Imaging the underground structure beneath river bottom by DC resistivity survey using streamer cable

Hyoung-Seok Kwon(1), Jung-Ho Kim(2), Hee-Yoon Ahn(3), Jin-Sung Yoon(3), Ki-Seog Kim(3), and Toshihiro Uchida(1)

(1) *Geological Survey of Japan, AIST, Japan (caf2-kwon@aist.go.jp),* (2) *Korea Institute of Geosciene and Mineral Resources, Korea,* (3) *Heesong Geotek Co., Ltd., Korea*

ABSTRACT

Recently, the imaging of underground structure at water-covered area is in great demand due to frequent construction activities of tunnel and bridge over river or lake site. However, since water layer keeps away surface geological survey, it is hard to delineate the weak zone distribution beneath river bottom. In this point of view, DC resistivity survey is effective method because it provides subsurface image including location of fault or weak zone beneath riverbed. Even though conventional DC resistivity survey, which installs the electrode on the water bottom, gives high-resolution subsurface image, it requires lots of time and effort for installing electrodes. Therefore, easier and more convenient method has to be designed to find the developing direction of fault especially for reconnaissance survey. In this paper, we introduce a new method, named as streamer DC resistivity survey, which accomplishes continuous resistivity profiling very rapidly using boat-towed streamer cable floating on the water surface.

Through the numerical experiments for water-covered area with vertical fault below sediment, we demonstrated that fault zone could be imaged not only by water bottom installing method but also by floating electrode method when the thickness of water layer is less than twice of electrode spacing. Based on numerical study, we carried out both conventional and streamer DC resistivity surveys for the planned under-river tunnel construction site located at Han River in Seoul, Korea. In order to get high-resolution image, we accomplished conventional method that installs electrodes on the water bottom along the route of the planned tunnel. We found three low resistivity anomalies inferred as fault zones. For detecting the developing direction of these three fault zones, we applied quick and convenient streamer DC resistivity survey for three-dimensional grid survey lines. Through this practical survey, we could delineate the developing direction of fault beneath the river bottom very economically.

KEY WORDS: streamer DC resistivity survey, streamer cable, continuous resistivity profiling, water-covered area, reconnaissance survey

INTRODUCTION

Since a waterway is likely to be developed along weak zones or geological lineaments, there may exist weak zones such as faults beneath a river or lake. Thus, in order to construct a bridge or tunnel passing through a river or lake, a careful evaluation of underground condition has to be carried out. Moreover, for a construction of a tunnel beneath riverbed, the developing direction of fault is one of crucial factors for tunnel design. However, since water overlays the underground structure, only in-situ and boring tests are applied until now. Although these tests request high cost for drilling, these provide only discontinuous information. Recently, DC resistivity survey played an important role at water-covered area because it efficiently produces continuous underground image (Kim et al., 2002, Chung et al., 2001, Cho et al., 2004). In addition, since DC resistivity survey has high sensitivity to vertical structure, we can easily delineate the location of weak zones by the interpretation of its inverted image.

We have two choices of electrode installation for obtaining the DC resistivity data at water-covered area. One is installing electrodes on the water bottom and the other is floating electrodes on the water surface. We called the former as water bottom installing method and the latter floating electrode method in this paper. The water bottom installing method has high resolving power to vertical structure below riverbed, even though the streaming potential reduces the data quality. However, since it takes lots of time and efforts to install the electrode, it is inefficient to apply this method to reconnaissance survey. On the other hand, conventional floating method could be used only over a small river or lake, because it has some difficulty to keep the cable straight during measurement while it does not need extra work for installation of electrodes.

In this study, we introduced a new floating electrode method suitable for reconnaissance survey by using boat-towed streamer cable. Several updated electronic systems were equipped to the survey vessel for recording of electrode location, rapid data acquisition and guidance of the navigation of vessel. In addition, some elaborated data processing techniques were adapted to measured data in order to use conventional two-dimensional inversion software.

NUMERICAL EXPERIMENTS FOR WATER-COVERED AREA

Since the DC resistivity data at water-covered area is greatly influenced by water layer, the resistivity and shape of the water layer must be described accurately in the numerical model to get the precise subsurface image.

