Mine Water Environ (2016) 35:381–388
DOI 10.1007/s10230-015-0371-3

TECHNICAL ARTICLE

# Detecting the Source of Contaminant Zones Down-Gradient of the Alborz Sharghi Coal Washing Plant Using Geo-electrical Methods, Northeastern Iran

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Received: 29 January 2015 / Accepted: 4 October 2015 / Published online: 26 October 2015


**Abstract** Environmental contamination from the Alborz Sharghi coal washing plant in northeast Iran was evaluated with geo-electrical techniques. The internal structure of a coal waste pile was first studied using one dimensional geo-electrical techniques, including a Schlumberger array. The oxidised zone had low resistivity while the unoxidised shallower and middle to deeper levels had higher resistivity. Next, the geo-electrical surveys were repeated after 6 months to investigate possible changes in the oxidation zone associated with seasonal variations. Precipitation affected the shallower levels of the pile. Two dimensional geo-electrical surveys, including a dipole–dipole array, were then conducted between the pile and tailings impoundments. Low resistivity values in the area appeared to indicate contaminated zones at depth. Again, two surveys were conducted at a 6 month interval. Results indicate the transportation of contaminants to deeper layers due to atmospheric precipitation. Considering the expansion of the contamination zones, the results of prior chemical analysis of the tailings impoundment water, and the increasing trend of the resistivity values in the deeper layers of the pile, seepage from the tailings impoundment is the most likely source of pollution in the area.

**Keywords** Coal waste pile · Tailings impoundment · Time lapse method · Transportation of contaminated plume

**Electronic supplementary material** The online version of this article (doi:10.1007/s10230-015-0371-3) contains supplementary material, which is available to authorized users.

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## Introduction

Unfortunately, coal mining, and associated coal washing processing and beneficiation, has frequently had serious environmental consequences, especially acid mine drainage (AMD) in these areas. The coal wastes produced by washing plants are generally placed in impoundments and coal waste piles near the plants. The impoundments contain wet, fine-grained particles derived from the flotation process, while the waste piles contain dry, coarser particles from jig machines.

Electrical and electromagnetic geophysical methods have increasingly been used to detect contaminated areas. There have been many geo-electrical investigations conducted to assess environmental problems posed from waste rock piles and tailings impoundments (Gómez et al. 2010; Mele et al. 2013; Rucker et al. 2009; Villain et al. 2015; Yuval and Oldenburg 1996).

The Alborz Sharghi coal washing plant is the largest coal producer in northeast Iran, with an annual production of 600,000 t. The area has a mountainous climate, with an average precipitation of 133.7 mm per year (Rainfall data of Semnan Province 2012). The temperature in the area ranges from about −10 °C in winter to about 40 °C in summer. The plant was established 35 years ago and processes coal extracted from the Tabas and Alborz Sharghi coal mines, including the Tazareh, Olang, and some private mines in the region. The coal is washed in the plant by flotation and jig processes, with a recovery value less than 50 %. Therefore, about 300,000 t of waste is annually produced by the plant. This waste is deposited in two tailings impoundments and several waste piles nearby (Fig. 1; modified from Jodeiri Shokri et al. 2014). The oldest coal waste pile was established in 1999 immediately down-gradient of the plant, and in 2012, it was approximately 20 m in height, and covered about 15,000 $m^2$. A residential area with agricultural activities is located 10 km further downstream.

Research on the problems being caused by the waste pile has been going on for several years. Doulati Ardejani et al. (2008) developed a combined mathematical-geophysical model for the pyrite oxidation in the pile. They also conducted a very low frequency (VLF) survey down-gradient of the pile to identify the likely contaminant plumes and conductive zones. Then, the expansion of plumes was investigated by a simple mathematical model and geo-electrical techniques incorporating a time-lapse technique. Both the geophysical investigation and mathematical model showed that the pollutants from the waste pile were being transported down-gradient. Doulati Ardejani et al. (2008) also characterized the geochemistry and mineralogy of the coal wastes, and studied the hydrogeochemistry of the water bodies in this area that might have been affected by the plant operations. They found that despite some physical changes to the stream, the coal waste pile had not adversely affected the water quality. Moreover, analysis of the groundwater indicated that it was even less affected by the coal washing operation. They also found that the water in the impoundments had a neutral pH, but elevated total dissolved solids (TDS) and sulphate.

