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The effectiveness of N-transformation method on vertical electrical sounding data processing

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Abstract

Improving the resolution and the localization of geoelectrical sections is important and essential in vertical electrical sounding (VES) data processing. PZ-transformation method (PZ) has used to change the apparent resistivity geoelectrical section ρk(x,r) with low resolution and localization to another one ρpz(x,zpz) which was proven to have higher resolution and better localization. However, PZ-transformation method has not calculated the effect of the anisotropic coefficient in the geological environment, so the localization was not optimal. This resulted in incorrect reflecting the depth of studied objects as well as geoelectrical layers. The N-transformation method was proposed by (Nguyen Trong Nga, Truong Thi Chinh, 2016) to overcome the PZ method's limitation and enhance the resolution and localization. In this paper, the authors applied this method in the different theoretical models. The results showed that the geoelectrical sections ρN(x,zN) changed by N-transformation method had higher resolution and better localization than the changed ones ρpz(x,zpz) by PZ-transformation method, therefore they displayed more accurately the parameters of studied objects and geoelectrical layers.

Keywords: Vertical electrical sounding (VES); N-transformation methods; resolution; localization.

1. Introduction

The first VES curve transformation method was produced by (Petrovski, 1980) called P-transformation method. After that, the Z-transformation method was established by American Geologist Zhondy. Both two methods were constructed with an aim to enhance the resolution and localization of geoelectrical sections by two formulas: one to change resistivity and one to calculate the transformed depth (Nguyen Trong Nga, 2005; Nguyen Trong Nga, 2007). The changed VES curves and geoelectrical sections by these methods have had higher resolution and better localization. However, P-transformation method has been used for the going down parts of curve whereas Z-transformation method better for the going up parts. Because the VES curves consist of both types, it was necessary to have a combination of two methods to PZ transformation method (Nguyen Trong Nga, 2005). The PZ method has optimized the advantages of the two P, Z component methods. However, the PZ method has been limitations to display thin layers and small objects and the parameters of studied objects as well as geoelectrical layers (Truong Thi Chinh, 2017) because of regardless the effect of anisotropy coefficient in the layered environment. With an aim to further improve the resolution and the localization of the VES curves and geoelectrical sections, N-transformation method was produced (Nguyen Trong Nga, Truong Thi Chinh, 2016). In the paper, the authors demonstrated the effectiveness of the method on improving the localization and the resolution of N – transformation method.

2. N – transformation method

2.1. Theoretical environmental model

Similar to the previous P, Z, PZ methods, the theoretical environmental models have been used in N –

transformation method being 1D ones including the system of parallel layers. However, the electrical current has been assumed to run in two directions, ie, perpendicular and parallel to the surface of layers (Figure 1) (Truong Thi Chinh, 2017)

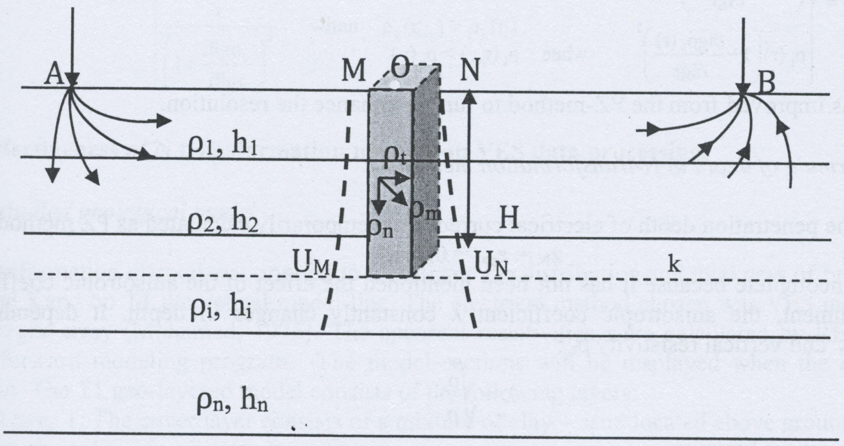

Fig 1. The 1D theoretical environmental model

At each point, resistivity consists of two components: a parallel component ρ_t and a perpendicular one ρ_n. The mean square resistivity was calculated by:

$$\rho_m = \sqrt{\rho_n \rho_t} \tag{1}$$

The parameters of each layer include the resistivity value ρ_i and the layer thickness h_i.

