Research and Application of High-Density Resistivity Method in Seawater Intrusion Investigation in Laizhou Bay

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Abstract The disaster of seawater intrusion seriously affects people's lives and restricts economic development, so the detection and treatment of seawater intrusion is a long-term task. On the basis of field investigation and water quality analysis, according to the change characteristics of apparent resistivity of groundwater after Cl^- reaches 250 mg/L, the theoretical basis for the application of high-density resistivity method was determined, and the characteristic values of apparent resistivity for seawater intrusion interfaces in different geological characteristic regions in Laizhou Bay area were determined by typical profile tests. Combined with water quality investigation and other means, profiles for the high-density resistivity method were arranged, and the interfaces between saline and fresh water were accurately divided.

Key words High-density resistivity method; Seawater intrusion; Laizhou Bay; Characteristic value

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At present, seawater intrusion has become a typical environmental disaster internationally[1-3]. It has been more serious in China in recent decades, especially in Shandong Province. Seawater intrusion has seriously damaged water resources in coastal areas and aggravated the contradiction between supply and demand of water resources, especially the invasion to shallow surface water, which has caused great harm to local people's lives and industrial and agricultural production and restricted the sustainable development of the economy[4-5].

In recent years, the resistivity method has been widely applied to study coastal groundwater[6]. However, due to the influence of various factors such as climate, Quaternary soil and thickness and bedrock lithology on apparent resistivity, as well as certain limitations of the ground resistivity method itself, the high-density resistivity method is rarely applied to study seawater intrusion both at home and abroad[7], and a systematic theoretical understanding has not yet been formed. In this study, the characteristic values of apparent resistivity for seawater intrusion interfaces in different geological characteristic regions in Laizhou Bay area were determined by the high-density resistivity method combined with water quality investigation, and the seawater intrusion interfaces were delineated, providing some reference materials for investigating seawater intrusion interfaces by using the resistivity method.

Test Background and Methods

Analysis of the causes of seawater intrusion

According to the geological characteristics of the coastal area of Laizhou Bay, the shallow landforms from south to north are the alluvial-proluvial plain in front of mountains, alluvial-marine plain, and marine plain[1].

An aquifer composed of Quaternary marine and alluvial-diluvial sands has a thick sand layer, which is formed with coarse particles and has good water permeability with a permeability coefficient of generally 50 - 150 m/d. It is distributed continuously, generally extending from freshwater areas to saline areas or the seabed. In addition, with the development of basement fault structures, there is a close hydraulic connection between groundwater and seawater, providing a channel for seawater intrusion. In the 1980s, successive years of drought occurred in Laizhou City, and agricultural irrigation and industrial production began to exploit a large amount of groundwater, which caused the water level to drop, and thus a large area of funnel area with a negative groundwater level appeared in the coastal plain area, which caused the original dynamic balance between fresh and salt water to be disturbed and seawater to invade[8-9].

Moreover, the evolution of sedimentary environment since the late century, ancient river sand layer, topography, storm surge invasion, the development of marine aquaculture on land and the construction of river closure projects in the middle and upper reaches are also important factors for the formation of seawater intrusion[8-10]. For example, the seawater downstream of the Xinhe sluice in the northern suburb of Laihe River goes up along the river channel, which makes the concentration of Cl^- in the downstream area of Xinhe sluice between 500 and 1 000 mg/L in most months, resulting in the seawater intrusion interface extending inland along the coast of Laihe River in the northern suburb[9,11].

Criteria for judging seawater intrusion

There are many criteria for distinguishing seawater intrusion, mainly including Cl^- content, mineralization, K^-, SO_4^{2-} and $rHCO_3^-/rCl^-$, among which Cl^- is the most widely distributed

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and the most important stable constant element in seawater[12]. The Cl^- content, which has a significant impact on electrical resistivity, was mainly used as the discrimination standard for seawater intrusion in this work. The use of Cl^- concentration reaching a certain critical value as the standard for seawater intrusion is also the most commonly used method internationally and domestically. Based on previous work, 250 mg/L was adopted as the discrimination standard for seawater intrusion in this study[8,10,12-15].

