



Detection of subsurface cavity due to old mine workings using electrical resistivity tomography: A case study

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The present study deals with the detection of underground concealed voids/cavities/galleries in Chinchuria railway station, Raniganj coalfield in India for ground stabilization using electrical resistivity tomography (ERT) technique. Initially, numerical analysis of ERT data was carried out using Wenner–Schlumberger and dipole–dipole array configurations corrupted by 5–10% Gaussian random noise for better understanding of real field conditions. The two types of voids, i.e., water and air, filled in old mine workings were simulated accordingly in the forward model. The dipole–dipole array provides superior results compared to Wenner–Schlumberger array. Considerable accuracy of voids/cavities/galleries dimension could be acquired from dipole–dipole array. In field, two number of ERT profiles (Profile-AA' and Profile-BB') were conducted over the study area using said configurations. The data was acquired using Syscal-Pro resistivity imaging system with 96 electrodes and the data processing was carried out using the tomographic inversion software RES2DINV to analyse true resistivity based on the robust or blocky regularization inversion technique (L_1 -norm). High resistivity contrast with backgrounds in the occurrence of possible old mine workings consisting of hard rock and alternative coal pillars interconnected cavities and mining galleries was identified. Considering the indirect approach of ERT method, a borehole was being drilled along the profile-AA' of dipole–dipole array, drilling and resistivity results indicated the presence of air-filled cavity associated with old mine workings. Hence, it is concluded that the technique used in this study is useful in increasing the technical merit of electrical resistivity interpretation for old mine workings areas.

Keywords. Cavity; ECL; ERT; Wenner–Schlumberger; dipole–dipole.

1. Introduction

In India, numerous underground mine workings are existing below railway lines and built-up areas, which is considered as the utmost of the mine workings that are old/abandoned and inaccessible. An analysis aftermath of the stability-issue condition is suspicion. Therefore, from the stability point of view, railway line is one of such important phenomena for the safety of passengers. An important issue is to identify underground cavities

due to old mine workings. It is an exciting and interesting deal for stabilization of the ground over a part of Chinchuria railway station situated in the Salanpur colliery, India.

Non-destructive methods are useful for precisely locating the cavity positions in some specific zones of interest from the surface. There are copious surface geophysical approaches to perceive subsurface cavities constructed on the physical properties of rock materials. Hutchinson *et al.* (2002) established a comparative work amid numerous

geophysical techniques over void investigation. Chalikakis *et al.* (2011) demonstrated an influence of geophysical measurements to complex environmental issues. Riddle *et al.* (2010) carried out research on surface geophysical performances and their superiorities as well as restrictions for tunnels and voids recognition and research done by Johnson *et al.* (2002) demonstrated all surface geophysical techniques and their limitations for delineation of underground old mine workings.

The electrical resistivity tomography (ERT) method was extensively espoused in the field of near-surface problems, complex environments and engineering geophysics that helps to get subsurface distribution of electrical properties. This technique is capable to detect subsurface buried cavities, geotechnical problems and geological structures such as faults, fractures, unconformities and depth of bedrocks. The subsurface voids that are related to old underground mine may be filled with air or water that could be smoothly mapped due to high resistivity incongruity with circumstances (Van Schoor 2005; Ezersky 2008; Cardarelli *et al.* 2010; Metwaly and AlFouzan 2013; Martínez-Pagán *et al.* 2013; Martínez-Moreno *et al.* 2014; Bharti *et al.* 2015, 2016a, b, c, 2021; Das *et al.* 2017; Singh *et al.* 2019; Saurabh *et al.* 2020).

Several studies on cavity detection were successfully carried out using ERT methods; Zhou *et al.* (2002) showed effective electrode configuration in demarcating of karst hazards using ERT method. They have used three distinct ordinary electrode arrays, i.e., Wenner, Schlumberger, and dipole–dipole. Among the three, dipole–dipole array delivers the superior result for characterization of possible sinkhole collapse area and is sensitive to vertical boundaries. Cardarelli *et al.* (2006) used electrical resistivity tomography to detect buried cavities. Their result showed that ERT is one of the most powerful techniques for the delineation of buried cavities and possible hazards in caves with respect to both performance and the low cost of investigation. Barbosa *et al.* (2020) assessed iron caves using electrical resistivity contrast to enhance certainty of cave injury and its monitoring issues and Bharti *et al.* (2019) have done a study on the detection of old mine workings using ERT technique. They have shown that coal pillars were recognized with comparatively high resistivity incongruity while galleries and goaf were demarcated with moderately low resistivity incongruity and their outcomes are well correlated with published results.

Balkaya *et al.* (2012) proposed high-resolution magnetic and electrical resistivity surveys for the exploration of caves in western Turkey. They suggested that the geophysical survey techniques provide useful information in detecting a cave located deep enough to make human exploration difficult. In the present study, geophysical ERT techniques were used to delineate and map underground concealed voids/cavities/galleries in Chinchuria railway station, Raniganj coalfield in India for ground stabilization.