2.2. Anisotropy coefficient

The anisotropic coefficient of the layered environment was calculated by the formula (Nguyen Trong Nga, 2005):

$$\lambda = \sqrt{\frac{\rho_n}{\rho_l}} = \frac{\sqrt{ST}}{H} \tag{2}$$

Where S is the total vertical conductivity and T is the total horizontal resistivity, H is the total length.

The anisotropic coefficient effects on the depth of electrical current. The relation between the real depth z and the conventional depth r of electrical current was shown by the formula (Truong Thi Chinh, 2017):

$$z = \frac{r}{\lambda} \tag{3}$$

Because of z = αr the coefficient of permeability α related the coefficient of anisotropy as follows:

$$\alpha = \frac{1}{\lambda} \tag{4}$$

The anisotropic coefficient is always greater than 1, so the real depth z is smaller than r. According to the formula (3), at each time the AB electrodes opened the real depth is proportional to r with different scaling factors $1/\lambda$. This means, when the anisotropy of the environment is mentioned, the changed depth is proportional to r with the constantly changing coefficient of permeability α.

2.3. The transformation formula of apparent resistivity in N-transformation method

In P, Z, PZ methods, the transformation formula of apparent resistivity was used to change the apparent resistivity to another one which has better resolution and more accurate value with the actual resistivity of the layers. These methods were done by numerical processing at each point (each size of AB) (Nguyen Trong Nga, 2005; Nguyen Trong Nga, 2007). Also, they can be treated by some algorithm such as automatic interpretation, automatic inversion (Zhondy, 1989; Zhondy and Bisdorf, 1975). The paper used interpretation algorithm (Nguyen Xuan Huan, 2004).

In the PZ-method, it was:

$$\rho_{PZ}(z) = \begin{cases} \dfrac{\rho_k(r)}{\left(1 - \dfrac{\partial \lg \rho_k(r)}{\partial \lg r}\right)} & \text{when} \quad \rho_k(r_{i+1}) < \rho_k(r_i) \\ \rho_k(r)\left(1 + \dfrac{\partial \lg \rho_k(r)}{\partial \lg r}\right) & \text{when} \quad \rho_k(r_{i+1}) > \rho_k(r_i) \end{cases} \tag{5}$$

And in the N-method, the formula as:

$$\rho_N(z) = \begin{cases} \dfrac{\rho_k(r)}{\left(1 - \dfrac{\partial \lg\rho_k(r)}{\partial \lg r}\right)^2} & \text{when} \quad \rho_k(r_{i+1}) \le \rho_k(r_i) \\ \rho_k(r)\left(1 + \dfrac{\partial \lg\rho_k(r)}{\partial \lg r}\right)^2 & \text{when} \quad \rho_k(r_{i+1}) > \rho_k(r_i) \end{cases} \quad (6)$$

The formula (6) was improved from the PZ-method to further enhance the resolution.

2.4. The calculation formula of depth in N-transformation method

At the beginning, the penetration depth of electrical current was temporarily calculated as PZ method:

$$z_N = z_{pz} = 0.35r.$$

This formula was incomplete because it has not been mentioned the effect of the anisotropic coefficient. In the geological environment, the anisotropic coefficient λ constantly changes in depth. It depends on the horizontal resistivity ρ_n and vertical resistivity ρ_t :

$$\lambda = \sqrt{\frac{\rho_n}{\rho_t}}$$

As demonstrated above we have:

$$z = \frac{1}{\lambda} r \,; \; \alpha = \frac{1}{\lambda} \quad (7$$

On the other hand, the apparent resistivity is the average square resistivity. With the going down parts of VES curve:

$$\rho_N(z) = \rho_t(z) \quad (8)$$

So:

$$\rho_k(r) = \rho_m(r) = \sqrt{\rho_n\rho_t} = \rho_t\sqrt{\frac{\rho_n}{\rho_t}} = \lambda\rho_t = \lambda\rho_N(z)$$