Working methods

The high-density resistivity method has the characteristics of small point distance, high data density, high observation accuracy, and automatic continuous measurement. It is a working method that can intuitively and accurately reflect the abnormal forms of underground electrical properties[17].

On the basis of field investigation and water quality analysis, the boundary line of seawater intrusion was determined using the high-density resistivity method based on the characteristics of electrical resistivity changes in the salt water formation. Its working principle and interpretation method are the same as those of conventional electrical method.

The working area was located in the coastal line, and the terrain was generally flat. In the exploration work, a "Wenner" device was used for measurement, with point distances of 5 and 6 m, and a total of 10 layers were measured. When laying out profiles, we consulted villagers about local water quality according to prelaid positions. According to villagers' reflection, wells could be basically divided into three categories: ① unusable salty wells, classified into Class I, ② wells that could be used for irrigation, classified into Class II, and ③ wells that could be used for drinking for people and livestock, classified into Class III.

Through laboratory analysis on water quality of above wells, the Cl^- content was basically 1 000 mg/L for wells of Class I, generally between 250 and 1 000 mg/L for wells of Class II, and basically below 250 mg/L for wells of Class III. The water quality of these three types of wells basically conformed to the water quality types of severe intrusion, light intrusion and non-intrusion areas[4,12,16].

According to the distribution of these three types of wells, the location and direction of high-density profile layout were determined in the actual field work.

Analysis of Resistivity Characteristics in Seawater Intrusion Area

Method effectiveness test

Determination of electrical parameters Different electrical characteristic values between the Quaternary sedimentary layers and bedrock, between the seawater intrusion layers and non-intrusion layers, and between various sedimentary layers of the Quaternary system in this area were obtained, by physical tests on the seawater intrusion and non-intrusion regions in the sedimentary layers and bedrock of the Quaternary system, as well as comparing them with drilling data and hydrogeological data (Table 1).

Table 1 Table of electrical parameters Ω · m

Name of stratum	Common resistivity value	Resistivity when saturated with salt water
Sandy clay, clayey sand	30 – 50	
Fine sand	40 – 80	5 – 15
Medium-coarse sand	80 – 150	>5
sand gravel	100 – 300	2 – 5
Dry medium-coarse sand	400 – 1 200	
Weathering crust of bedrock	>150	2 – 5

From Table 1, it can be seen that there was a significant difference in electrical resistivity of the similar rock type between seawater intrusion and non-intrusion regions, providing favorable geophysical conditions for using the high-density resistivity method to delineate the boundary between salt and fresh water. Meanwhile, it also indicated that it is feasible to divide the boundaries of seawater intrusion regions by measuring electrical resistivity parameters[18].

Relationship between resistivity and chloride ion content Fig. 1 shows the relationship between measured Cl^- content and apparent resistivity, of which the Cl^- content was based on the test results of water sampled from wells, and the apparent resistivity was based on the apparent resistivity of moist soil near wells. From the curve, it can be seen that the higher the Cl^- content, the lower the resistivity. When the Cl^- content was between 250 and 5 000 mg/L, the rate of decrease in resistivity with the increase of Cl^- content slowed down, but the overall trend of decrease in apparent resistivity due to high Cl^- content remained unchanged[19]. According to different concentrations of Cl^- in groundwater, there were significant differences in apparent resistivity, which made the high-density resistivity method more effective in investigating seawater intrusion.

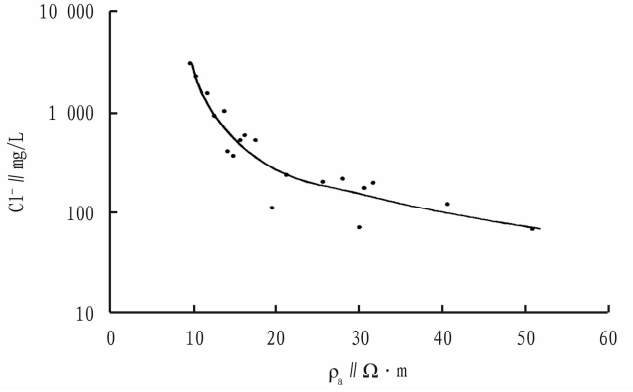

Fig. 1 Correlation curve of resistivity and chloride ion content

Determination of characteristic values of apparent resistivity for salt water and fresh water

When using the resistivity method to detect a seawater intrusion interface, the first step is to determine the characteristic values of apparent resistivity for the interfaces of salt and fresh water[18], and delineate the intrusion interfaces based on the characteristic values.