In numerical experiment and inversion of field data, we used the DIPROfWin, the two-dimensional resistivity interpretation software developed by KIGAM, coded based on the 2.5-dimensional finite element modeling and the smoothness constrained least-squares inversion adopting Active Constraint Balancing (ACB) method (Yi et al., 2003).

In the DC resistivity survey at water-covered area, electrodes could be installed on the water bottom or float on the water surface. Direct contact to the earth for the former case increases the emitting current to the earth and sensitivity to the subsurface anomaly. However, since it requires hard works for installing electrodes on the water bottom, it is inefficient for reconnaissance survey. Thus, we have investigated the adaptability of floating electrode on the water surface through numerical experiments, by comparing the variation of sensitivity and resolution of inverted image due to the change of the installed location of electrodes and the thickness of water layer. Figure 1 shows numerical model of the water-covered area. The vertical fault having 20 ohm-m resistivity is embedded in a 1,000 ohm-m basement below the thin sediment layer with 200 ohm-m resistivity.

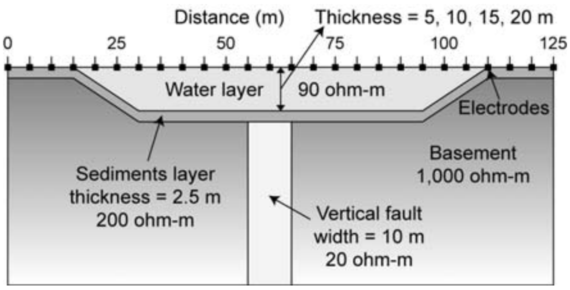
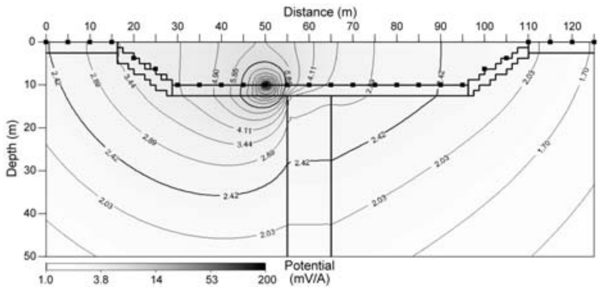


Figure 1. A schematic diagram of the numerical model of the DC resistivity survey at the water-covered area.

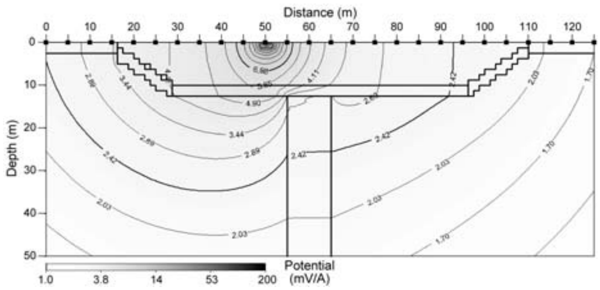
Potential distribution variation with the installing location of electrodes

Figure 2 shows one of the numerical experiments of potential distribution variation when electrode installed on the water bottom (a) and floated on the water surface (b). For this case, the thickness of water layer is set to 10 m, twice of electrode spacing, and the positive current electrode is located at 50 m position. As we can expect, for the water bottom installing method, the distortion of potential contours by the vertical fault is more evident than that of the floating case. The inverted images for these two different electrode installing cases also clearly demonstrate the same result as shown in Figure 3. Figure 3 (a) shows the inverted subsurface image of dipole-dipole survey data by water bottom installing method and (b) represents the image by the floating electrode method. The water layer is incorporated into the inversion as a fixed model and dipole-dipole array is deployed for both cases.

As numerical experiments show, the floating electrode method has disadvantage in the point of resolving power than the water bottom installing method. However, in practical sense for field survey, the floating electrode method is easier and more convenient. In addition, the numerical experiment (Figure 3 (b)) indicates that the existence of the embedded vertical fault can be recognized by this method, even though it is hard to delineate the size and location of the fault because of smearing.