Amirkhani Shiraz et al. (2013) investigated the contaminant plumes down-gradient of the coal washing plant using a combination of geo-electrical and electromagnetic (EM) methods, including EM-34 conductivity, VLF-EM, and direct current (DC) resistivity. Their 2-D resistivity models (created by inverting the EM34 conductivity data) showed some low-resistivity contaminant plumes.

Jodeiri Shokri et al. (2014) used a combination of geochemical and geo-electrical methods on the surface of the same waste pile. They used several geo-electrical methods, including 1-D sounding with a Schlumberger array, and 2-D profiling with a dipole–dipole array and the time-lapse technique. They showed that the pile has four ascending resistivity layers and that the pyrite oxidation was occurring in the shallower layers of the pile where the oxygen was reaching the waste particles. They also presented a

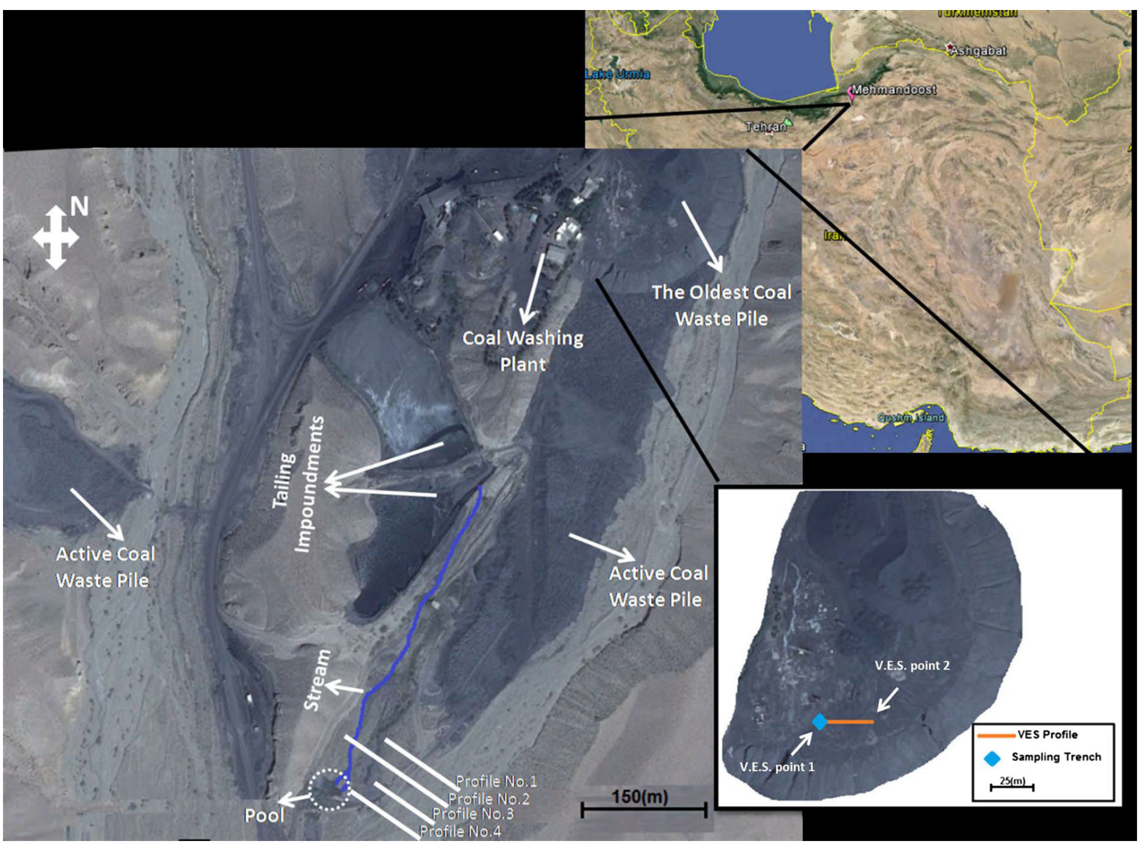


**Fig. 1** Geographical situation of the study area (modified after Jodeiri Shokri et al. 2014)

simple linear relationship between the fraction of pyrite remaining versus measured apparent resistivity from their 1-D investigation.