2. Study area

The study was conducted in Chinchuria railway station situated in the Salanpur colliery, ECL, Raniganj coalfield in India as shown in figure 1. Salanpur area covers two coal mine collieries, viz., Bonbiddi village and Balsuk ceramics and colony. Balsuk ceramics and colony is considerably exaggerated by the uncertainty due to the unnecessary withdrawal of underground coal. Previously, the area was affected by extensive extraction of coal by illegal miners, hence the deficiency of sand stowing in the area turns out to be unstable. The coal formation in Raniganj coal belt is deposited in the Gondwana period. Different depositional strata, coal thickness, and the value of coal were eventuated by different geological formations conferring to geological era, rock type, and the study between coal fire and geology. Coal seams are situated in the Raniganj and Barakar rock formation. The coal substances of upper Permian age contain fine-grained feldspathic sandstones and shales with coal seams. Raniganj coal-bearing formation is influenced by igneous invasion as a form of sills and dykes (Gupta 1999; Guha and Vinod 2012).

3. Methodology

To demonstrate the process and magnitude of subsurface structure effects on 2D ERT surveys, a synthetic model was conducted using RES2DMOD software. It is useful in geophysics both as a tool to interpret data in a research setting and as a tool to develop physical understanding in an educational setting. In the present work, water and air-filled cavities due to underground old/abandoned coal mine working were modelled through forward model. The forward model, shown in figure 2(a) contains three subsurface layers, viz., (i) soil/alluvium (100 Ω m), (ii) sandstone/shale

