CHAPTER 5

RESULTS AND INTERPRETATION

Several experiments were performed with mixed specimens of 25, 50, and 100% leachate solution and the four types of sediment samples. As the degree of saturation of the samples progressed from partially saturated to fully saturated, the variation of resistivity value were measured. The resistivity results were then fitted with Archie's equation to derive the mathematical relationship between the resistivity and saturation degree. The complete results in graphical form are presented in this chapter, along with an example of how to use the mathematical relation for quantitative interpretation of the results.

5.1 Resistivity of saturated samples

Archie's experiment (Archie, 1942) demonstrated that the resistivity of a saturated material (bulk resistivity) is proportional to the resistivity of the pore fluid. This constant of proportionality is termed the formation resistivity factor F. The formation factor can be obtained by plotting the bulk resistivity against the resistivity of the pore fluid.

$$F = \frac{\rho_{bulk}}{\rho_{fluid}} = a\varphi^{-m} \tag{5.1}$$

$$\frac{\log F}{\log \varphi} = -am \tag{5.2}$$

By applying the porosity of the sediment (obtained from the physical properties of the soil, see Chapter 4), the constants a and m can be obtained from

Equation 5.2. The calculated values of *a* and *m* for each sediment sample used in this experiment are included in Table 5.1.

The resistivity values measured with the sample saturated with 25%, 50%, and 100% leachate are plotted against the resistivity of the leachate solution (1.64, 0.86, and 0.45 ohm-m). The resulting graph (Figure 5.1) shows that the formation factor (F) of sand, clayey sand, sandy clay and clay are equal to 2.90, 5.77, 7.85 and 7.50, respectively. This data from the fully saturated sediments show an increase in bulk resistivity with increasing pore fluid resistivity in a linear relationship.

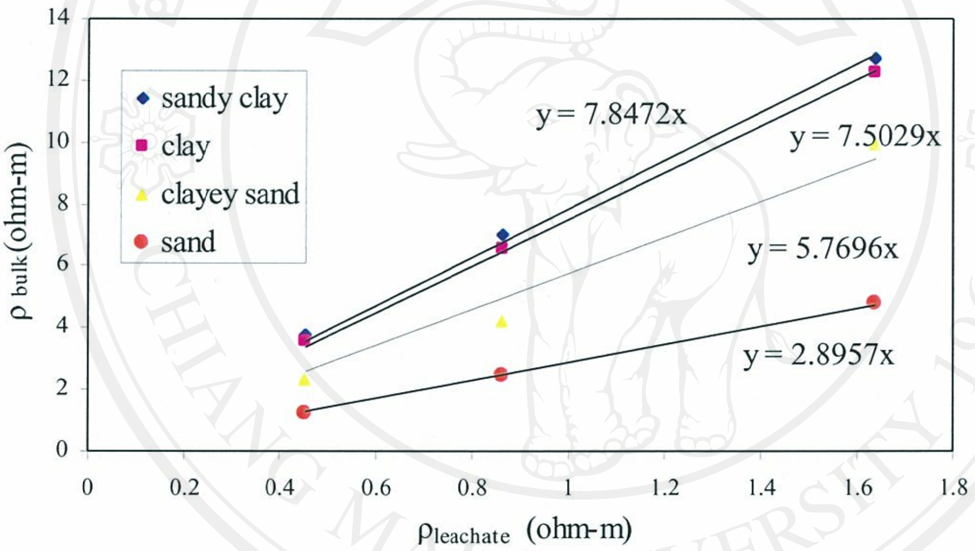

Figure 5.1 The bulk resistivity versus the resistivity of saturating leachate in four fully saturated sediment samples.

In a perfectly insulating matrix, the resistivity of a saturated rock is expected to increase linearly with resistivity of the pore fluid. For a porous medium where the matrix does not contribute to the conduction of electricity, the linear relationship is valid at all electrolyte salinities. But if the matrix is conductive, Archie's equation will only be valid at high pore-liquid salinities (Archie, 1942).

A study of sandstone in electrolytic pore fluid (Taylor and Barker, 2006), suggested that if the resistivity of pore fluid is too high, this linear relationship will not hold. The author's experiment with low salinity fluids (see Chapter 4) likewise found a non-linear relationship. It was found in several tests that at low salinity (such as 2.5% leachate, tap water, rain water and normal water), there is a marked departure from the Equation 5.1 and the formation factor F, is not a constant.

For the high-salinity leachate solution, Archie's equation held and obtained a reliable set of four constants that coincide with the sediment's characteristics as shown in Table 5.1.

Table 5.1 The product of pore geometry factor *a* and cementation factor *m* calculated from the formation factor.

Sediment	% leachate	ρ_{fluid} (ohm-m)	ρ_{bulk} (ohm-m)	Porosity (φ)	F	$\frac{\log F}{\log \varphi} = -am$
Sand	25	1.64	4.80	0.4902	2.90	-1.49
	50	0.86	2.45			
	100	0.45	1.2			
Clayey sand	25	1.64	9.92	0.3611	5.77	-1.63
	50	0.86	4.23			
	100	0.45	2.36			
Sandy clay	25	1.64	12.70	0.3409	7.85	-1.92
	50	0.86	6.97			
	100	0.45	3.76			
Clay	25	1.64	12.22	0.4065	7.50	-2.24
	50	0.86	6.55			
	100	0.45	3.54			

Note that the product of cementation factor *m* and pore geometry factor (*a*) cannot be determined separately. These parameters are not fully established yet how are they related to the electrical properties of the rock.

Though, Archie's law ignores the effect of pore geometry *a*, a reasonable approximation of *a* is needed. For most carbonates and highly cemented sands *a* is about 1(Asquith and Gibson, 1983). However, in reality, *a* can vary between 0.5 to 2.5 depending on the amount of compaction and the structure of pores. The value of the cementation factor *m* is about 1.5 for sediments with perfectly spherical grains, and about 2 for sediments with subspherical grains, as a rough estimation m increases as the angularity of the grains increases.

However these estimates of *a* and *m* are insufficient Tao and Yue (2004) recently studied the effects of matrix-pore geometry, pore-filling electrolyte and clay contents on Archie's parameters *a, m* and *n* with 2-D Lattice Gas Atomic. They suggested that the parameter *m* is not a measure of the pore structure complexity, but of rather a measure of porosity complexity. Therefore, the parameter *m* is not constant, but a function of porosity and clay content and the parameter *a* increases with an increase of clay content.

5.2 Results of partially saturated samples

In case of partially saturated sediment, a decrease in saturation will be accompanied by a marked increase in its resistivity. This being due to a replacement of the electrolyte with infinitely resistive air. Relationships, based on theoretical models where partial saturation exists, require the use of a complex component, the saturation index (n).

An empirical relationship between bulk resistivity, the resistivity of the pore-liquid saturating the rock and the porosity of the rock is (Archie, 1942)

$$\rho_{bulk} = \rho_{fluid} a \varphi^{-m} S_w^{-n} \tag{2.1}$$

To investigate the effects of the saturation degree of the soil on resistivity values, the pores of four sediment samples were filled with known volumes of fluid to obtain a certain saturation degree, and the resistivity was measured. Then more fluid was added to increase the saturation degree, and the resistivity was measured again. This was repeated until the sample was fully saturated.