The southeast bank of Laizhou Bay is mainly located in Laizhou and Laixi cities. The shallow surface is mainly sandy clay, and the lower part is fine or medium-coarse sand with relatively coarse particles. The south bank is mainly located in Changyi and Shouguang cities, and the shallow surface is mainly composed of clayey sandy soil. Due to the large and relatively-coarse sand particles in sandy clay, its electrical resistivity is relatively high, while the sand particles of clay are small and fine, and its electrical resistivity is already very low, so if seawater intrusion occurs, the apparent resistivity will be lower. It is obviously inappropriate to use the same apparent resistivity value to determine interfaces of seawater intrusion. To determine the apparent resistivity value of Cl^- content at 250 mg/L and ensure that high-density electrical measurement can achieve good results in practical work, typical profiles were selected for testing during the work.

Determination of characteristic value for the interface of salt and fresh water in areas covered by sandy clay The Laizhou Municipal Government has built an underground slab wall curtain in the Yinjia – Houdeng – Xiyou area downstream of the Wanghe River on the southeast bank of Laizhou Bay. The slab wall curtain cuts off the seawater intrusion channel during the dry season, preventing seawater from continuing to invade, and it blocks fresh water from flowing into the sea during the flood season, effectively preventing seawater intrusion[20]. The test profile was selected near Xujia Village where the slab wall curtain passes through.

Fig. 2 shows the ρ_a pseudosection map obtained by the high-density resistivity method in Xujia Village (profile 15). As can be seen from the figure, the resistivity ρ_a values at the side of small points of the underground slab wall curtain were low. Especially when AB/3 was greater than 30 m, the ρ_a values were generally below 20 Ω · m, and lower than 10 Ω · m or even 5 Ω · m within point 200. The resistivity ρ_a values at the side of large points of the underground slab wall curtain were higher, and generally above 30 Ω · m in the section without seawater intrusion, but there was a section near the underground slab wall showing values smaller than 20 Ω · m. It was because this section had been invaded by seawater before the construction of the underground slab wall, and although the groundwater was desalinated by the increase of water storage in the later stage, the original invaded seawater was still stored in the deep underground, and the apparent resistivity of the area near the east side of the underground slab wall curtain was still low. However, the apparent resistivity ρ_a values on both sides of the underground slab wall and in areas with and without seawater intrusion were obviously different, which showed that it is feasible to distinguish the seawater intrusion areas from the non-intrusion areas by the high-density resistivity method, and meanwhile, 30 Ω · m could be determined as the ρ_a characteristic value of the interface between salt and fresh water in areas covered by sandy clay.

Determination of characteristic value for the interface of salt and fresh water in areas covered by clay The test profile for the interface of salt and fresh water in areas covered by clay was selected in the Shuangtai area of Changyi City. From Fig. 3, it can be seen that from starting point 0 in the south of the profile to point 450, the apparent resistivity values were generally above 20 Ω · m, and locally reached 40 Ω · m or even higher, and there was a known freshwater well near point 500 of the profile with a chloride concentration of 71.205 mg/L, indicating that the area belonged to a "non-intrusion" region and its apparent resistivity was also high. There was a known water well near point 3 000 with a chloride concentration of 215.13 mg/L, and the shallow apparent resistivity values near point 3 000 were generally between 16 and 18 Ω · m, while the deep apparent resistivity values were generally below 15 Ω · m, indicating that the area belonged to a transitional zone of seawater intrusion.