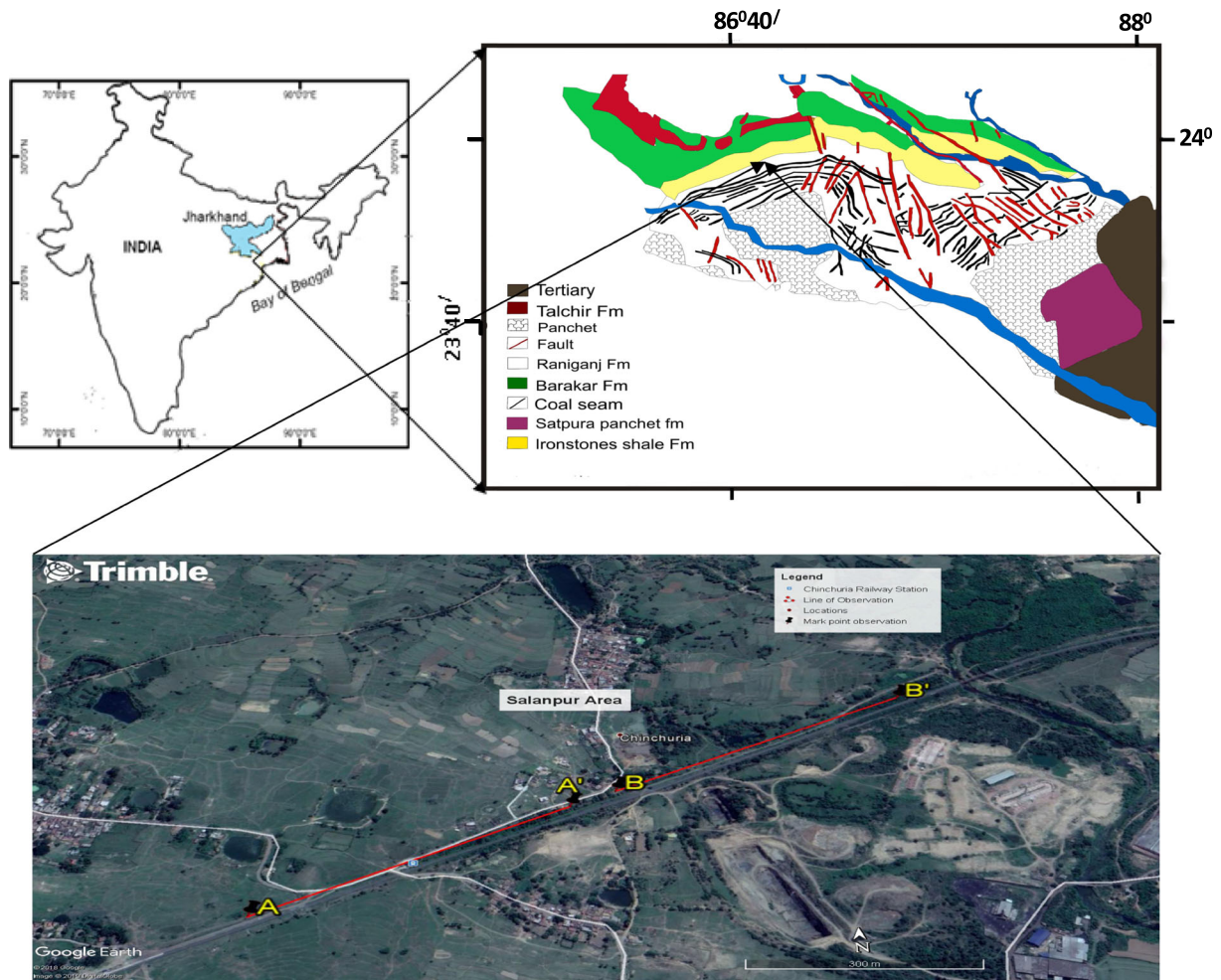


Figure 1. Location map of the study area along with generalised geological map of Raniganj coal field (modified after GSI 2003).

layer ($500 \Omega\text{m}$), and (iii) coal-bearing strata ($700 \Omega\text{m}$) with water-filled ($10 \Omega\text{m}$) and air-filled ($10000 \Omega\text{m}$) cavity were designed through RES2DMOD software. Finite difference algorithm technique was implemented, in which the subsurface was divided into numerous rectangular blocks (Loke and Barker 1996).

The forward model comprised of 64 electrodes with interval of 5 m (figure 2). The subsurface cavities associated with old mine workings are expected to be filled with derbies of stone, gravels and coal crumbles, etc., produced by natural slabbing and roof falls of developed galleries with time. The model has been framed keeping in view all the possibilities of expected fully water-filled cavity (WFC) and air-filled cavity (AFC) which is characterized by relatively low-resistivity and high-resistivity values, respectively. Wenner-Schlumberger and dipole-dipole array were used for simulation of resistivity response in the model for acquiring more realistic information of

resistivity variation with depth. Gaussian noise of 5–10% was included in the synthetic data to simulate field conditions. It is estimated that the dipole-dipole array gives better results with approximate locations, extensions, dimensions and depths of air and water-filled cavity associated with old mine workings compared to the Wenner-Schlumberger array.

Additionally, figure 3 represents the geological formation assuming a water- and air-filled cavity without the coal-bearing layer to identify the effects of final inversion tomogram. All model parameters and geological formations were kept identical to the previous model. Noise is added to the synthetic data by random values generated with Gaussian distribution (i.e., with the mean value equal to zero and the standard deviation equal to 5–10% of the unperturbed resistivity values). In this model, only dipole-dipole array could be able to delineate the water-filled cavity with its location, depth, and extent, but failed to delineate