There were consistent trends in resistivity with increasing saturation degree and leachate concentrations for the four types of sediment. In all cases, the resistivity of the sample decreased as the saturation degree and leachate concentration increased. The electrical resistivity of the sediment is inversely correlated to the saturation degree as indicated by Archie's equation (Equation 2.1).

The data from experiments with partially saturated sediment produced a good fit to Equation 2.1 and the resulting curve produced the saturation exponent *n*. The resistivity measurements of sand, sandy clay, clayey sand and clay were done on three various concentrations of leachate at a variety of saturation indices as shown in Figures 5.2, 5.3, 5.4 and 5.5.

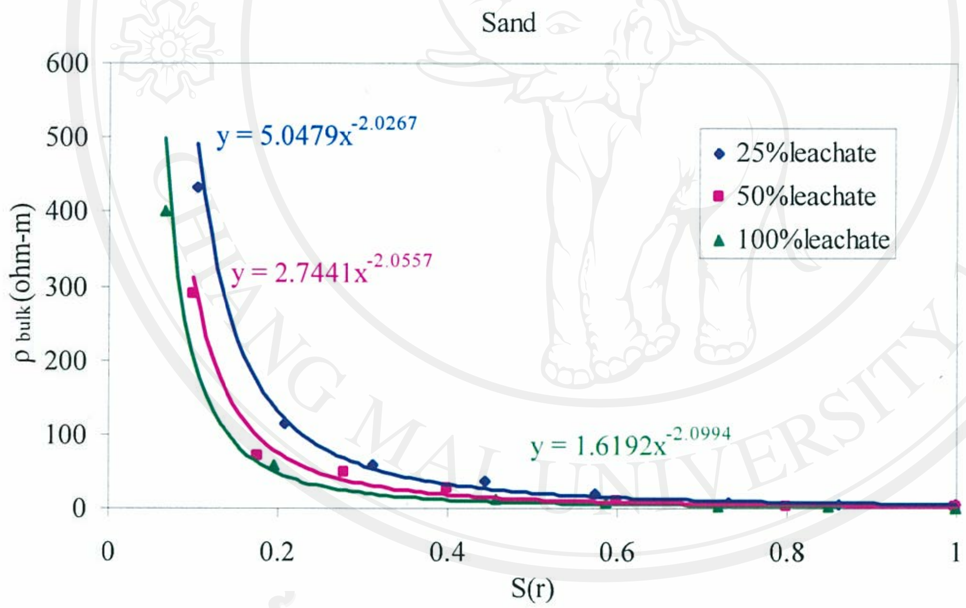

Figure 5.2 Variation of electrical resistivity with degree of saturation for different concentrations of leachate in partially saturated sand sample.

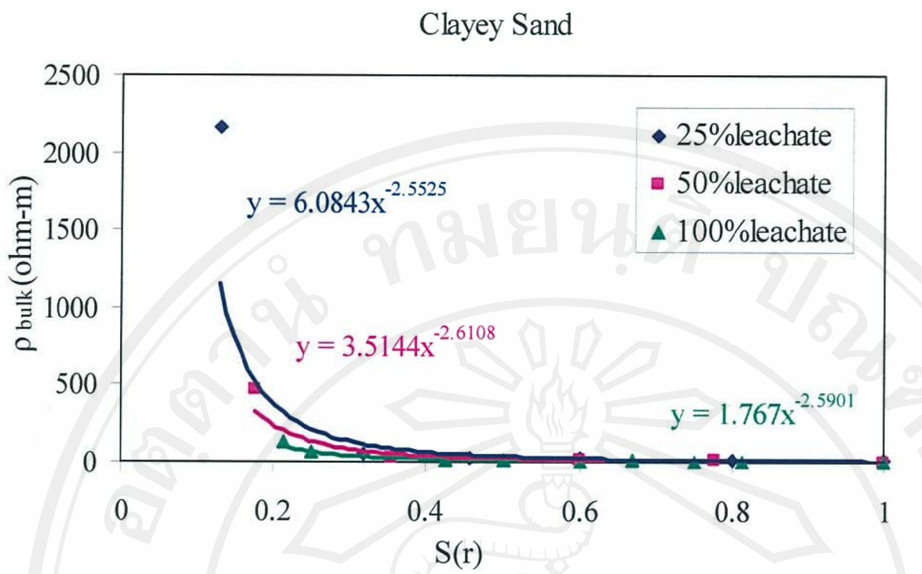

Figure 5.3 Variation of electrical resistivity with degree of saturation for different concentrations of leachate in partially saturated clayey sand sample.

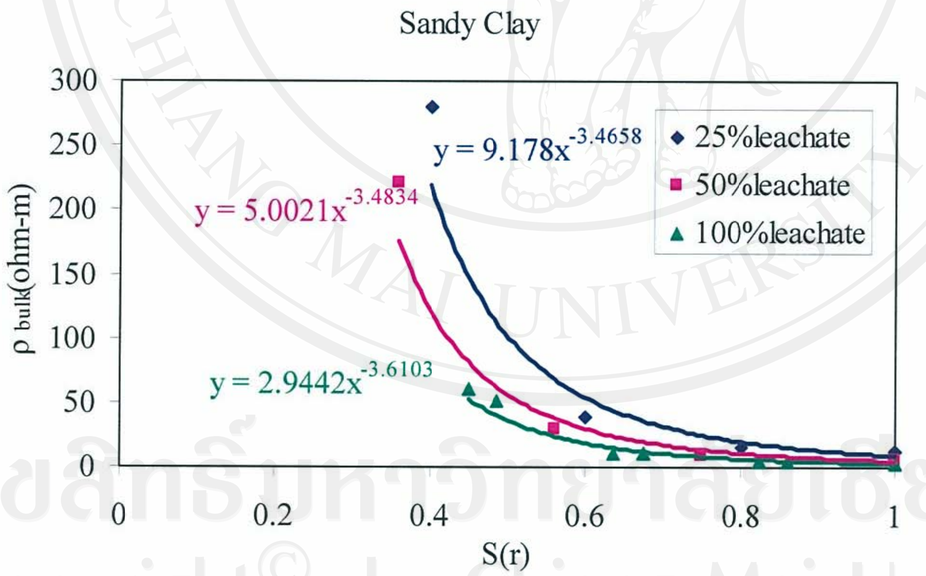

Figure 5.4 Variation of electrical resistivity with degree of saturation for different concentrations of leachate in partially saturated sandy clay sample.