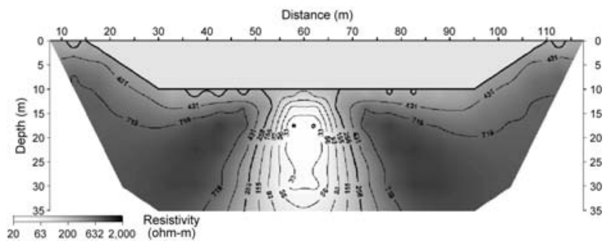


(a) Electrodes installed on the water bottom

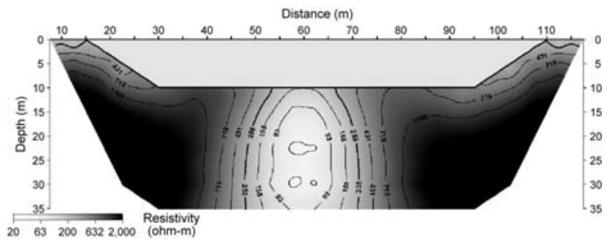


(b) Electrodes floated on the water surface

Figure 2. Potential distribution variation due to the change of installation location of electrodes when the thickness of water layer is 10 m. Black points represent the measurement points or electrode positions, and the current electrode is located at 50 m position.



(a) Electrodes installed on the water bottom



(b) Electrodes floated on the water surface

Figure 3. Inverted subsurface images, when electrodes are installed on the water bottom (a), and floated on the water surface (b). The dipole-dipole array is deployed and the thickness of water layer is set to 10 m, twice of electrode spacing.

Effect of the thickness of water layer

The thickness of water layer is also a very important factor to the resolving power in DC resistivity survey at water-covered area. In order to investigate the effect of water layer thickness for the floating method, we have drawn apparent resistivity curves for four different water layer thickness to electrode spacing (t/d) ratio (Figure 4). All models are the exactly same as shown in Figure 1. Current electrode and vertical fault are located at the position of 30 m and 55 ~ 65 m, respectively. For the aid of interpretation, we added the land survey case as dashed line to the graph in Figure 4. As shown in Figure 4, the apparent resistivity curves of the water-covered area have their minimum near the current electrode position regardless of the thickness of water layer, while that of land survey shows its minimum at the right above the vertical fault. It suggests that the water layer severely affects the measured data. However, the apparent resistivity curves for the water-covered area illustrate the decrease of the apparent resistivity around the vertical fault, but this effect diminishes as the thickness of water layer increases. From the Figure 4, it seems very hard to get the image of the fault when the water thickness is greater than twice of electrode spacing. In other point of view, through this experiment, we know that the rough image of the underground structure could be obtained by the floating electrode method if the thickness of water layer is less than twice of electrode spacing.

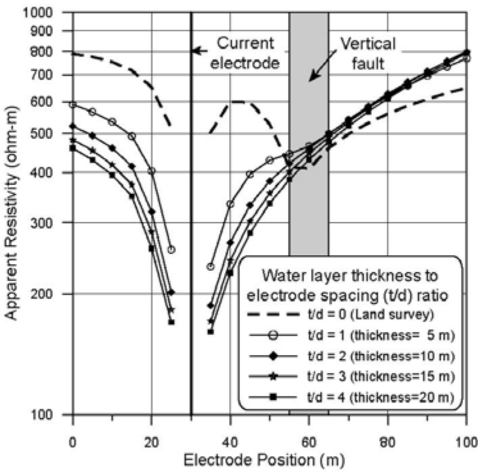


Figure 4. Variation of apparent resistivity along the profile line depending on the change of water layer thickness. The pole-pole array is deployed and electrodes are floated on the water surface with 5 m spacing. Current electrode and vertical fault are located at the position of 30 m and 55 ~ 65 m, respectively.