However, the source of the contamination downstream of the plant remained undefined; instead, the oldest waste pile was simply assumed to be the main contaminant source. The possibility that the impoundments could be responsible for the contaminated area downstream of the pile was apparently not considered. In this study, we used geo-electrical methods to identify the likely source of the pollution down-gradient of the Alborz Sharghi coal washing plant and investigate contaminant transport. To do this, we conducted the relatively simple 1-D geo-electrical sounding with a Schlumberger array on the surface of the oldest waste pile, and combined those results with a geochemical analysis to study the pile's effect on the environment. We also used 2-D geo-electrical techniques with a dipole–dipole array in the area encompassing the impoundments and the oldest waste pile to assess whether the contamination was coming from the impoundments or the waste pile. Finally the results from the 1-D and 2-D geo-electrical surveys were combined with the geochemical data to identify the main source of the contaminant plume. In addition, the effect of seasonal precipitation variations on the waste pile and the contaminated zone was evaluated by the time-lapse method at a 6 months interval.

## Materials and Methods

### Sampling

To investigate the pyrite oxidation process within the pile, four samples about 1 kg each were vertically taken at 0.5 m intervals from a trench that had been excavated on the surface of the pile. The sampling was carried out from the pile surface to a depth of 2 m, in June 2012. The samples were then transported to the mineral processing laboratory of Tehran Polytechnic where the chemical and mineralogical constituents of the wastes were determined by X-ray diffraction (XRD), using an Equnix 3000. For this purpose, the solid samples were ground with an agate mill and analysed immediately. In addition, all of the samples were fixed in epoxy resin and then prepared as standard polished sections. Optical microscopy was used to characterise the oxidation process within the waste particles.

### Geo-electrical Survey Design

To investigate the inner structure of the oldest waste pile, 1-D geo-electrical soundings were carried out in two locations on the pile surface in June 2012 and January 2013, using a Schlumberger array with a 15 m interval. The main objective of this 1-D investigation was to determine if there was any seepage leaching from the pile into groundwater by further investigating the layered resistivity. One of the sounding locations coincided with the sampling trench. The AB/2 distance varied from 1 to 35 m. As mentioned above, the surveys were then repeated 6 months later at the same locations to investigate the effects of seasonal variations. 2-D geo-electrical profiling surveys with a dipole–dipole array were also conducted downstream of the waste pile in June 2012 and January 2013. The geo-electrical data were measured using an ABEM SAS 1000 C instrument. The objective of the first surveys was to investigate potentially contaminated zones downstream of the area. For this purpose, four parallel profiles were surveyed 30 m apart (Fig. 1). The electrode spacing was 10 m. Given the circumstances, profile locations, and operational limitations, the length of the surveyed lines ranged from 90 to 150 m. A computer program, RES2-DINV (RES2-DINV Manual 2002), was then used to perform an inversion analysis of the measured geo-electrical data.

### Time Lapse Survey

Time-lapse surveys give valuable information about pollution monitoring, infiltration or recharge zones, and leachate recirculation hydrodynamics (Clément et al. 2011). In this method, resistivity measurements are repeated at different times using the same survey lines or surveys grids (Loke et al. 2013). Seasonal parameters, such as temperature and precipitation, can directly affect measured resistivity data in time-lapse surveys (Hayley et al. 2007; Leroux and Dahlin 2006; Singha et al. 2015), especially when the data are being used for quantitative estimation of ionic concentrations or moisture content (Hayley et al. 2007). In this study, the second survey was conducted to better understand how the anticipated plumes might have changed over time. To achieve this, the 2-D surveys were repeated 180 days after the first survey, along profiles No. 1 to 4 (Fig. 1).

## Results and Discussion

### Geochemical Investigations

Figure 2 shows polished sections of the samples collected from the trench at three different depths; the remaining pyrite can be easily seen. As it is evident from the figure, the pyrite content increased from the surface to a depth of 2 m. It seems that the oxygen easily diffused into the pore space at the shallower depths and oxidised the pyrite. There is a sharp increase in the pyrite content in the upper layers of the pile below that.