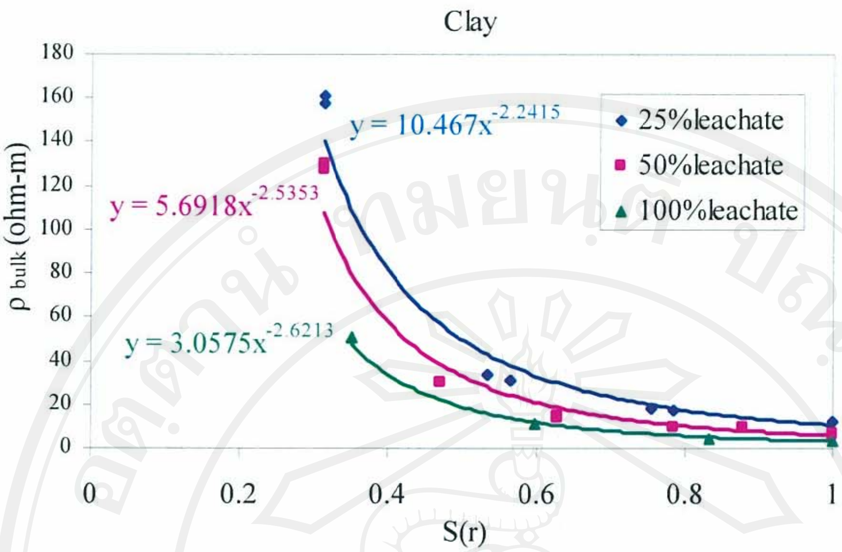

Figure 5.5 Variation of electrical resistivity with degree of saturation for different concentrations of leachate in partially saturated clay sample.

In certain types of sediment, using each of the solutions results gained one value for saturation exponent (*n*). The saturation exponent for each soil was derived by averaging the 3 values of n using three concentrations of solution in the pores. For sand, clayey sand, sandy clay and clay, the saturation exponent are 2.06, 2.58, 3.52, 2.46 respectively. This indicates that the value of n is increasing, as the percentage of the conductive matrix in the soil sample increased.

According to the grain size analysis (see Chapter 4), sandy clay sample has a higher percentage of clay than in the clay sample, but also a higher percentage of sand and less in total proportion of fine particles, so it was named as sandy clay. While clay sample have more percent of fine particles though have a bit smaller amount of clay particles than in sandy clay sample, this may considered as silty clay or mud, but it got the name clay after the categorize done by WADIS Project.

The value of n must be greater if the sample contains more conducting matrix, as determined by the physical and chemical analysis of the sediment (see Chapter 4). Because the sandy clay sample has a higher percentage of conductive heavy minerals and also a higher percentage of clay minerals, the measured saturation exponent of the sandy clay sample differed from the other samples by up to an order of magnitude.

Archie (1942) found that for clean unconsolidated or consolidated sand, the value of *n* is to be approximately 2. My results were similar: they were arrived at an average *n* value for sand of 2.06.

Additionally, a log-log plotting of resistivity against degree of saturation for the four types of sediment, at 3 different leachate concentrations had been done as show in Figure 5.6, Figure 5.7 and Figure 5.8. In all concentrations of leachate, clay-rich samples tend to have a higher resistivity especially in partially saturated samples. The steep slopes of the plots for clay-rich samples indicates that clay is very sensitive to changes in the degree of saturation; just small decreasing of saturation degree can cause a big change in the resistivity value of clay.

In contrast, in fresh water, clay rich sediment always has a lower resistivity than sand. But this experiment shows that when contaminated with a highly saline solution, clay-rich sediment has a higher resistivity than similarly contaminated sandy sediment.

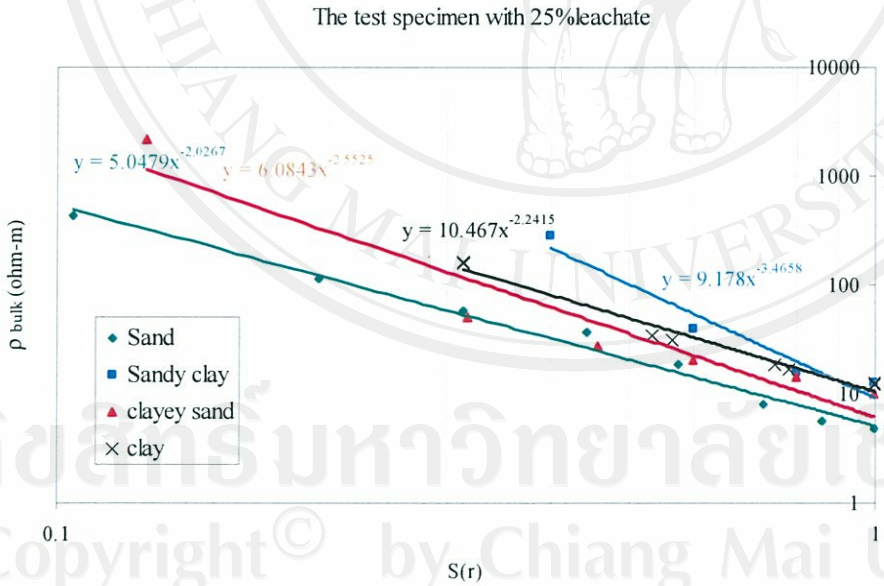

Figure 5.6 The resistivity variations of the test specimens in 25% leachate versus degree of saturation.

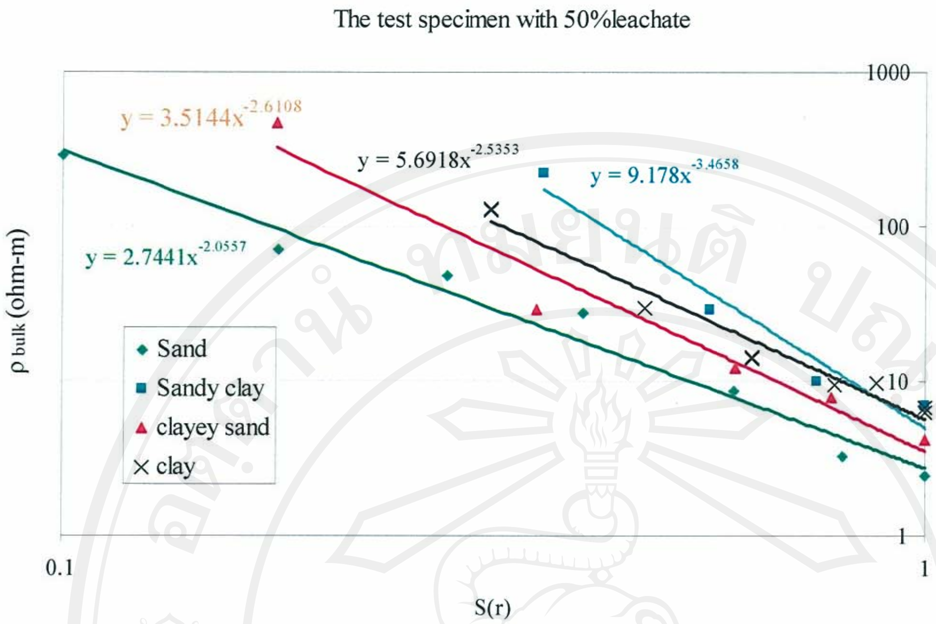

Figure 5.7 The resistivity variations of the test specimens in 50% leachate versus degree of saturation.