Or:

$$\rho_N(z) = \frac{\rho_k(r)}{\lambda} \quad (9)$$

Comparing the two formulas (6) and (9), the anisotropic coefficient is calculated as follows:

$$\lambda = \left(1 - \frac{\partial \lg\rho_k}{\partial \lg r}\right)^2 \text{ when } \rho_k(r_i+1) \le \rho_k(r_i) \quad (10)$$

With the going down parts of VES curve:

$$\rho_N(z) = \rho_n(z) \quad (11)$$

So:

$$\rho_k(r) = \rho_m(r) = \sqrt{\rho_n\rho_t} = \rho_n\sqrt{\frac{\rho_t}{\rho_n}} = \frac{\rho_n}{\lambda} = \frac{\rho_N(z)}{\lambda}$$

$$\Rightarrow \rho_N(z) = \rho_k(r)\lambda \quad (12)$$

Comparing the two formulas (6) and (12) the anisotropic coefficient is calculated as follows:

$$\lambda = \left(1 + \frac{\partial \lg\rho_k}{\partial \lg r}\right) \text{ when } \rho_k(r_i+1) > \rho_k(r_i) \quad (13)$$

Combining the two formulas (10) and (13) to have a complete formula of the anisotropic coefficient at each distance r :

$$\lambda = \begin{cases} \left(1 - \dfrac{\partial \lg\rho_k}{\partial \lg r}\right)^2 & \text{when} \quad \rho_k(r_{i+1}) \le \rho_k(r_i) \\ \left(1 + \dfrac{\partial \lg\rho_k}{\partial \lg r}\right)^2 & \text{when} \quad \rho_k(r_{i+1}) > \rho_k(r_i) \end{cases} \quad (14)$$

The inference coefficient formula can be inferred:

$$\alpha = \frac{1}{\lambda} = \begin{cases} \dfrac{1}{\left(1 - \dfrac{\partial \lg\rho_k}{\partial \lg r}\right)^2} & \text{when} \quad \rho_k(r_{i+1}) \le \rho_k(r_i) \\ \dfrac{1}{\left(1 + \dfrac{\partial \lg\rho_k}{\partial \lg r}\right)^2} & \text{when} \quad \rho_k(r_{i+1}) > \rho_k(r_i) \end{cases} \quad (15)$$

So, the formula of depth in N-transformation method was shown:

$$z_N = \begin{cases} \dfrac{r}{\left(1-\dfrac{\partial \lg\rho_k}{\partial \lg r}\right)^2} & \text{when} \quad \rho_k(r_{i+1}) \le \rho_k(r_i) \\[2ex] \dfrac{r}{\left(1+\dfrac{\partial \lg\rho_k}{\partial \lg r}\right)^2} & \text{when} \quad \rho_k(r_{i+1}) > \rho_k(r_i) \end{cases} \qquad (16)$$

3. The effectiveness of N transformation method on VES data processing.

3.1. The studied geological model

N transformation method was applied to investigate the distribution and thickness of broken limestone blocks prospected Karst on T1 theoretical model line. The electrical method chosen was VES method using Wenner – Schlumberger array (Mohamed, 1975). The apparent resistivities were calculated by RES2DMOD which is a free 2D forward modeling program. The model sections will be displayed when the calculations are being carried out. The T1 geo-layered model consists of the following layers:

- Layer 1: The cover layer consists of a mixture of clay – sand located above ground water. The thickness is 7 meters, the value of resistivity is $\rho_1 = 100\ \Omega m$
- Layer 2: It is hydrated clay – sand mixture with thickness 43 meters, the resistivity $\rho_2 = 30\ \Omega m$
- Layer 3: This is solid limestone layer. The resistivity is $\rho_3 = 800\ \Omega m$. In this layer, there are broken limestone zones prospected Karst with resistivity about $120\ \Omega m$. In this paper, the authors used 3 theoretical models with different distribution and thickness of broken limestone blocks prospected Karst to demonstrate the applied effectiveness of N-transformation method (Figure 1,2,3).