DC RESISTIVITY SURVEY INSTALLING ELECTRODES ON THE WATER BOTTOM

We carried out DC resistivity survey for the planned under-river tunnel construction site located at Han River in Seoul, Korea to delineate the embedded faults beneath river bottom. At the beginning, three survey lines parallel to tunnel route were designed as shown in Figure 5 (bold solid lines). One is set along the central axis of the planned tunnel route and the others are set 15 m apart from the central line to the upstream and downstream directions, respectively. Through the naked eye observation of drilled core and in-situ borehole test of this area, several faults are estimated and illustrated as dashed line in Figure 5. In order to obtain reliable high-resolution image, electrodes were installed on the river bottom. The average depth of the water layer is about 4.8 m and the maximum reaches 5.7 m. We adopted a dipole-dipole array, which shows high resolving power to the vertical structure, with 5 m electrode spacing. Waterproof electrode cable containing 30 even spaced electrodes were installed on the water bottom by scuba divers with the help of Differential Global Positioning System (DGPS) for the accurate positioning of the electrodes. As a measurement system, we used Supersting R8IP with Swift box manufactured by Advanced Geosciences, Inc. (AGI), USA. The conductivity and depth of water layer along the survey lines were also measured by digital conductivity meter and multi-beam echo sounding (MBES) device, respectively.

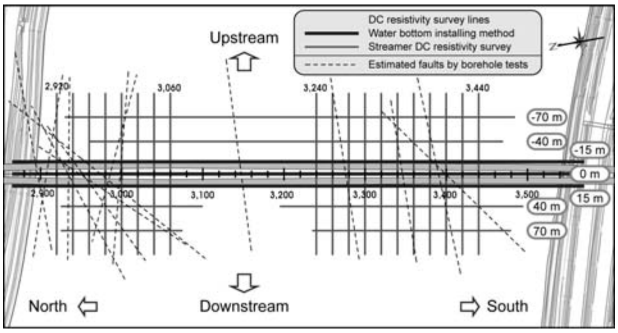


Figure 5. Location map of DC resistivity survey at Han River in Seoul, Korea. There are 7 parallel lines and 19 orthogonal ones to the planned tunnel route. Water bottom installing method is applied to central three bold lines, while streamer DC resistivity survey is applied to the others.

DC resistivity data and other information obtained through all these elaborated works were used to construct the subsurface image below the water bottom. We have illustrated inversion results with some interpretation in Figure 6. The overall resistivity value appearing on the image ranges from 100 to 5,000 ohm-m. Except for some anomalous zones, this area consists of high resistivity value higher than 1,000 ohm-m, inferred as fresh rock, below 10 m depth. For low resistivity anomalies, as expected in the stage of borehole tests, they show some connection in east-west direction. As shown in Figure 6, two or three distinctive low resistivity anomalies are appeared at the intervals of 2,920 ~ 3,040 m and 3,320 ~ 3,380 m. These are good agreements with the location of estimated faults by borehole tests shown in Figure 5. Thus these three anomalies are interpreted as fault zones that are the weakest zones in this site.

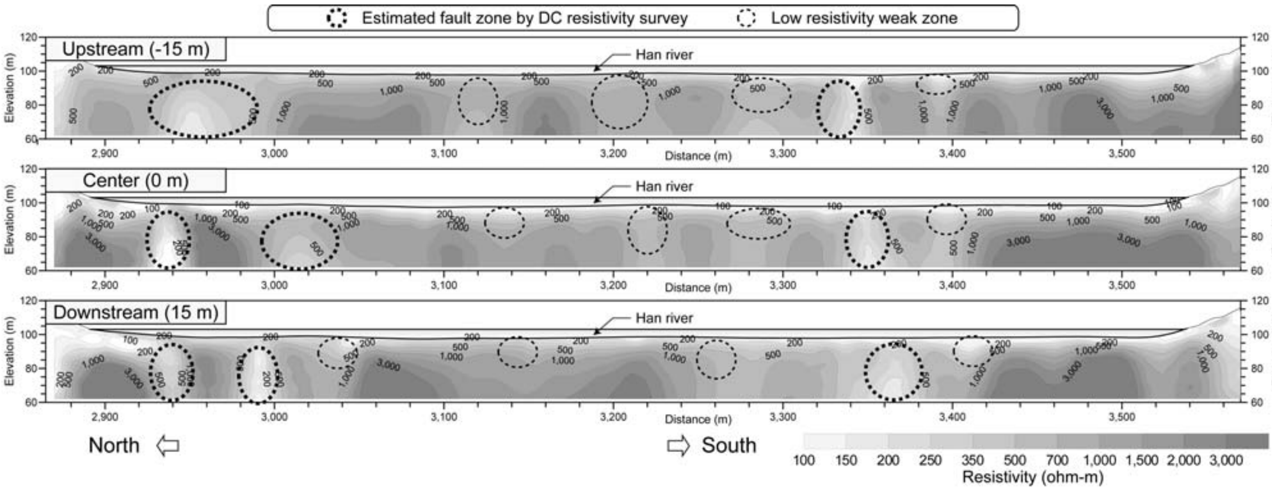


Figure 6. Three subsurface resistivity images obtained by water bottom installing method. The interpreted low resistivity weak zones are superimposed on the inversion image as dashed circle.