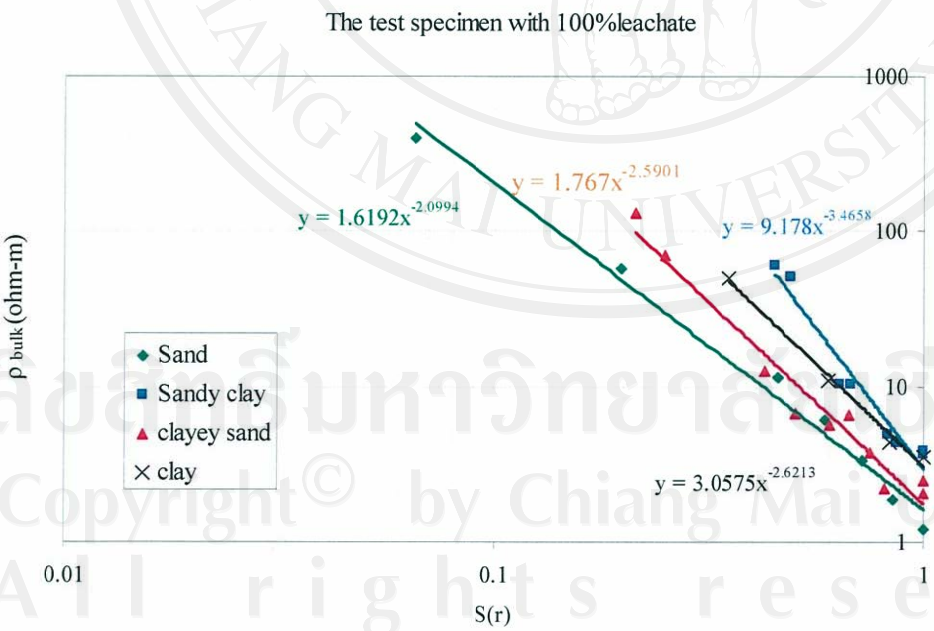

Figure 5.8 The resistivity variations of the test specimens in 100% leachate versus degree of saturation.

5.3 Interpretation

In order to correlate the resistivity measurement results from the laboratory to the data from the field investigation it is first necessary to consider the field data. The electromagnetic map (Figure 1.1) reveals that the lateral variation of resistivity, given a high frequency survey of an area with low resistivity, and given a coil separation of 40 m; the information depth is likely reduced to about 10 m. This depth is also confirmed by the two dimensional resistivity profiles (Figure 5.9).

From this resistivity investigation, there are 2 interesting observations, first the high range of resistivity value were found to be in the contaminated prospect area which according to the groundwater flow direction, is the southern part of the landfill. The general direction of groundwater flow is probably in Northwest-Southeast direction(Karnchawong and Kootatep, 1993) Second, the low resistivity values appears in the area upstream of the landfill, which would seem to make it impossible for the pollutants from the landfill to migrate in that direction. Therefore, the leakage flow from the waste dump suggested by Grissemann (2004) can not be confirmed. This study even suggests that the low resistivity that exists in northern part of landfill could be influenced by a nearby animal husbandry.

Result from this experiment may be used reinterpretation these data. To make this reinterpretation, the study area was divided into 3 zones. The first zone is in the northern part of landfill, which has a low range of resistivity values of about 4-26 ohm-m; the second zone is in the eastern part of the landfill with medium resistivity values of about 16-25 ohm-m, and the third zone is in the southern part of the landfill, which is the suspected area of contamination, but has the highest resistivity of about 40-50 ohm-m.

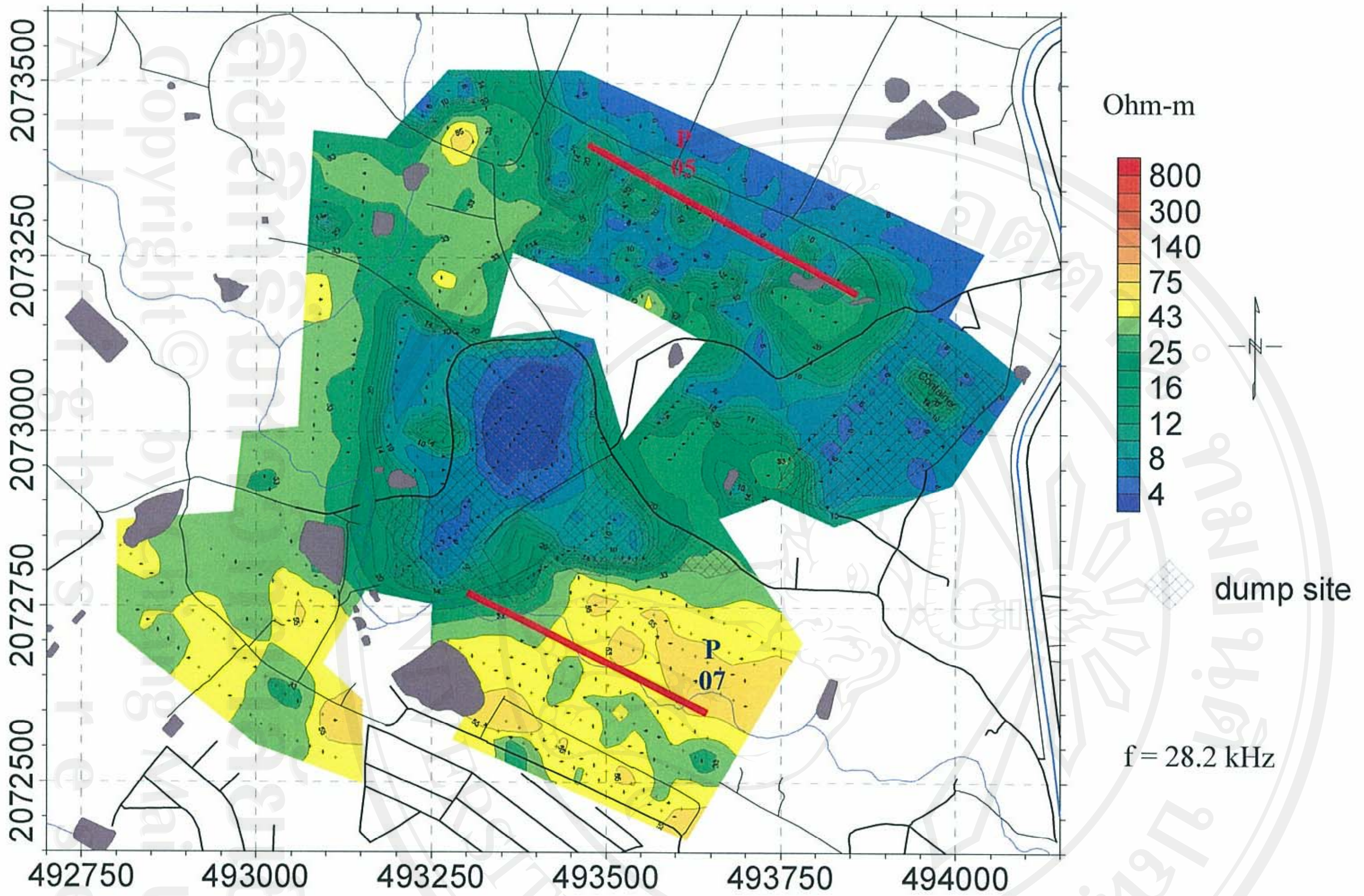

Figure 1.1 Electromagnetic resistivity map of the Mae-Hia landfill, using a horizontal loop with a separation of 40 m, and a frequency of 28.2 kHz (modified from Grissemann *et al*., 2004).