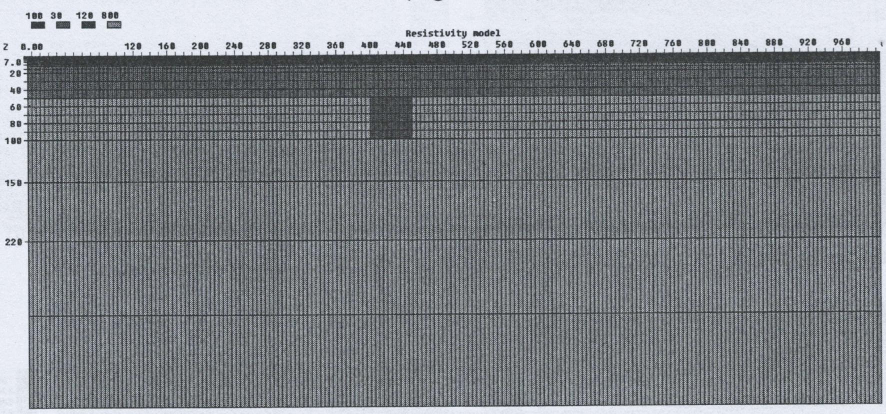

Fig 2. The resistivity model of section 1

In Figure 2, we can see that Karst zone develop both horizontal and vertical direction (site 400 to site 450) in section 1, its thickness is 50m and the depth is from 50m to 100m.

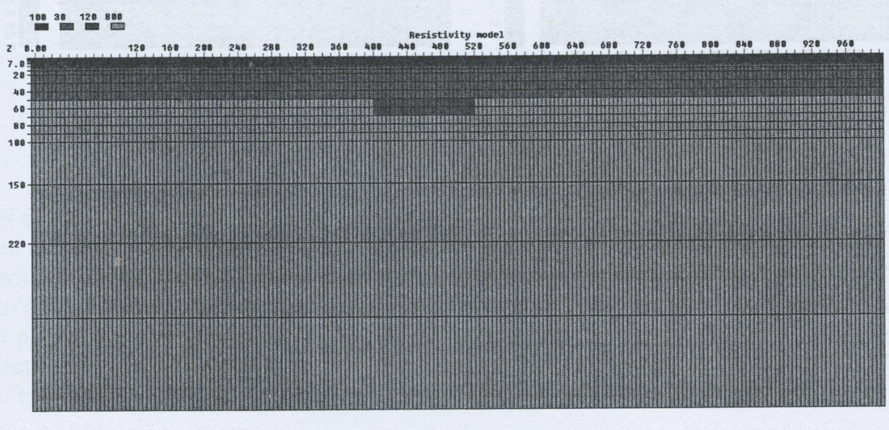

Fig 3. The resistivity model of section 2

The resistivity model of section 2 was displayed in Figure 3. There is a Karst zone developing horizontal (site 400m to site 520m) with the change from 50 meters to 70 meters in depth.