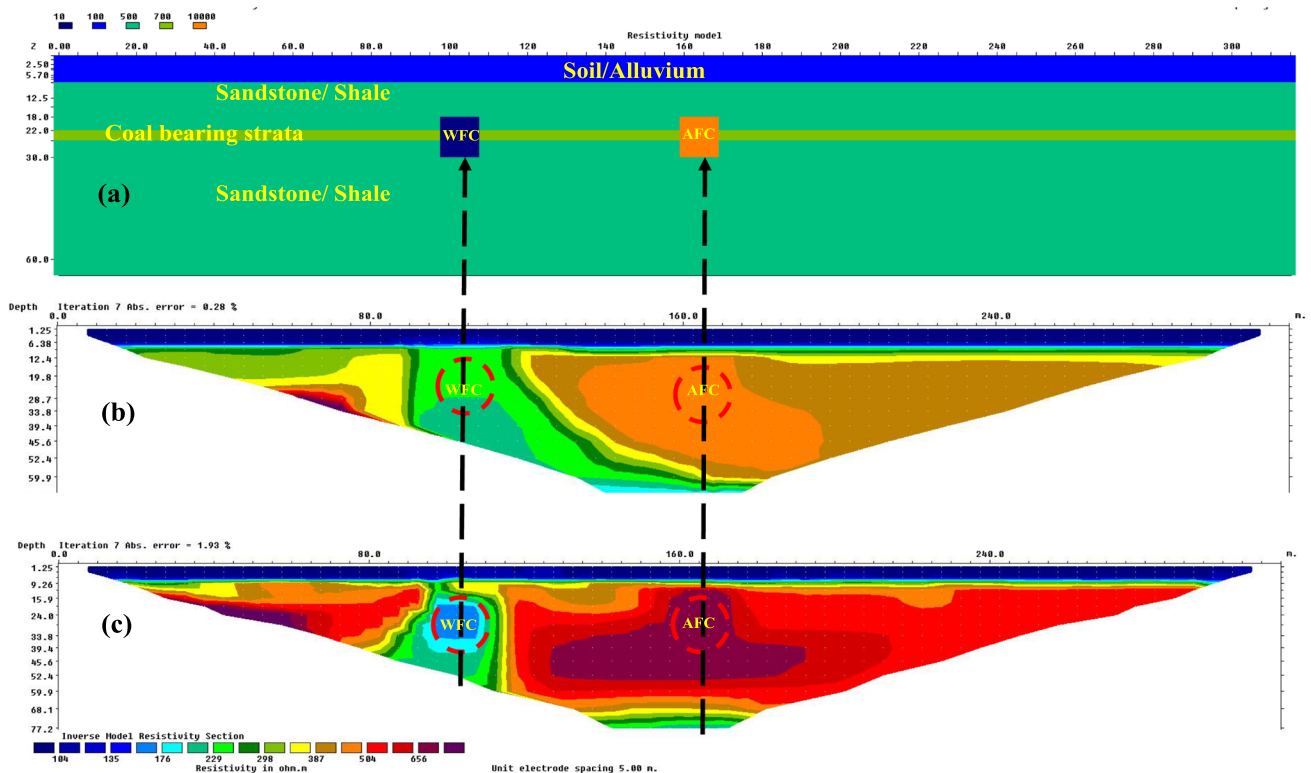


Figure 2. (a) 2D ERT section of a synthetic geoelectric model of underground old/abandoned coal mine working. Inverted resistivity section generated by (b) Wenner–Schlumberger and (c) dipole–dipole configurations.

the air-filled cavity associated with sandstone/shale formations.

Further, geoelectric field data are acquired using Syscal Pro 10-channel resistivity imaging system with 96 electrodes commonly referred to as multi-electrode resistivity technique, which includes a large number of electrodes located along a line at the same time and carries out an automatic switching of these electrodes for acquiring profile data. The Syscal Pro measures voltages between electrodes resulting from an applied current, which is set in terms of the applied voltage. Data was collected with the stacking (min-3 and max-6) and quality factor (Qmax-5). Quality factor is defined as the standard deviation of the ratio of voltage to current of consecutive readings and is expressed in percentage. Quality factor, i.e., standard deviation is expressed in %. As long as the quality factor is greater than the introduced value, the measurement will run-up to the specific stack max, i.e., maximum number of stacks (injection cycle). If not, it will stop the stack min, i.e., minimum number of stacks (injection cycle). Quality factor X means that the (100–X)% of the acquired data is of good quality whereas X% is noisy. This also indicates that (100–X)% of the acquired data is under

desired confidence level with good quality and consistency.

4. Results and discussions

2D ERT profiles, viz., AA' and BB' were preferred over Chinchuria railway station situated in the Salanpur colliery, ECL, Raniganj coalfield in India to map subsurface concealed voids/cavities/galleries associated with abandoned/old underground mine workings for evaluation of ground stabilization and any potential subsidence hazards using Wenner–Schlumberger and dipole–dipole array. The grid of depth level of collected data of both arrays was the same. The software (ELECTRE-PRO) allows to use up to nine different spacings in the sequence ($a = X$ grid spacing); this is very useful for quality improvement and especially in case of measurements in conductive areas. So, from a depth level (generally 6 or 8), the spacing is doubled ($2 \times X$ grid spacing) and could be also tripled or more ($n \times X$ grid spacing) for higher values of depth levels to be able to get relatively high-level signals for large investigation depths. The survey consisted of two number of ERT profiles, parallel