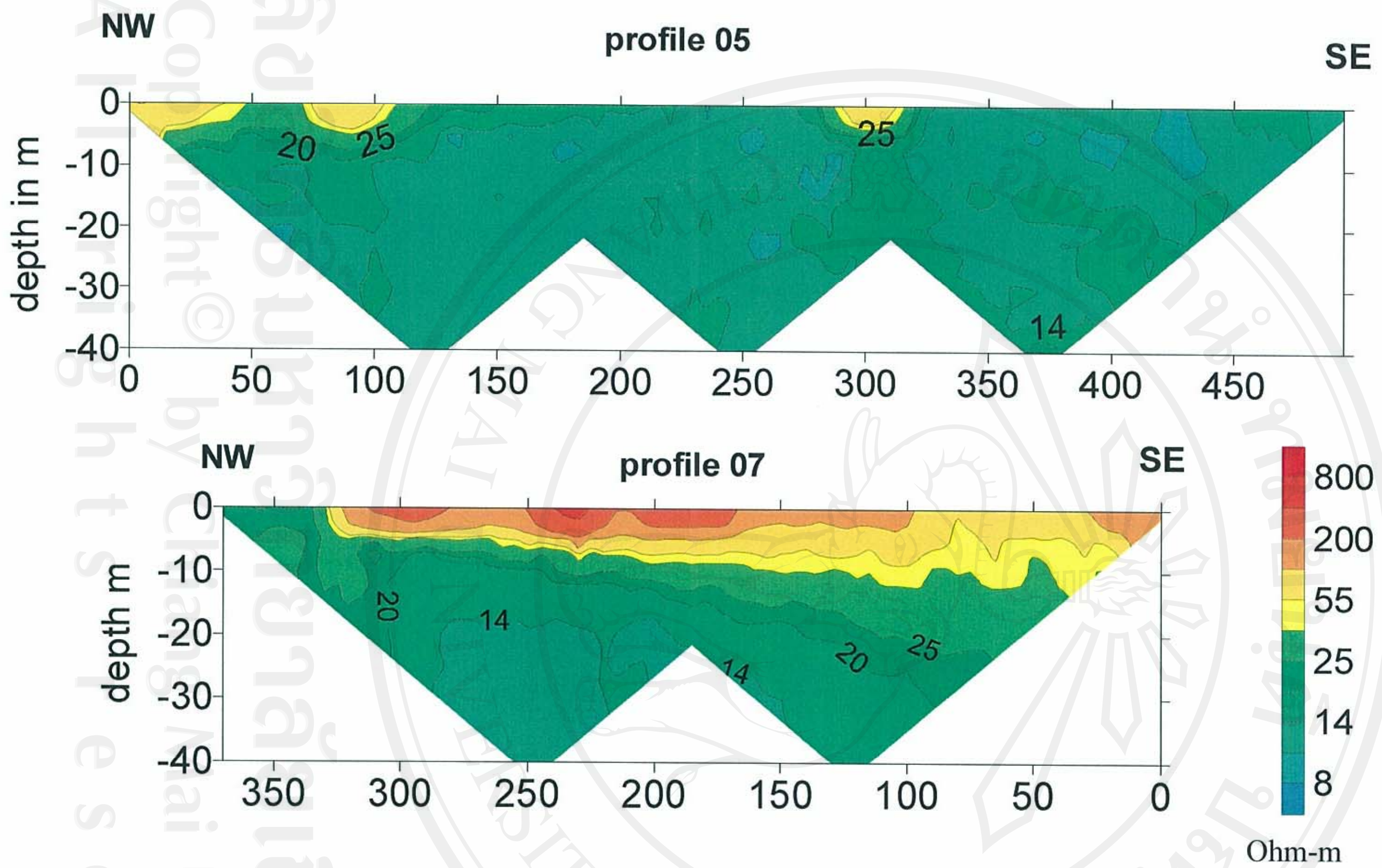

Figure 5.9 Mae-Hia 2D resistivity section of profile P05 and P07, using a Wenner configuration with a spacing of 5 m (Grissemann *et al*., 2004).

To correlate the laboratory data to the field data, the sediment type and the saturation degree of the sediment must be matched. The lithology study of the area by the Thai-German Research project (WADIS), the entire disposal area is located on impermeable, clay rich substratum, with interfingering of clay-bearing colluvium and sandy alluvium. The lithology of the three divided zones of different resistivity range were catagorized, by using the drill cutting data of borehole in Mae-Hia area given by Radschinski(2005). Figure 5.10 shows the lithology of 4 boreholes in the southern part of Mae-Hia landfill, which are clay down to a depth of 10 m. Figures 5.10 and 5.11 shows that the lithology of the southern and eastern part of Mae-Hia landfill, down to 10 m, is also clay–rich sediment. However, the eastern part contains more sand and gravel mixed in with the clay. My own observations in the field confirmed this. The southern part of landfill is silty clay; and the clay samples use in the laboratory were collected here.

The northern part of the landfill is more complicated, how the area has not been explored in detail because it is upstream from the landfill. The sediment here consists of gravelly sand and gravelly clay, although the electrical behavior of gravelly sediment is difficult to understand.

To simplify the interpretations, it was assumed that, 1) clay sediment is the main constituent of the southern area, 2) sandy clay underlies the eastern area, and 3) the northern area could be sand or clay or a mix of the two, so there were two interpretations as if they are clay and sand.

Next, some assumptions about the degree of saturation of each sediment at a depth of 10 m must be made. According to a previous study (Iamboon, 2002), the water table level of this area is at a depth of 3-9.55 m with the main aquifer at depths of 7-30 m. As seen in Figure 5.9, a resistivity profile of P05 and P07, the level of the water table in the area varies considerably. As seen in the profiles, this can be interpreted that the water table on the west side of the landfill is higher than in the east side. The elevation of water level can be between 9 m to 26 m from the ground surface. While the water table in the northern part of the landfill is only 0.5-8 m below the surface, higher than in the southern part of the landfill, with a gradual changing elevation compare to the eastern and western parts. These interpretations are supported by the resistivity sounding surveys of Yordkhayun (2001).

So they were assumed that 1) saturation degree of the northern part of landfill is 1 because the water table is above a depth of 10 m, the level of this investigation, and 2) the saturation degree of the southern and eastern parts of landfill are partially saturated at a depth of 10 m; without capillary effects the saturation degree is at its field capacity which are 0.96 for sandy clay and 0.76 for clay.