STREAMER DC RESISTIVITY SURVEY

In tunnel design, the information about fault direction is one of crucial factors. Thus, in order to obtain more reliable fault information, we decided to supplement dense DC resistivity survey lines around interpreted weak zones as shown in Figure 5. Even though water bottom installing method shows high resolving power and good S/N ratio, it is inefficient for grid style survey lines because it needs lots of time and effort for field work. On the other hand, conventional floating electrode method does not request time-consuming electrode installation. However, it also seems to be very hard to keep the electric cable straight against water stream when the length of survey line exceeds two or three hundred meters. So, we introduced a new quick and convenient survey method, named as streamer DC resistivity survey, which is suitable for reconnaissance survey at water-covered area (Snyder et al, 2002).

Streamer DC resistivity survey uses streamer cable towed by ship or boat, so we can easily accomplish continuous resistivity profiling without any effort for electrodes installation. However, since the streamer cable is likely to be drift by water stream, we always have to pay attention to making the cable to be straight. We devised waterproof streamer cable which is approximately 100 m in length and contains 19 electrodes with even 5 m spacing. In addition, we attached Styrofoam pipe to the streamer cable to keep electrode floating just below the water surface as shown in Figure 7. For a navigation of vessel and recording of electrode positions, DGPS system with several tenth of centimeter accuracy was boarded on the boat. Digital conductivity meter and hand-held Fathometer were also used to record the conductivity and the depth of water layer of each measurement position.

For conducting continuous resistivity profiling, the high speed multi-channel measurement system is essential, thus we used Supersting R8IP with Swift box. This instrument measures 8 potential data for single current source at the same time. Streamer DC resistivity survey also keeps away adopting some electrode arrays which have to install remote electrodes such as pole-pole, pole-dipole and dipole-pole array. Besides, it is also hard to use Schlumberger or Wenner array, because these method have to change the current electrodes as the increasing of the electrode spacing. It means that we could not measure several data simultaneously despite of using multi-channel system.

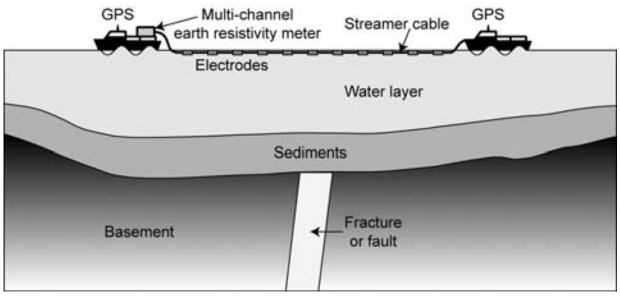


Figure 7. Schematic diagram of the layout of streamer DC resistivity survey at water-covered area. GPS is mounted on the vessel to provide the exact location of electrodes for each measuring moment. The streamer cable contains 19 electrodes with even 5 m spacing and it is towed by vessel.

Considering all the conditions, in this survey, we used two different kinds of electrode arrays; dipole-dipole and modified pole-pole arrays, per each survey line to enhance the reliability of measured data. The modified pole-pole array is a new technique to replace the remote negative current and potential electrodes with the electrodes located at two ends of the streamer cable (Kim et al., 2001). In order to reduce measuring time and number of stacking, we tried to increase the current emitting. The 3.6 second measuring time and no stacking of data could produce a reliable data quality due to this high current emitting about 350 mA, and each data was acquired with about 6.5 second interval. Consequently, since the navigating speed of vessel is 35 m/min, we could obtain one data set for each current source with 4 meter interval.