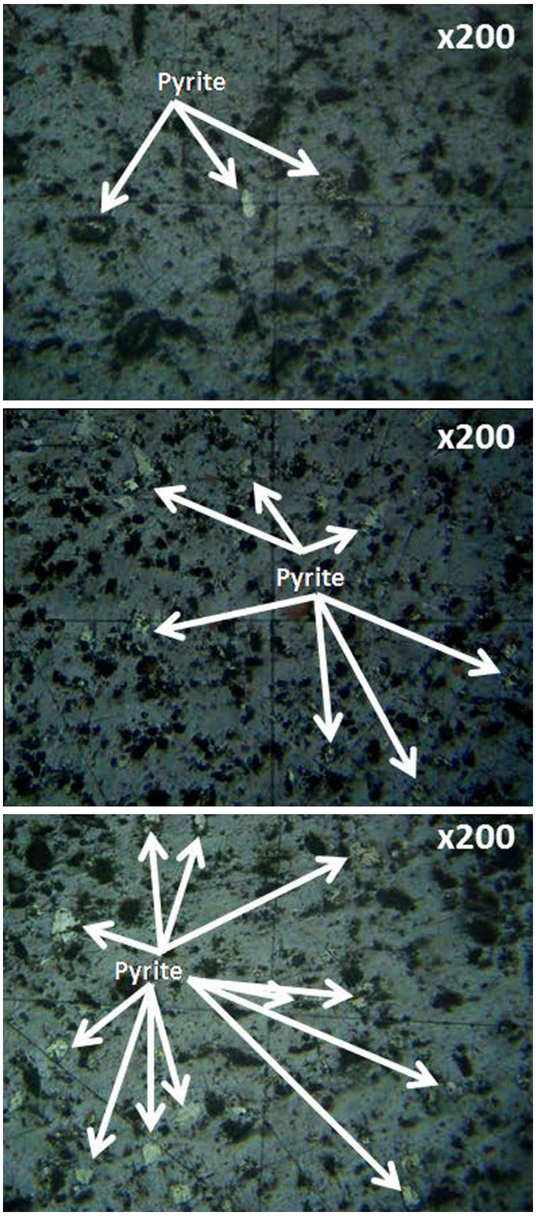


**Fig. 2** Polished section of the solid samples in the waste pile

The XRD results for the quantitative comparison of the waste are shown in Supplemental Figs. 1 and 2 for the 1 and 2 m depth samples. Cristobalite and quartz were the primary minerals, and gypsum, illite, and clinochlore were present as secondary minerals. The increase in the secondary minerals intensities (gypsum, for instance) with depth indicates that a hardpan layer may have formed at a depth of 2 m.

## Interpretation of the 1-D Geo-electrical Surveys

The results of resistivity models for soundings Nos. 1 and 2 are given in Table 1 and Fig. 3. As is evident from the table, the first layer, with a thickness of 1.5 m, has a very low resistivity value (35 Ω m), while the second and third layers are thicker (2.5 and 15 m, respectively) and more resistive (around 70 and 150 Ω m, respectively). The low resistivity values in the shallower depth could be due to various reasons, including pyrite oxidation and higher moisture content. However, it appears likely that it is due to more pore space due to less compaction of coal in the surface layers. This allows oxygen and surface recharge to reach the reaction sites within the waste more easily, which facilitates pyrite oxidation and AMD generation. Pyrite oxidation and its subsequent reaction products lead to lower resistivity values in the shallower zones.

Based on previous studies in the area, oxygen diffusion virtually ceases below a depth of 2 m. The oxidation products (dissolved $Fe^{2+}$, $Fe^{3+}$, sulphate, and trace metals), reduces the resistivity values in the shallower depths. The existence of a hardpan layer at depths between 2 and about 4 m (Jodeiri Shokri et al. 2014) also limits oxygen diffusion by decreasing the porosity and permeability. In contrast, deeper layers of the pile include unoxidised pyrite, which along with the presence of variable amounts of coal impurities, such as ash, would also increase the coal waste's resistivity.