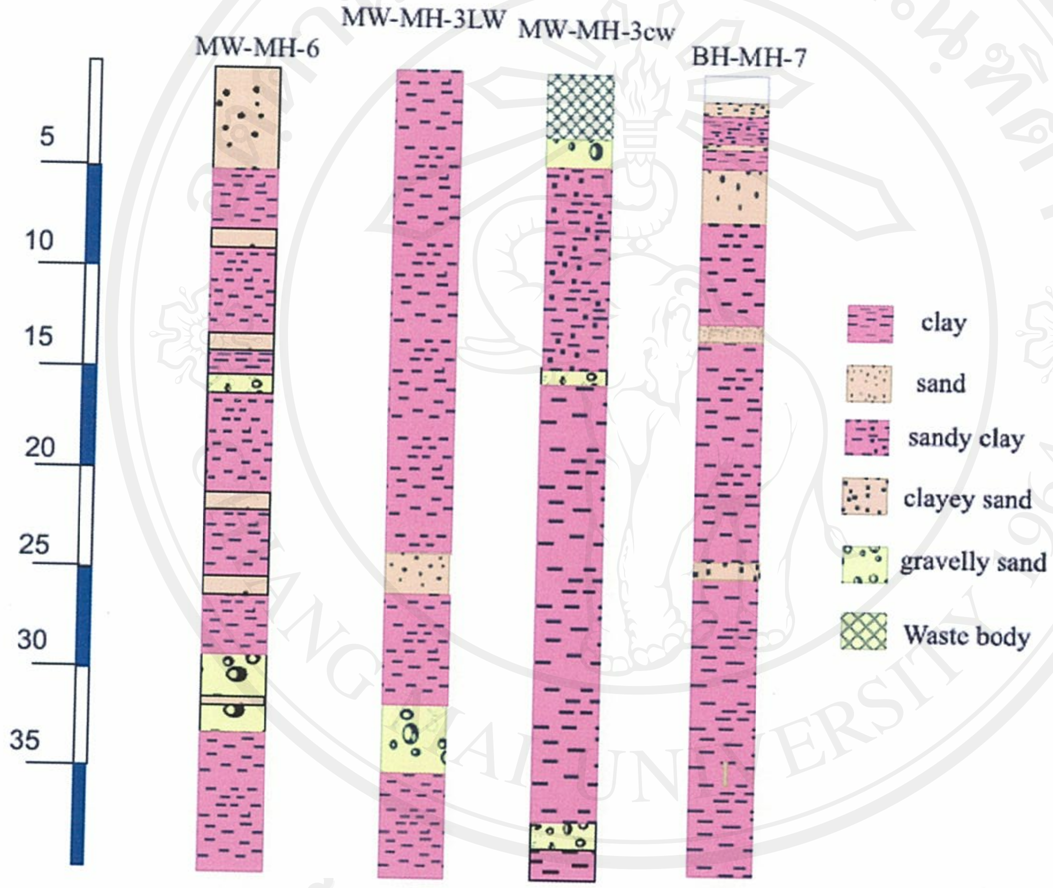

Figure 5.10 Logs of borehole in the southern part of Mae-Hia landfill (depth from ground surface in m) (modified from Radschinski, 2005).

Note: Although these logs extend to a depth of 35 m, they are presented for comparison of the sediment types in the area.

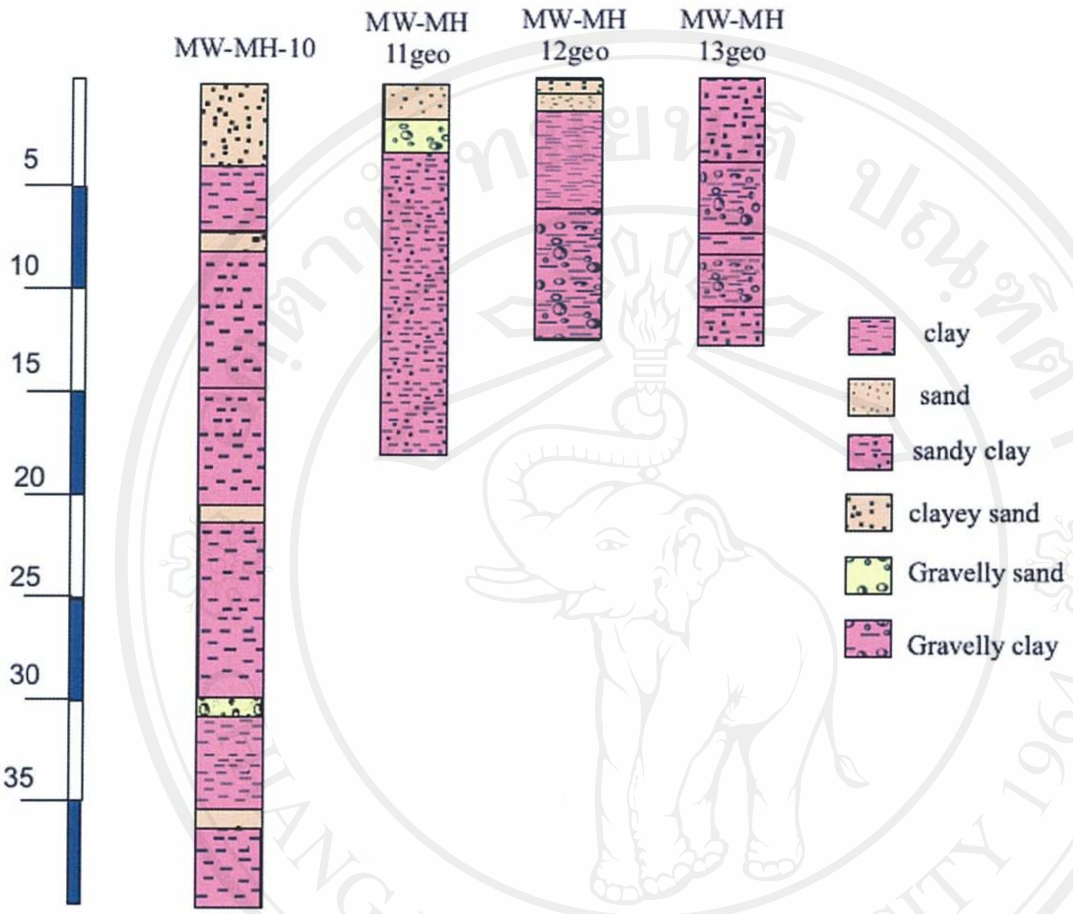

Figure 5.11 Logs of borehole in the eastern part of Mae-Hia landfill (depth from ground surface in m) (modified from Radschinski, 2005).