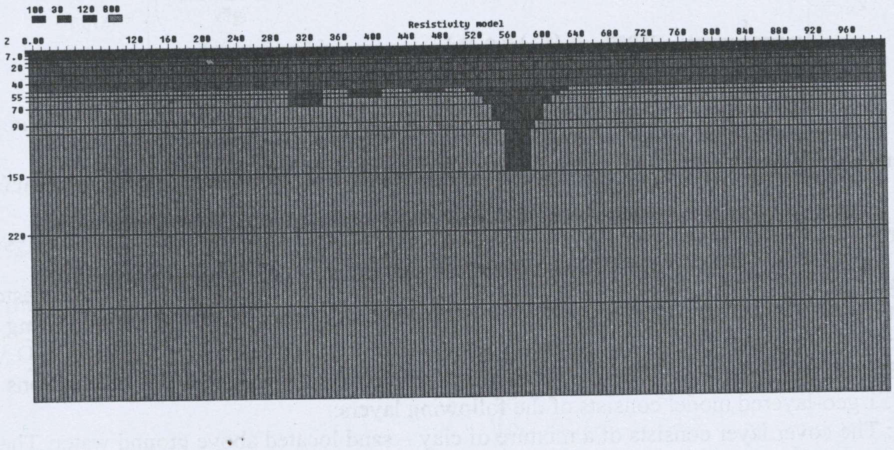

Fig 4. The resistivity model of section 3

Figure 4 is the resistivity model of section 3 which consists of 4 Karst zones with different distribution and thickness. The first one is 40m in width and 20m in thickness (site 300m to site 340m). The next one is also 40m but only 10m in depth (site 370m to site 410m). The third Karst zone was located at site 440m to site 480m with the thickness of 5m. The last one is the biggest one developed both horizontal and vertical direction from site 510m to site 630m.

3.2. The applied results

3.2.1. The applied results on section 1

After using the RES2DMOD program to calculate the resistivities, we obtained the apparent resistivity section ρk(x,r). After that N and PZ transformation method were applied to change ρk(x,r) section to ρpz(x,zpz) and ρN(x, zN) ones. The results were displayed in Figure 5.

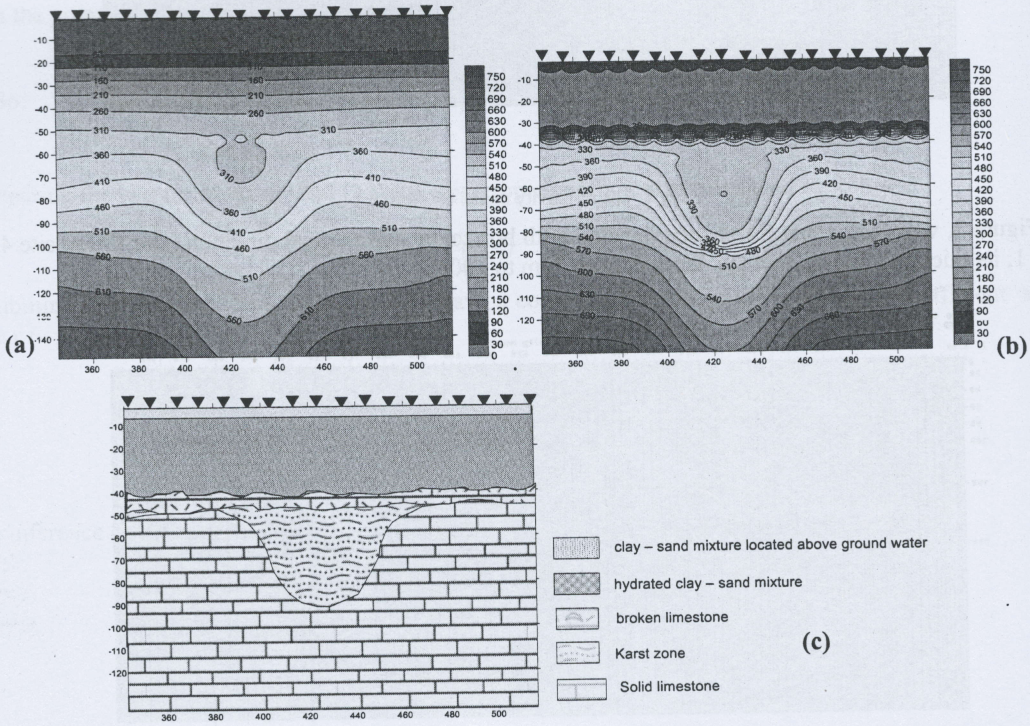

Fig 5.(a) The $\rho_{pz}(x,z_{pz})$ section 1; (b)The $\rho_N(x, z_N)$ section 1; (c)The geological section 1

As the results of Figure 5, the broken limestone zones prospected Karst develop both horizontal and vertical direction (site 400 to site 450) on both $\rho_{pz}(x,z_{pz})$ section and $\rho_N(x,z_N)$ one.