The fourth resistive layer, with a resistivity value of 250 Ω m, at a depth of 20 m below the pile surface, showed that pyrite oxidation has ceased at shallower depths of the pile, and that oxidation products had not reached the bottom of the pile. This would seem to imply that the pile might have a less significant impact on the downstream area. Comparison of the first and second geo-electrical surveys revealed that seasonal variations in precipitation had little effect on the pile's resistivity.

## Interpretation of the 2-D Geo-electrical Surveys

The resistivity inverse models of the first 2-D surveys are shown in Fig. 4. The RMS errors along the four parallel profiles, No. 1 through 4, were 3.3, 5.6, 3.4, and 3.2 %, respectively. The low RMS errors of the models indicate good correlation between the field data and the model responses. As is evident from the figure, two major zones were detected downstream of the plant:

(a) Resistive Zone

The upper segment contains a series of resistive layers with resistivities greater than 120 Ω m (green to purple). The high resistivity may be due to the presence of alluvial sediments that included coarse particles. However, the first surveys were carried out in the dry season, which also might have impacted the resistivity. The thickness of the zone ranged from the ground surface to an approximate depth of 18 m. According to the field observations, some of

**Table 1** (1-D) resistivity model of soundings 1 and 2 of the first and second surveys

| Layer | Station 1 | | | | Station 2 | | | |
|---|---|---|---|---|---|---|---|---|
| | First survey | | Second survey | | First survey | | Second survey | |
| | Resistivity (Ω m) | Depth (m) | Resistivity (Ω m) | Depth (m) | Resistivity (Ω m) | Depth (m) | Resistivity (Ω m) | Depth (m) |
| 1 | 35 | 1.7 | 27 | 1.8 | 35 | 2 | 27 | 1.7 |
| 2 | 66 | 4.1 | 59 | 3.7 | 57 | 4 | 53 | 3.6 |
| 3 | 135 | 19 | 130 | 18 | 123 | 17 | 129 | 17.5 |
| 4 | 254 | | 267 | | 248 | | 258 | |
| RMSE (%) | 3.99 | | 3.47 | | 3.44 | | 4.32 | |

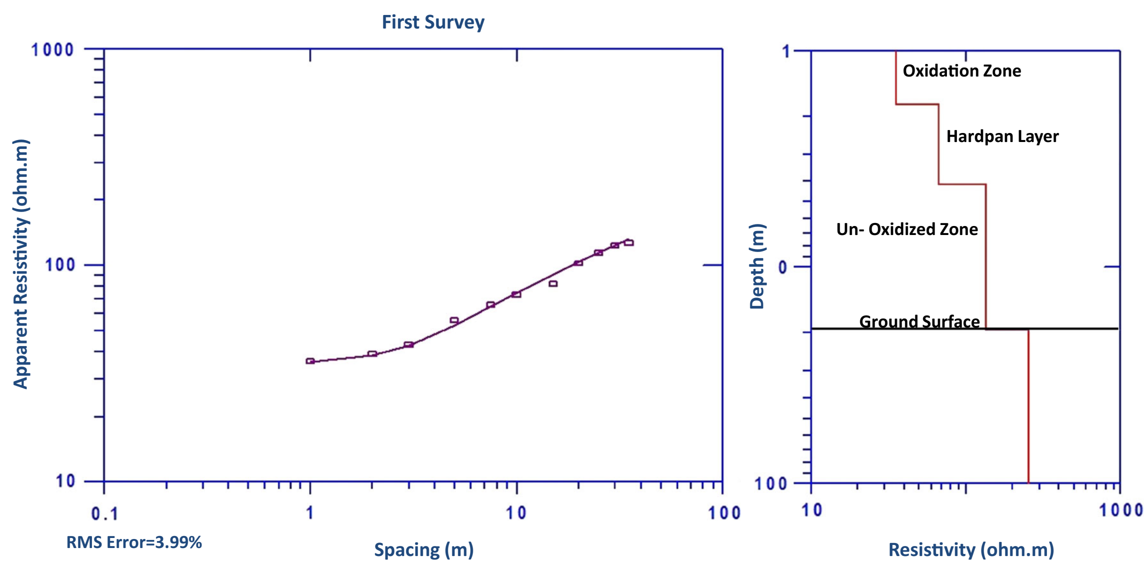


**Fig. 3** Inverted resistivity model (*right*) and *curve* fitting of measured and calculated apparent resistivity (*left*) of sounding No. 1 of the first survey

the profiles, i.e. profiles 2 through 4, intercepted the surface streams.