In the processing stage, first of all, we evaluate the electrode position and water depth for all measurement data. Second, all the measured data are projected onto the planned straight survey line with the assumption that there is no severe horizontal variation of resistivity. In this stage, we eliminated some data which are projected onto the outside of the survey line. Next, we calculated even spaced resistivity and water depth using numerical interpolation which is essential for using commercial two-dimensional inversion scheme. Finally, we constructed the subsurface resistivity image by applying two-dimensional inversion to create DC resistivity data with the information of water layer.

In order to investigate the reliability and resolution of the inversion result by streamer DC resistivity, we demonstrated the inverted images of this method with those of water bottom installing method (Figure 8). In this figure, the central three images of -15, 0 and 15 m are obtained from water bottom installing method, while all the other images from streamer DC resistivity survey. As shown in Figure 8, even though the resolving power of streamer DC resistivity survey is lower than that of water bottom installing method, the inverted images clearly and consistently show the existence of low resistivity anomaly in almost all sections.

We displayed all inverted resistivity images by streamer DC survey for 4 longitudinal and 19 latitudinal survey lines with two longitudinal ones by water bottom installing method in Figure 9 using three-dimensional fence diagram for more efficient interpretation. The high resistivity more than 1,000 ohm-m at the two ends and the central part of the river are consistently delineated in most inversion sections. Moreover, the low resistivity anomalous regions less than 200 ohm-m are clearly imaged in almost all sections. Thus, we can more easily catch out the direction as well as extent of the fault using three-dimensional grid images just like Figure 9. The interpreted weak zones are developed in east-west direction as shown in Figure 9 and it matches very well to the predicted fault direction by borehole tests.

CONCLUSIONS

In water-covered area such as river or lake, water bottom installing method is suitable to the detailed survey due to high resolving power, whereas streamer DC resistivity survey, which floated electrodes on the water surface, is efficient to the reconnaissance survey owing to continuous resistivity profiling with high speed of field work.

In order to apply streamer DC resistivity survey to real field, which needs precise positioning of electrodes and high speed measurement of potential, we designed boat-towed resistivity measuring system by assembling updated electronic measurement devices. This new system mainly consists of waterproof streamer cable, multi-channel resistivity instrument, DGPS, digital conductivity meter and hand-held Fathometer. Moreover, some elaborated data processing techniques were designed for the two-dimensional interpretation. By applying these techniques, deviated measurement data are projected onto the even spaced positions of straight survey line using numerical interpolation.

Through this study, we could well demonstrate that streamer DC resistivity survey, one of the modified DC floating survey method, is powerful tool to produce a continuous subsurface resistivity image at water-covered area in a quick and economical way.

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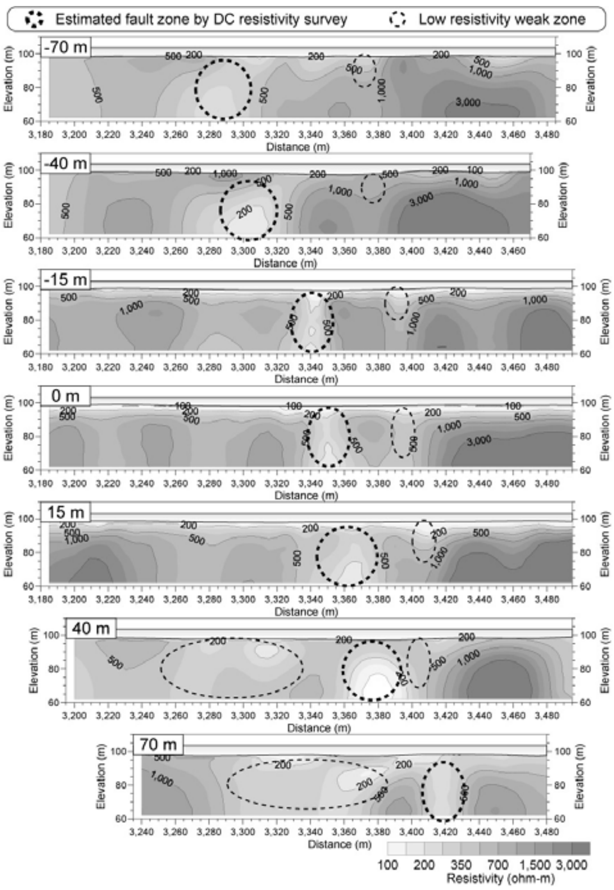

Figure 8. Comparison of inverted DC resistivity images of water bottom installing method (-15, 0 and 15 m) and streamer DC resistivity survey (-70, -40, 40 and 70 m). The survey lines of these images are parallel to the planned tunnel route with some apart to upstream or downstream side and located at south part of survey area.