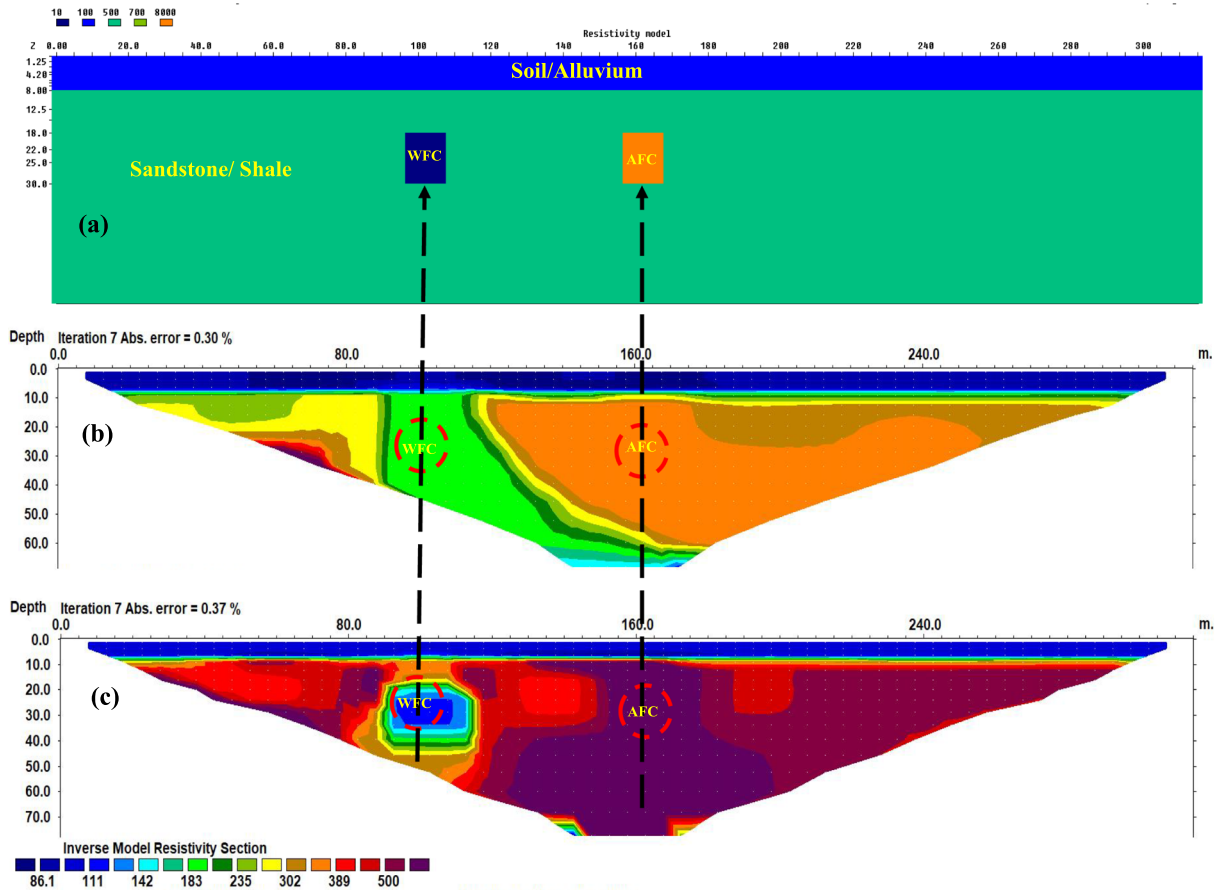


Figure 3. (a) 2D ERT section of a synthetic geoelectric model of underground old/abandoned coal mine working without coal-bearing strata. Inverted resistivity section generated by (b) Wenner–Schlumberger, and (c) dipole–dipole configurations.

to railway track at an offset of 10 m at different locations approximately 480 m in length due to space constraint with electrode interval of 5 m. The collected data were processed using PROSYS II software. Further, optimum fit for resistivity model, L_1 -norm regularization inversion technique (also called robust or blocky method) was used for inversion by handling software RES2DINV (Sasaki 1992; Loke and Barker 1996; Loke 1997). This technique minimizes the absolute differences between measured and calculated apparent resistivity values by an iterative process (Loke *et al.* 2003; Wolke and Schwetlick 1988), in which the accuracy of the data fit is expressed in terms of the absolute error (Claerbout and Muir 1973). The calculated pseudo-sections could be achieved by either finite-difference or finite-element methods (Coggon 1971; Dey and Morrison 1979).

The interpretation of 2DERT section is based on the inverse model created by RES2DINV, which used variation of resistivity range to high and low anomalous identified by separate resistive value. A minimal difference was identified between model

response and measured data so that many iterations were carried out over this study. This difference is computed in the form of an absolute (Abs.) error value. 2D ERT models of profile AA' and profile BB' were projected by Wenner–Schlumberger and dipole–dipole array based on the inversion modelled resistivity. Details of the possible stratigraphic model are shown in figures 4 and 6, respectively.

5. Geoelectric section of profile AA'

The inverse model of the geoelectric section of profile AA' estimated by Wenner–Schlumberger array, topmost layer possibility of alluvium/soil having relatively low resistivity ranging 02–62 Ω m with depth of \sim 10 m was recognized throughout the profile (figure 4a). A prominent, highly resistive zone more than 800 Ω m is visible near-surface distance of about 80–240 m. This zone seems to have a depth extent of 30–80 m. Observing from huge resistivity distinction, it is likely that this