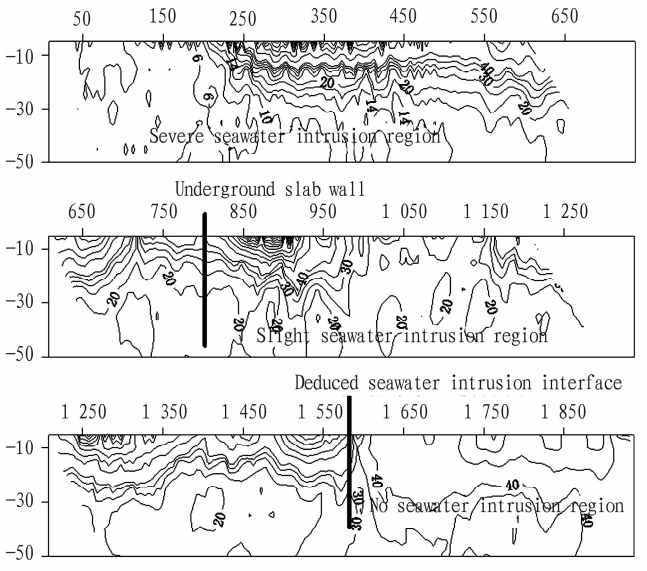

Fig. 2 Profile obtained by the high-density resistivity method in Xujia Village

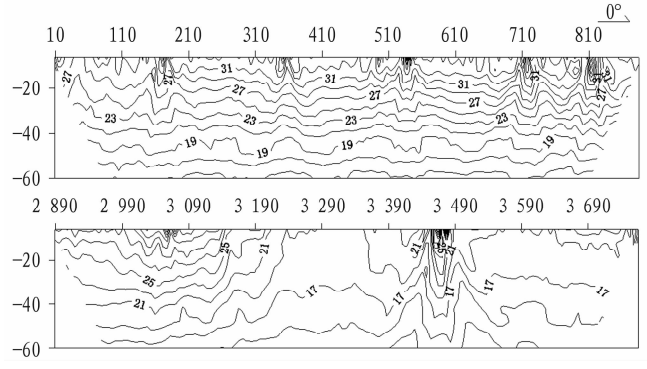

Fig. 3 Profile obtained by the high-density resistivity method in non-intrusion regions in Shuangtai area

In Fig. 4, it can be seen that the apparent resistivity on the left side of point 850 in the profile was relatively high, with values generally above 15 Ω · m, and the apparent resistivity on the right side of point 850 was relatively low, with values generally below 15 Ω · m. There was an obvious gradient change in ρ_a value near point 850. Through consulting local villagers who were watering the land, wells south of point 850 could still be used to irrigate the land, and wells north of point 850 had been basically abandoned. Therefore, the vicinity of point 850 was determined as the

interface of seawater intrusion. It could be basically determined that for clay sections with soil quality similar to that in Shuangtai area, the apparent resistivity value of 15 Ω · m in the profiles of the high-density resistivity method could be considered as the characteristic value of the interface between salt and fresh water.

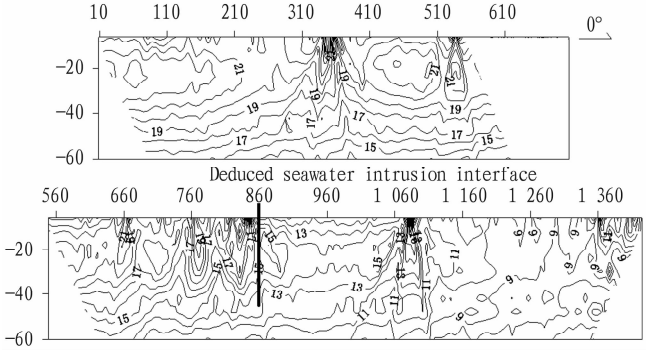

Fig. 4 Profile obtained by the high-density resistivity method at the interface of seawater intrusion in Shuangtai area

It can be seen from Fig. 5 that the apparent resistivity of the whole profile was generally below 15 Ω · m, and locally below 10 Ω · m or even lower. There was a known salty well near point 600 of the profile, and its chloride concentration was 365.62 mg/L, indicating that the area had been invaded by seawater, and the reliability of the characteristic value was also verified.