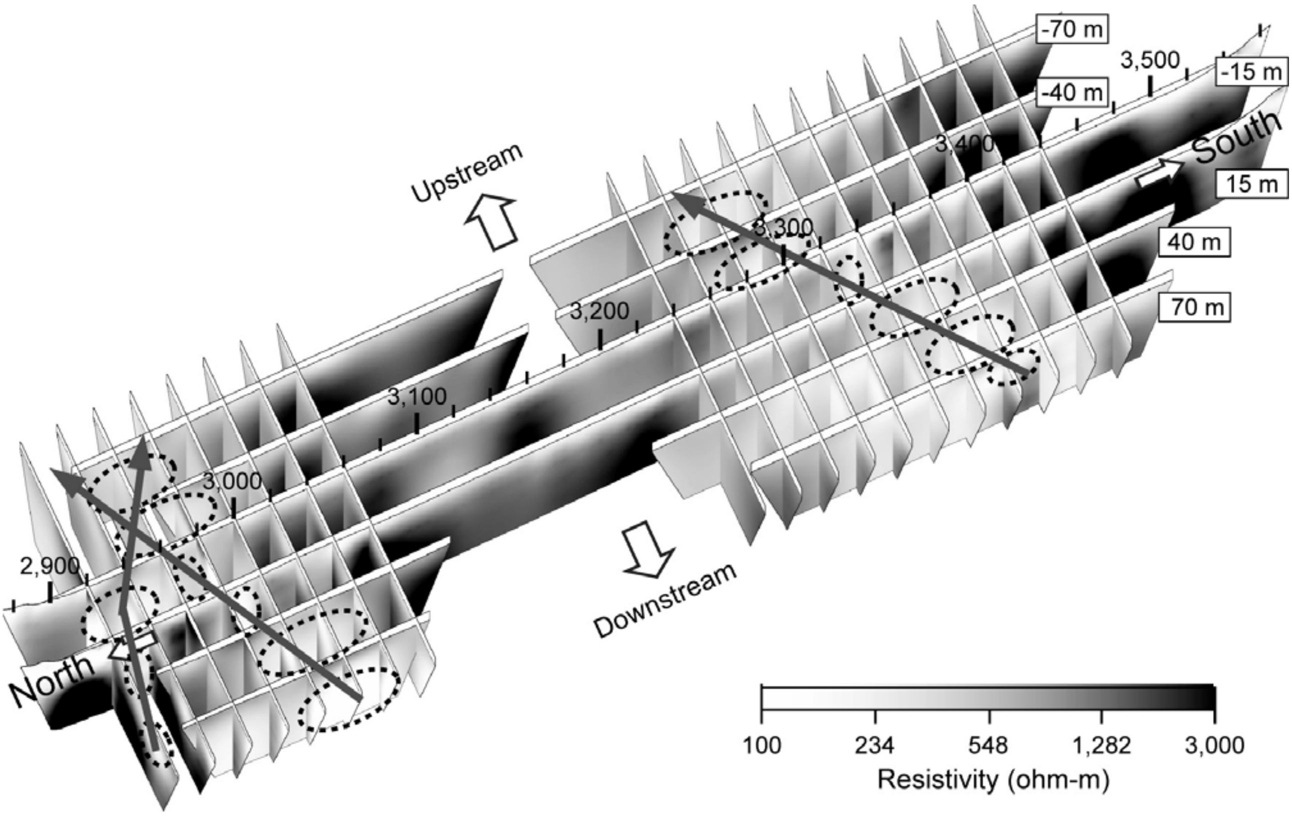

Figure 9. Three-dimensional fence diagram made by streamer DC resistivity images. The central two ones are obtained from water bottom installing method. It clearly shows the range and direction of three distinctive weak anomalous zones.

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