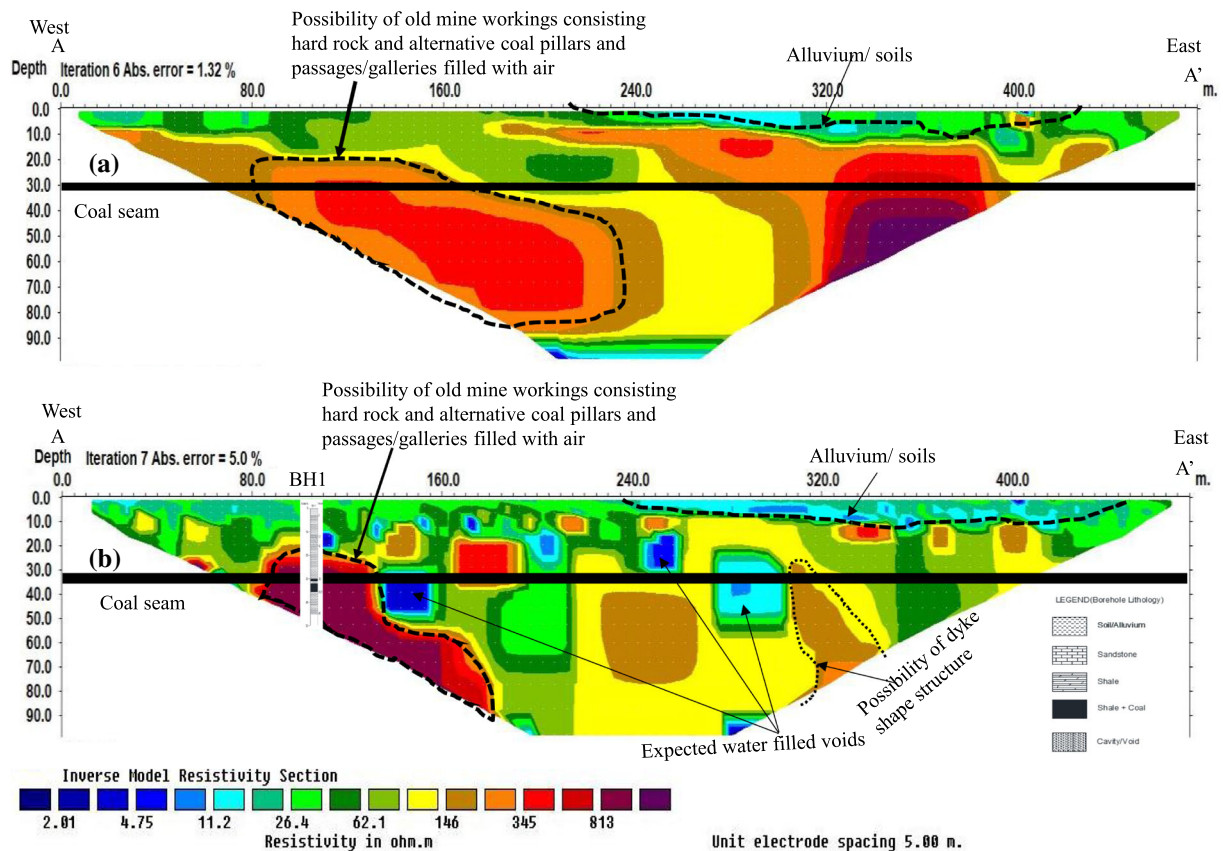


Figure 4. 2D ERT section along profile AA' over Chinchuria railway station (a) Wenner–Schlumberger array and (b) dipole–dipole array with quality factor 5.

feature is the response of an old mine working consisting of hard rock and alternative coal pillars and passages/galleries filled with air. Beneath this, a low resistivity region 2–26 Ωm revealed at a depth up to the depth of penetration lying at a surface distance between 170 and 265 m, which is inferred as the possibility of water-filled cavity, the corresponding features are marked by a black thick dotted line.

The resistivity model displays a heterogeneous subsurface outline of the geological formation appearance, a huge distinction in resistivity from near-surface layers to the deeper depths, which is estimated based on dipole–dipole array (figure 4b). Alluvium/soil having a relatively low resistivity ranging 2–62 Ωm with a depth of ~ 10 m was identified throughout the inverse model section. The possibility of old mine workings consisting of hard rock and alternative coal pillars and passages/galleries filled with air was delineated at near-surface distance of about 80–200 m with depth from 30 to 85 m, having comparatively high resistivity of more than 800 Ωm , the corresponding features are marked by black thick dotted line. The general anomaly pattern in both sections is almost

similar. In addition, a possible three voids filled with loose sediments partially saturated by water having low resistivity of about 2–11 Ωm were identified at surface distance of nearby 140–165 m, 240–260 m and 275–300 m with a depth range of 30–45 m, 12–28 m and 18–45 m. The existence of the low zone filled with water was not delineated by Wenner–Schlumberger array caused by possible deviation from the 2D ERT data that interrupts the arrays differently, depending on different sensitivity patterns. Further, a signature of comparatively high resistive fractured rock/ weathered rock/dyke like structure at lateral distance of 305–340 m at a depth of about 22 m were recognized with resistivity of ~ 300 Ωm , the corresponding features are marked by black thin dotted line.