(b) Conductive Zone

The second zone includes a series of conductive layers with resistivity values less than 20 Ω m (light blue to dark blue), which can be interpreted as a contaminant zone. Previous studies revealed that TDS, TSS, and sulphate were high (1977, 3780, and 1600 ppm, respectively) within the tailings impoundments (Ardejani et al. 2011), which would greatly lower resistivity (Benson et al. 1997; Ebraheem et al. 1990; Gómez et al. 2010; Yuval and Oldenburg 1996). It seems that the most likely source of the contaminated groundwater are the tailings impoundments and the surface stream located southeast of the tailings impoundments. The contaminants were then transported from the ground surface (e.g. in profile No. 2 and the segment between 7.5 and 25 m from the beginning of the profile) to the deeper layers and spread laterally.

## Interpretation of the Time-Lapse Surveys

A time-lapse technique was used to further investigate the contaminant plumes (Figs. 5, 6). The inverted resistivity models of the second survey are shown in Fig. 5, while the percentage changes in resistivity along the profiles are illustrated in Fig. 6. In other words, Fig. 6 indicates the differences in resistivity between the first and second surveys.

Due to temperature differences (40 °C during the first survey and 0 °C during the second), the resistivity values of the second survey was less than the first, at depths of 0–2 m. Below that, the overall decline in resistivity to an approximate depth of 11 m, is believed to be due to the effects of precipitation and the higher water content of these layers. Moreover, it seems that the contaminants were transported deeper, since the percentage changes in resistivity increased (e.g. in profile No. 2, the segment between 45 and 65 m, and at depths between 12 and 21 m).