On the $\rho_{pz}(x,z_{pz})$ section (Figure 5a), the depth of Karst zone changed from 60m to 85 m, while it was 50 – 90m on $\rho_N(x,z_N)$ section (Figure 5a). with changed resistivity was 120 - 360Ωm (Figure 5b). This means that the geoelectrical sections $\rho_N(x, z_N)$ changed by N-transformation method had better localization than the changed ones $\rho_{pz}(x,z_{pz})$ by PZ-transformation method because displayed relatively accurate the real depth (50 -100m) of Karst block.

On the other hand, the boundaries between layers were described more clearly in the $\rho_N(x, z_N)$ section because the resistivity values change complicating. They allowed to explicitly define the boundaries of the layers. As the result of the geological section 1 (Figure 5c) there were 3 layers : layer 1 was about 7m, the resistivity was 80-90Ωm (mixture of clay – sand located above ground water); layer 2 was about 35m, the resistivity was around 30Ωm (hydrated clay – sand mixture); the bottom one had the resistivity being 360-800 Ωm (solid limestone). The Karst zone was in the solid limestone layer having the resistivity from 120 Ωm to 360 Ωm.

Briefly, the changed results from the $\rho_N(x, z_N)$ section displayed the depth and thickness of the layers and karst zone to be more suitable with the theoretical geological model than one by PZ method. In another word, the geoelectrical section $\rho_N(x,z_N)$ changed by N-transformation method have higher resolution and better localization than the changing ones $\rho_{pz}(x,z_{pz})$ by PZ-transformation method.