Measurement errors could play a pivotal role in ERT inversion. To enhance the scientific sound of investigations, we prepared a statistical analysis of calculated apparent resistivity, observed apparent resistivity, true resistivity and measured resistivity dataset of profile-AA' (dipole–dipole array) as shown in figure 5. It represents the calculated apparent resistivity, and observed apparent

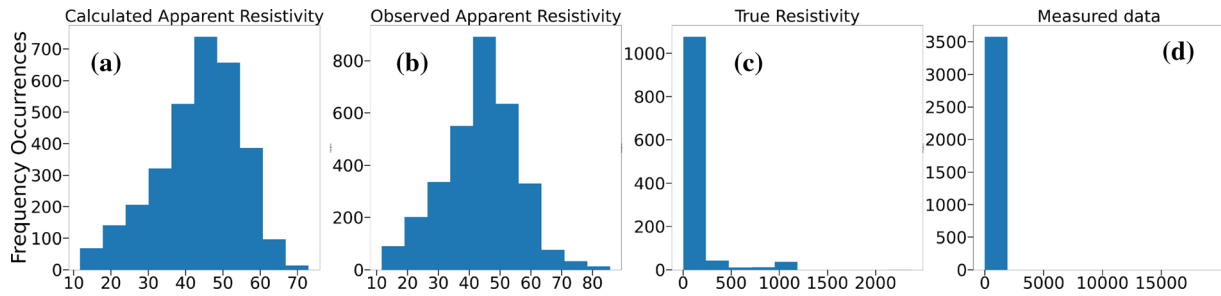


Figure 5. Statistical analysis of profile AA' (a) calculated apparent resistivity, (b) observed apparent resistivity, (c) true resistivity, and (d) measured resistivity data.

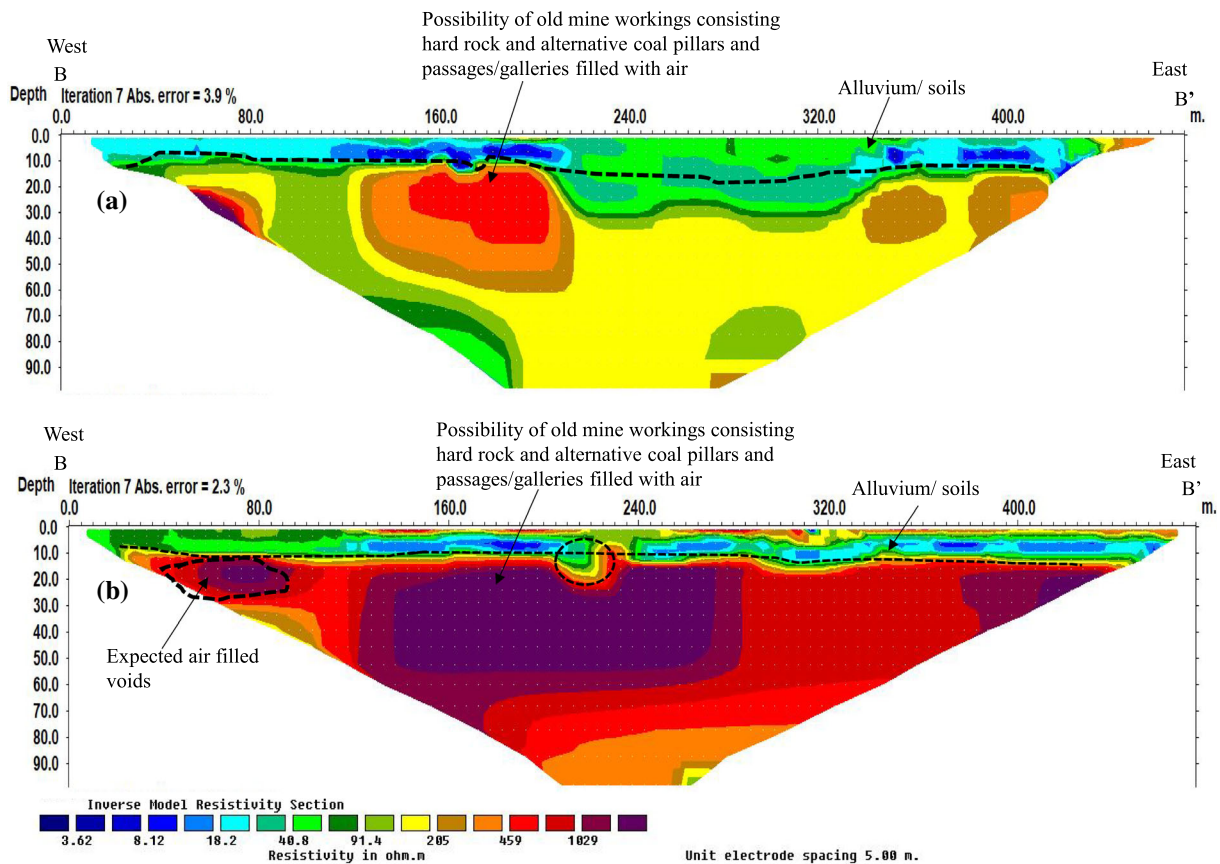


Figure 6. 2D ERT section along profile BB' over Chinchuria railway station (a) Wenner-Schlumberger array and (b) dipole-dipole array with quality factor 5.

resistivity data were almost the same pattern with some deviations. The true and measured field data was showing the spike-like pattern which was effectively identical. Therefore, it is a much better fit obtained by each of 96 electrodes datasets individually. This process is easy to implement and requires minimal changes to the current practice. Extensively applying this process in imminent ERT studies could significantly improve their overall reliability.