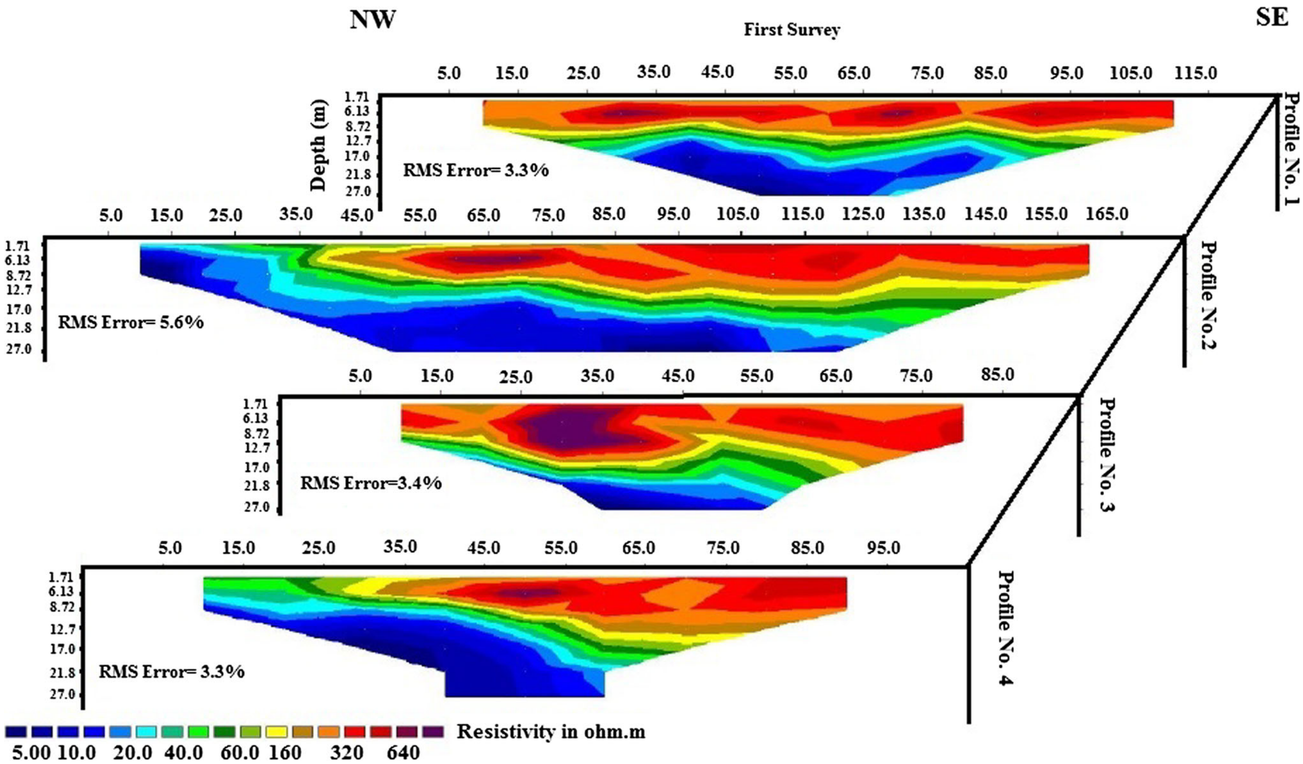


**Fig. 4** Inverted resistivity models of the first survey along four parallel profiles down-gradient of the plant

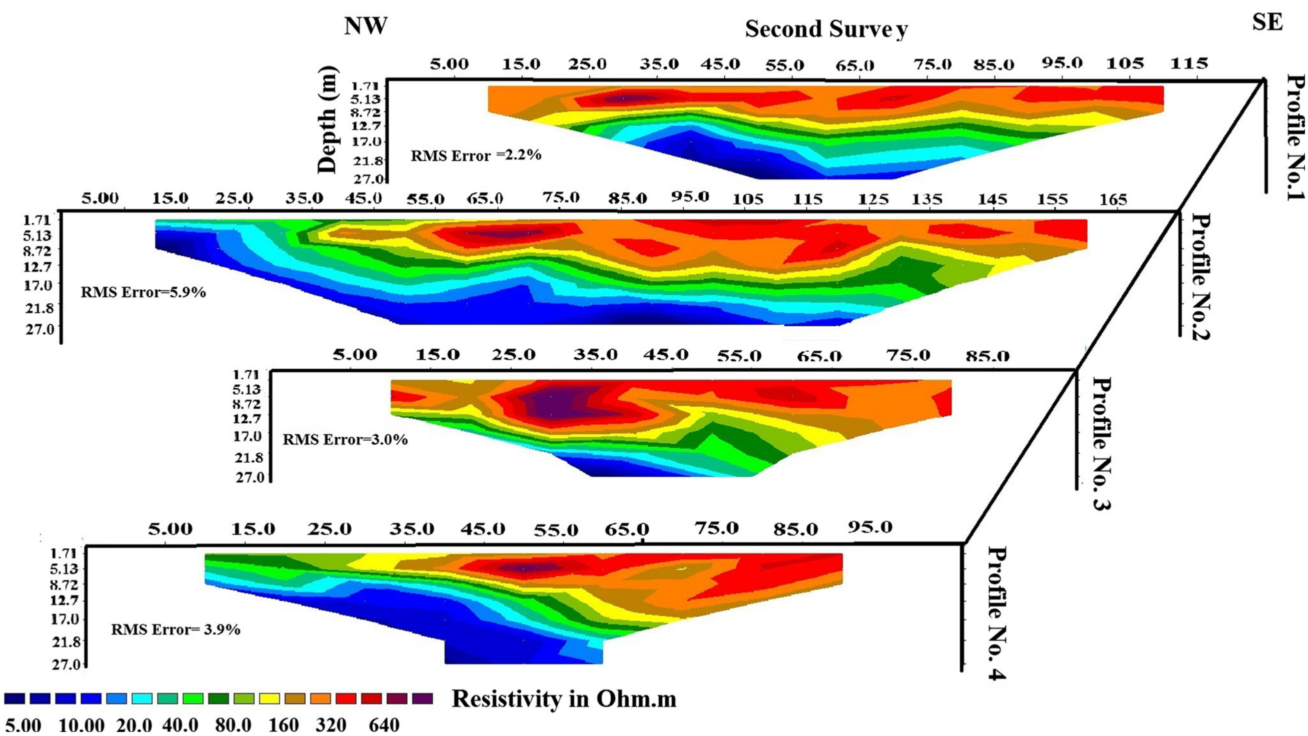


**Fig. 5** Inverted resistivity models of the second survey along four parallel profiles down-gradient of the plant

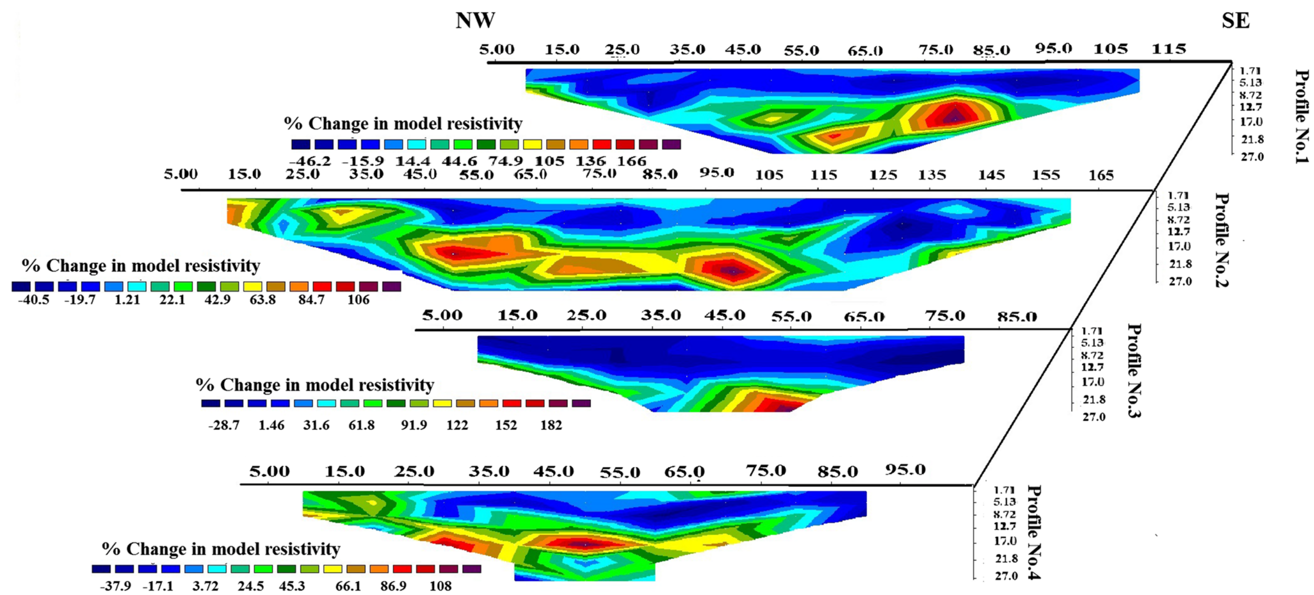


**Fig. 6** Percentage changes in model resistivity of the second survey with respect to the first survey along four parallel profiles down-gradient of the plant

## Conclusions

One dimensional geo-electrical sounding with a Schlumberger array was used to investigate the internal structure of the oldest coal waste pile and detection of the any seepage to groundwater in the Alborz Sharghi coal washing plant. The results indicate that the pile is a four-layer ascending resistivity system. It seems that pyrite oxidation is mostly limited to the shallower depths of the pile where the resistivity is low. These corresponded to the geochemical analysis. However, the high resistivity values beneath the pile indicated that the pile might not be the major source of contaminated zones downstream of the pile. 2-D geo-electrical surveys with a dipole–dipole array were conducted along four parallel profiles to investigate the likely contaminated zones downstream of the plant. The results showed two different resistivity zones. The resistive zones were in the upper layers, from the ground surface to an approximate depth of 12 m. Below that zone, low resistivity values are believed to indicate contaminated zones derived from the tailings impoundments. Finally, changes in the resistivity trends appeared to indicate that the contaminants penetrated to deeper layers due to atmospheric precipitation.

**Acknowledgments** The authors acknowledge the technical support of the Amirkabir University of Technology (Tehran Polytechnic). We are also grateful to the Alborz Sharghi Coal Company for supporting this research.

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