3.2.2. The applied results on section 2

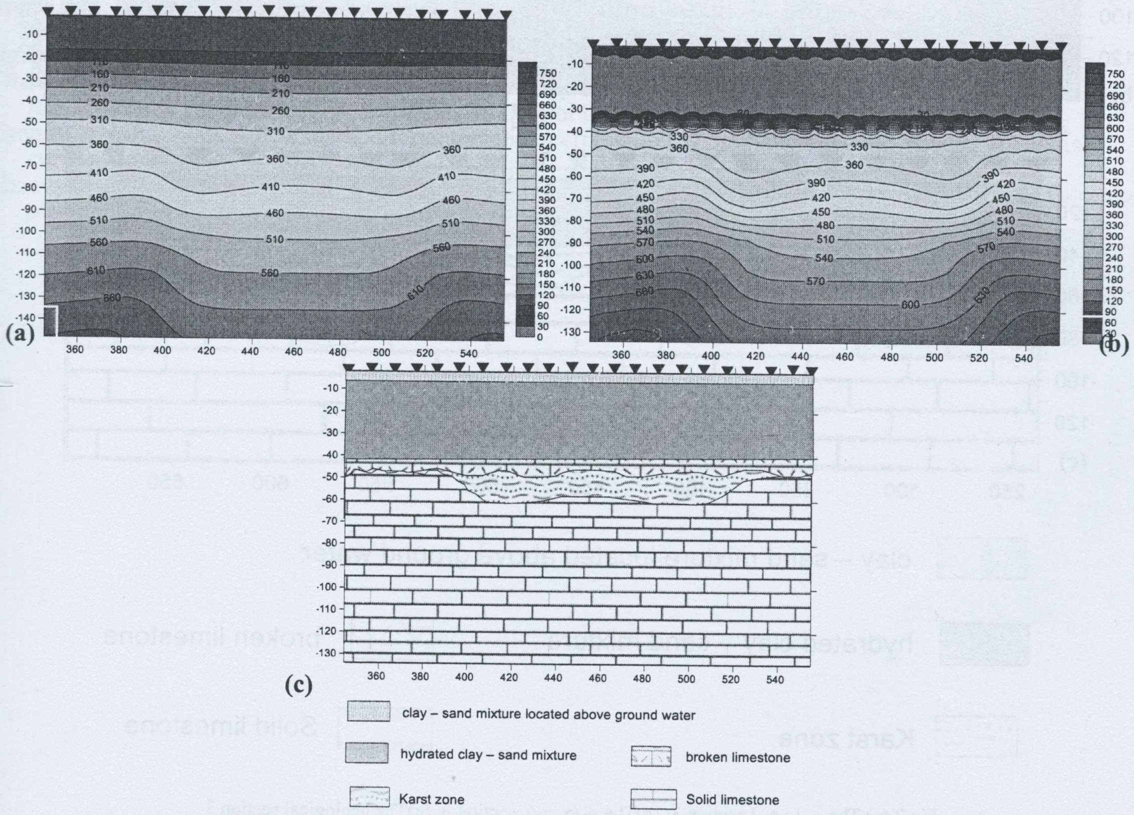

Fig 6.(a) The $\rho_{pz}(x,z_{pz})$ section 2; (b)The $\rho_N(x, z_N)$ section 2; (c)The geological section 2

Figure 6 displayed results of the theoretical geoelectrical section which consists of a karst block along the line. We can see that the $\rho_N(x, z_N)$ (Figure 6b) section showed the depth and the thickness of this zone more consistent with the theoretical model than $\rho_{pz}(x,z_{pz})$ (Figure 6a). In the concrete, the depth of Karst zone changed from 50m to 62m, the changed resistivity was 120 - 360Ωm on the $\rho_N(x, z_N)$ section (Figure 5a) and it was 60 – 70m on the $\rho_{pz}(x,z_{pz})$ section (Figure 5b). Similar to the result on section 1, the layer boundaries shown in the $\rho_N(x, z_N)$ section were more appropriate than the $\rho_{pz}(x,z_{pz})$ section. On the geological section (Figure 6c), the thickness of layers were 7, 35, ∞ respectively compared with 7, 43, ∞ on model section.