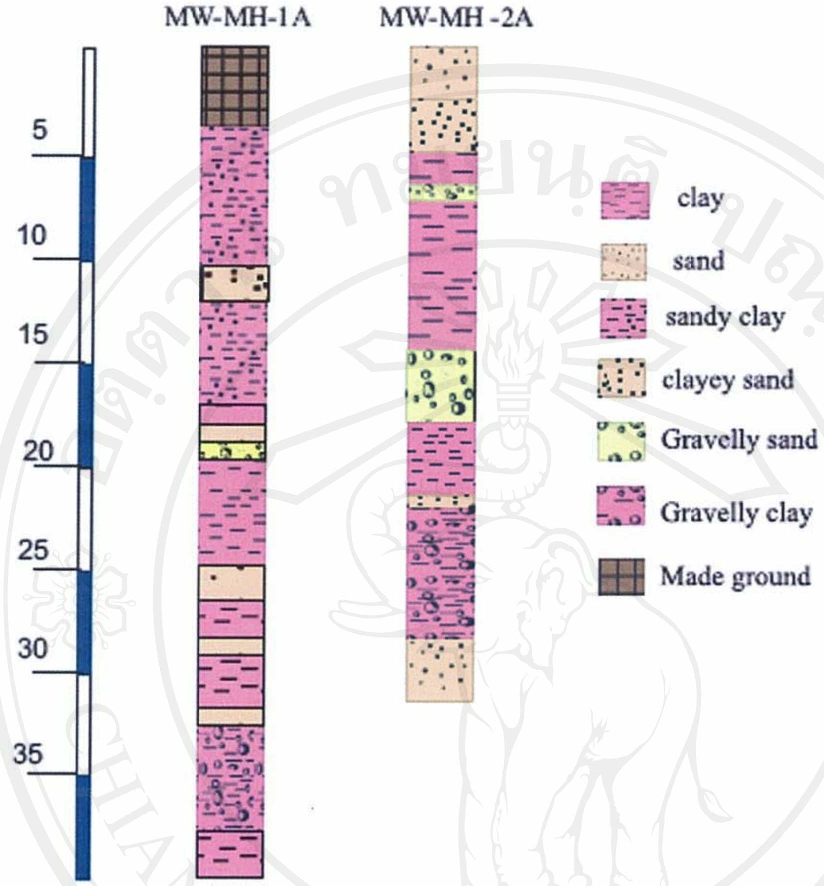

Figure 5.12 Logs of borehole in the northern part of Mae-Hia landfill (depth from ground surface in m) (modified from Radschinski, 2005).

This discussion of the lithology, degree of saturation and the field resistivity values is meant to define the parameters for correlation with the laboratory result. As it was discovered in laboratory, when a sample is soaked with the same concentration of leachate, highly contaminated clay samples tend to have higher resistivity value than in contaminated sand samples. So the priority hypothesis was that the high resistivity range found in the southern part of the landfill might be within a contaminated clay layer and the low resistivity found in the northern part of landfill may not represent a contaminated zone but rather an uncontaminated water-saturated clay-rich layer.

After those parameters and hypothesis mentioning above, the levels of contamination were quantitatively interpreted. The interpretation is based on the mathematical functions for each type of sediment summarizes in Table 5.2.

Table 5.2 Summary of the mathematical relationship for each type of sediments

Sediments	*F*	*-am*	Mathematical relationship	
Sand	2.90	-1.49	$\rho_{bulk} = \rho_{fluid} 2.90 S_w^{-2.06}$	$\rho_{bulk} = \rho_{fluid} \varphi^{-1.49} S_w^{-2.06}$
Clayey Sand	5.77	-1.63	$\rho_{bulk} = \rho_{fluid} 5.77 S_w^{-2.58}$	$\rho_{bulk} = \rho_{fluid} \varphi^{-1.63} S_w^{-2.58}$
Sandy Clay	7.85	-1.92	$\rho_{bulk} = \rho_{fluid} 7.85 S_w^{-3.52}$	$\rho_{bulk} = \rho_{fluid} \varphi^{-1.92} S_w^{-3.52}$
Clay	7.50	-2.24	$\rho_{bulk} = \rho_{fluid} 7.50 S_w^{-2.46}$	$\rho_{bulk} = \rho_{fluid} \varphi^{-2.24} S_w^{-2.46}$

5.3.1 Quantitative interpretation of high resistivity zone (Southern area)

According to a simply assumption, the sediment underlying the southern part of the landfill are similar to the clay sample used in the experiment, and that its degree of saturation is 0.76, as discussed above.

The mathematical relationship for the resistivity of clay is

$$\rho_{bulk} = \rho_{fluid} 7.50 S_w^{-2.46} \qquad (5.3)$$

While the bulk resistivity range of southern area is about 40 ohm-m, and that the porosity of the clay is similar to the porosity measured in the laboratory. By replacing the bulk resistivity and saturation degree in the above equation and solving it, the resistivity of the fluid will be known. Using the values given above, the resistivity of the pore fluid in the southern area is approximately 2.72 ohm-m. For typical pore fluid, the total dissolved solids of the fluid can be calculated as shown in Figure 5.13 and using Equation 5.4

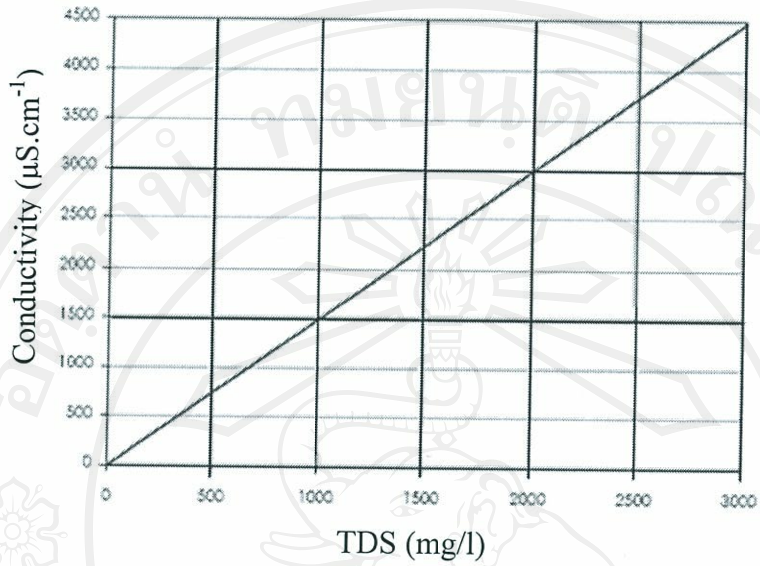

Figure 5.13 Conductivity versus total dissolved solids of pore fluid, when 0.67 mg/l TDS is contributed to 1μS.cm^{-1}(modified from Lloyd and Heathcote, 1985).

As shown in Figure 5.13, knowing the resistivity of the pore fluids, the total dissolved solids in the fluid can be calculated using

$$\rho_{fluid}(\Omega.m) = \frac{6667}{TDS} \tag{5.4}$$

where TDS is the total dissolved solids in mg/l

In this case the total dissolved solids of the pore fluid in southern part of landfill is about 2415.6 mg/l which would be the same as 13.65 % of the leachate from the Mae-Hia landfill.

5.3.2 Quantitative interpretation of medium resistivity zone (Eastern area)

Using the same principle as above, the medium resistivity zone in the eastern part of the landfill has a bulk resistivity value of about 16-25 ohm-m. The area is underlain by sandy clay with a saturation degree equal to its field capacity of 0.96.

The mathematical relationship for sandy clay is

$$\rho_{bulk} = \rho_{fluid} 7.85 S_w^{-3.52} \quad (5.5)$$

In this case the resistivity of the pore fluid in the eastern area is approximately 1.77– 2.76 ohm-m and the total dissolved solids is about 2,416.12-3,766.66 mg/l which is equivalent to 13.65-21.28 % of the Mae-Hia landfill leachate.

5.3.3 Quantitative interpretation of low resistivity zone (Northern area)

The third zone is at the northern part of the landfill, the suspected area of contamination, with the lowest resistivity values in the area of about 6-8 ohm-m. The type of sediment underlying the area is unknown, but at a 10 m depth the area should be below the watertable and thus fully saturated. For the purpose of this discussion, the area was considered to be underlain by clay and sand.