According to the test profile results in Shuangtai area, 15 Ω · m is the characteristic value of the interface between salt and fresh water in Quaternary clay stratum, that is, when measured in areas with similar geological conditions, areas with apparent resistivity less than 15 Ω · m are seawater intrusion areas, and those with apparent resistivity greater than this value are fresh water areas.

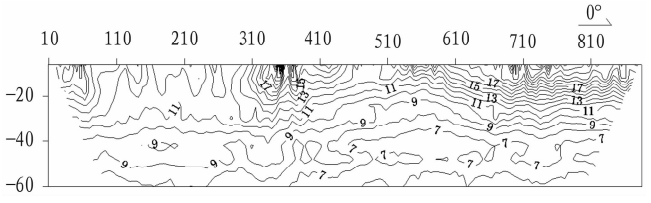

Fig. 5 Profile obtained by the high-density resistivity method in seawater intrusion regions in Shuangtai area

Delineation of seawater intrusion interface

In Laizhou Bay area, 16 profiles were laid out by the high-density resistivity method. During the layout of the profiles, hydrogeological visits were made to field wells. Finally, the measurement results of the seawater intrusion boundary determined by ρ_a characteristic values were in good agreement with the actual situation.

From west to east, it was roughly along Taitou, Wanggao and Houzhen in Shouguang City, Gudi, Shuangtai, Liutuan, Xiadian and Buzhuang in Changyi City, Xinhe and Huibu in Pingdu city, and Haizheng, Shahe, Zhuwang and Xujia in Laizhou City (Fig. 6). The invaded areas on the south bank of Laizhou Bay were distributed along the coastline in a nearly east-west direction, while the invaded areas on the southeast bank of Laizhou Bay were distributed along the coastline in a northeast-southwest direction, with local protrusions or depressions and significant width changes. The width of the surveyed area in the northeast section of Jiangjia and Dazhugao was the smallest at 0.6 km, while the width of the southern section of Shuangtai and the southwest section of Taitou was the largest at 25 km. There was a significant fluctuation between Magezhuang and Liutuan in the central region, mainly due to the influence of seawater ascending along the Laihe River in the northern suburb, but the bedrock in the western part of the river was shallow, indicating that after ascending, the seawater in the Laihe River in the northern suburb invaded mainly along the east bank where the bedrock was buried deeply[11].

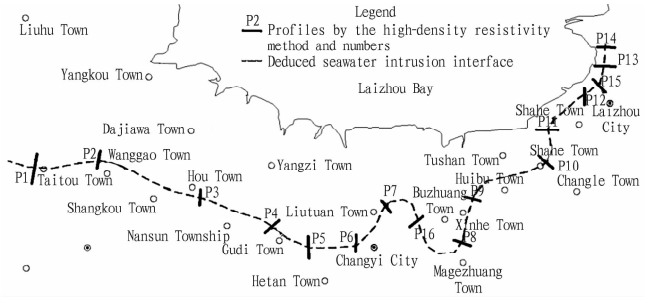

Fig. 6 Positions of profiles for the high-density resistivity method and deduced seawater intrusion interface

Conclusions and Discussion

The comprehensive factors such as the thickness of the Quaternary system, shallow surface water, surface and bedrock lithology have a significant impact on seawater intrusion and apparent resistivity. On this basis, it is necessary to comprehensively consider the use of the apparent resistivity method to investigate seawater intrusion, in order to determine the characteristic values for seawater intrusion interfaces and obtain accurate data on seawater intrusion.

The high-density resistivity method mainly measures the variation characteristics of apparent resistivity in the shallow surface, and the quality of groundwater in this part directly affects people's lives and agricultural production. Therefore, determining the interfaces of shallow surface seawater intrusion can effectively delineate disaster areas and facilitate governance and prevention.

This work determined the apparent resistivity characteristic values of seawater intrusion interfaces according to different geological conditions, and achieved good results, providing important reference materials for the use of the resistivity method in the detection of seawater intrusion disasters.

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