3.2.3. The applied results on section 3

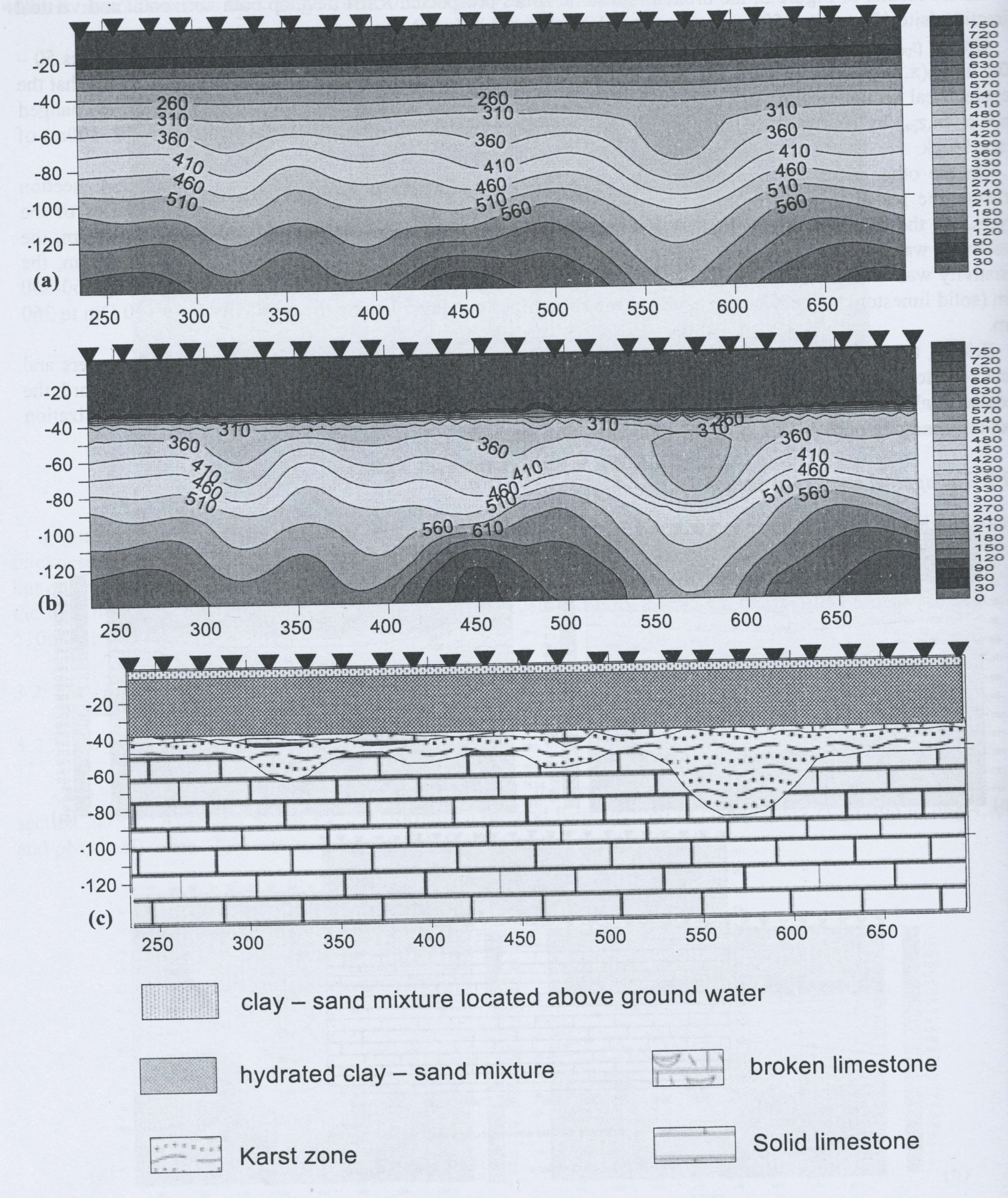

Fig 7.(a) The $\rho_{pz}(x,z_{pz})$ section 3; (b)The $\rho_N(x, z_N)$ section 3; (c)The geological section 3

Section 3 consists of 4 Karst zones with the largest one at the bottom of the line. These zones were shown at site 300m – 340m; 370 - 410; 440m-480m and 510m-630m on both the $\rho_{pz}(x,z_{pz})$ section (Figure 7a) and the $\rho_N(x, z_N)$ section (Figure 7b). However, the thickness of layers was 10m, 5m, 10m, 35m respectively on $\rho_{pz}(x,z_{pz})$ and 25m,10m, 10, 50 m on $\rho_N(x, z_N)$. Thus, the processing results by N and PZ method both displayed exactly the position of the bursting blocks, but the N method reflected more accurately their thickness in the theoretical model.

In adition, the layer number and the boundaries between layers were described more clearly in the $\rho_N(x, z_N)$ section because the resistivity values transformed complicating and allowed to explicitly define the boundaries of the layers. On the geological section 3 (Figure 7c) there were 3 layers : layer 1 was about 7m but wasn't described clearly, the resistivity was 80-90Ωm (mixture of clay – sand located above ground water); layer 2 was about 35m, the resistivity was around 30Ωm (hydrated clay – sand mixture); the bottom one had the resistivity being 360-800 Ωm (solid limestone). The karst zones were in the solid limestone layer having the resistivity from 120 Ωm to 360 Ωm.

4. Conclusion

The N and PZ transformation methods were used to process ensure the VES data obtained the theoretical model. Comparison of treated results has demonstrated the effectiveness of the N-transformation method:

The N-transformation method improved the resolution of geoelectrical sections. The results on 3 theoretical models showed that the changed sections $\rho_N(x, z_N)$ reflected more clearly the number and the boundaries of the layers and karst zones than the $\rho_{pz}(x,z_{pz})$ ones. Besides, the small karst zones, thin layers were described in the $\rho_N(x, z_N)$ sections in an authentic way.

The N-transformation sections had better localization because of calculation the effect of the anisotropic coefficient in the geological environment. The $\rho_N(x, z_N)$ sections allowed determining relatively the number of geological layers, the position, the boundaries, the thickness of layers and karst zones compared to theoretical models. Meanwhile, the $\rho_{pz}(x,z_{pz})$ section described the site of layers accurately but the number of layers unclearly and the thickness of layers not suitable for theoretical models.

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