If the area's sediment is clay, a representative bulk resistivity of 4 ohm-m should be used in Equation 5.3. In this case, the resistivity of the pore fluid in the northern area is approximately 0.8-1.07 ohm-m and the total amount of dissolve solids is about 6,230-8,333.8 mg/l which is equivalent to 35-47 % of the Mae-Hia landfill leachate.

Alternatively, if this area is underlain by sand or gravelly sand, the mathematical function (for sand sediment) is

$$\rho_{bulk} = \rho_{fluid} 2.90 S_w^{-2.06} \quad (5.6)$$

In this case resistivity of the pore fluid in northern area is approximately 2.07-2.76 ohm-m and the amount of total dissolved solids is about 2415.6-3220.8 mg/l which is equivalent to 13.7-18.2 % of the Mae-Hia landfill leachate.

Based on these calculations, the southern part and eastern part of the landfill are considered to be contaminated. Since the pollutants will transport with groundwater, then the clay and sandy clay layer at 10 m depth might have been contaminated during the rainy season when the water table is higher. After the water table is lowered, some pollutants would remain trapped in the pore. As high range of bulk resistivity value belongs to 21% of leachate partially saturated in sandy clay layer. A higher level of contamination near the watertable was expected to see, within the more compacted layer at a depth of 10 m.

After reinterpreted with the laboratory result (as shown in quantity interpretation in Section 5.3.3.), the pore fluid saturated in the northern part of the landfill, showing high contaminations of total dissolved solids. This represents some degree of polluted, though the contaminated source still unclear. But if this area is truly underlain by sandy sediment, this area likely has a relatively low level of contamination. Furthermore, if significant amounts of gravel underlay this area, the empirical equation might not be applicable. Additional investigation should be done to verify the sediment type in the northern part of the landfill.

Based on the above calculations, a roughly quantitative map of the contaminated plume can be made (Figure 5.14).

From the chemical analysis result of those groundwater samples collected from the monitoring well in upgradient and downgradient location of the landfill (see Chapter 4), in the well no.MW-MH-8 on the west border of the landfill, the total dissolved solids of this well was 448 mg/l while from above empirical estimation the upgradient position appears to be 962 mg/l. Where the groundwater sample from well no. MW-MH- 3uw in the downgradient position, the total dissolved solids of this well was 1,900 mg/l while from my empirical estimation the total dissolved solids of pore fluid in the downstream position appears to be about 2415.6 mg/l.

The error in the case of downstream location is considered to be acceptable, as the screen filter of well no. MW-MH- 3uw is at the depth of 6-7 m. compare to the depth of interpretation at 10m. But in the well no. MH-MW-8 where its depth of screen filter is about 13 m. still the error that happened is way too big to be accepted, referred to the limitation of Archie's equation which is not valid in the low resistivity pore fluid. Also the inhomogeneity of the sediments and porosity variation in the area might be responsible for the error.

Anyway, a more detailed estimated total dissolved solid map on the investigation area shall be done further in order to tracking the contaminated pathway in the area.

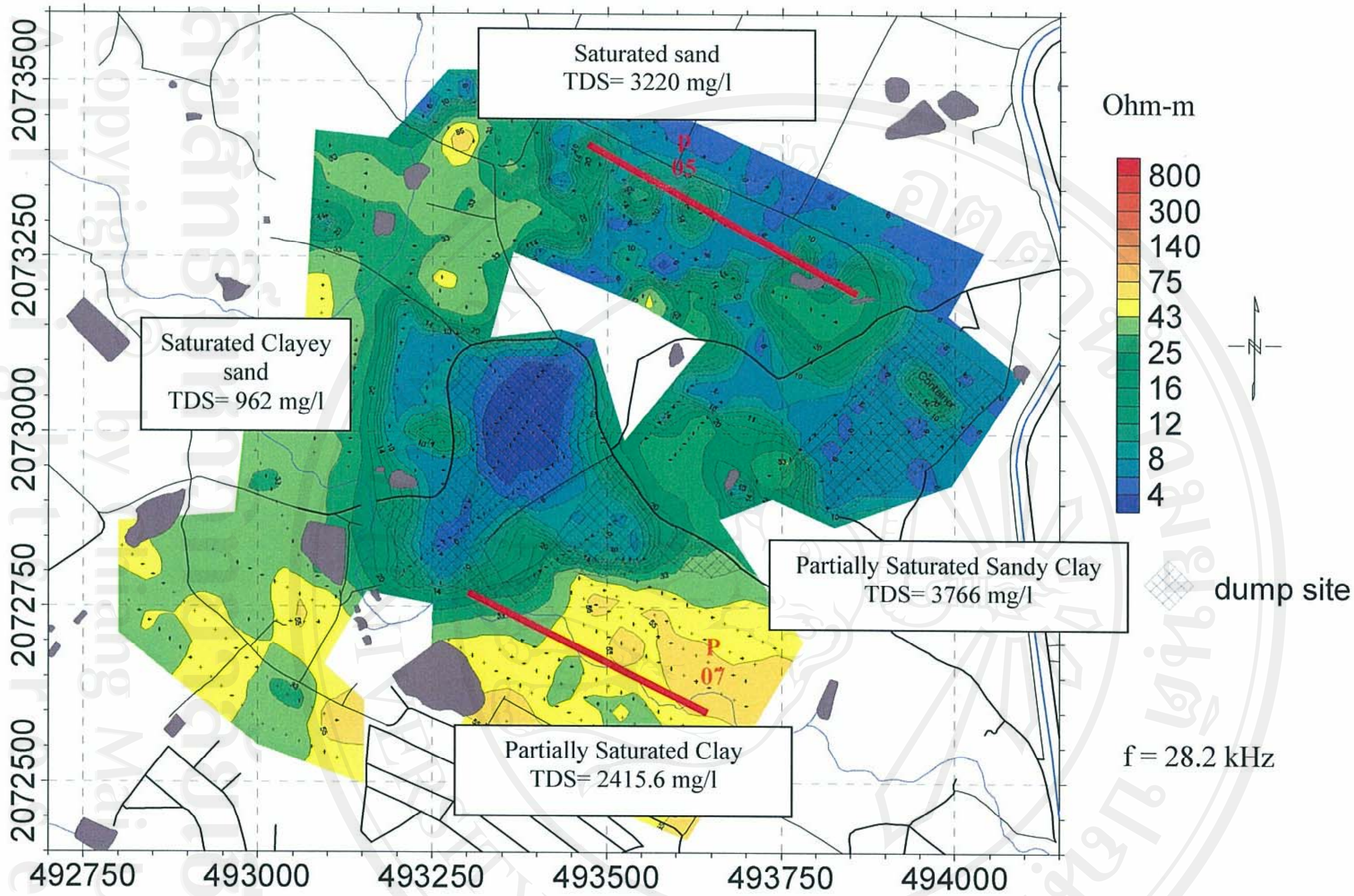

Figure 5.14 Estimated total dissolved solids of pore fluid from the empirical resistivity function obtained in the laboratory experiment.