerse the net with rock sample inside in a water tub. Record the reading of the scale. This reading is the weight of rock sample in water, $W_{water}$.
4) The density of the rock sample ($\rho_{rock}$) can be calculated from the following equation;

$$\rho_{rock} = \frac{W_{air}}{(W_{air} - W_{water})} \cdot \rho_{water} \qquad (2.17)$$

Table 2.12: Example of data sheet for density measurement of rock samples

| Site No | Weight in air (g) | Weight in water (g) | Density (g/cm$^3$) |
|---|---|---|---|
| A01 | 1,556.80 | 928.50 | 2.48 |
| A02 | 1,551.80 | 912.70 | 2.43 |
| A03 | 2,645.00 | 1,563.70 | 2.45 |
| A04 | 3,076.10 | 1,844.30 | 2.50 |
| A05 | 2,443.20 | 1,445.70 | 2.45 |
| A06 | 1,692.90 | 1,012.30 | 2.49 |
| A07 | 1,240.10 | 753.20 | 2.55 |
| A08 | 1,309.50 | 795.40 | 2.55 |