6. Geoelectric model of Profile BB'

A layer formation of alluvium/soil with average thickness of ~10 m from the surface having low resistivity of about 03–90 Ωm, which is growing thicker in west to east direction, were identified in 2D ERT section of profile BB' based on Wenner-Schlumberger array as shown in figure 6(a). A possibility of an old mine workings consisting of hard rock and alternative coal pillars and

passages/galleries filled with air was delineated at a surface distance of 125–215 m with high resistivity of about more than 1000 Ωm at the depth of about 15–55m.

Further, in the 2D ERT imaging section of profile BB' estimated by dipole–dipole array, a layer formation of alluvium/soil with typical thickness of ~8 m from the surface having relatively low resistivity of about 3–90 Ωm were delineated (figure 6b). Afterwards, it is followed by an increase in resistivity with depth. A possible old mine working consisting of hard rock and alternative coal pillars and passages/galleries filled with air was delineated near-surface distance of about 125–265 m with relatively high resistivity of about more than 1000 Ωm at the depth of about 15–65 m, the corresponding features are marked by black thick dotted line. The low resistivity zone with ~40 Ωm between surface distance 205–220 m possibly indicated fractured and subsidized zone just above the sandstone/coal-bearing strata. In addition, expected air-filled void having

moderately high resistivity of about more than 1029 Ωm were identified at surface distance of nearby 50–90 m with shallow depth range of 10–22 m.

7. General discussions

It is perceived from both synthetic and field data of profiles AA' and BB' that horizontal structures were demarcated healthy in 2D geoelectric sections estimated by Wenner–Schlumberger array but it is bad for determining vertical features (Loke 1999; Dahlin and Zhou 2004, 2006). However, dipole–dipole array is moderately good to determine vertical resistivity contrast. Wenner–Schlumberger configuration which gives good quality data both in lateral and vertical variations to delineate subsurface complex geometry and to identify the potential location of subsurface features. The choosing of this array was because of its significance to study areas in which both lateral and vertical

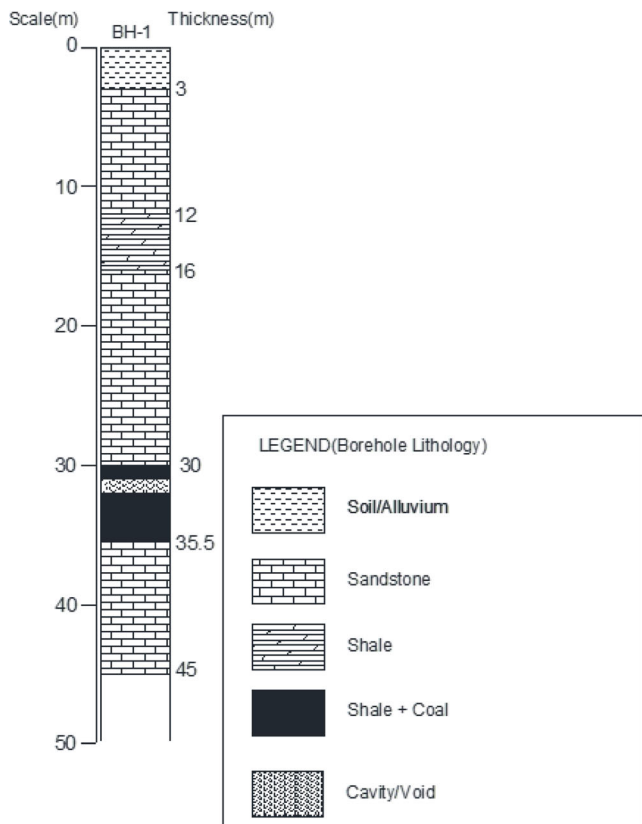


Figure 7. Borehole lithological section of BH-1 along profile AA' with core sample.

discrepancies of resistivity are existing. The resultant in regions where both types of geological structures were anticipated, this array capacity be a good compromise between the Wenner and the dipole–dipole array. Dipole–dipole array is ascetically sensitive to horizontal resistivity dissimilarity, nevertheless reasonably insensitive to vertical resistivity dissimilarity. Therefore, the dipole–dipole results are more predictable to be affected by near-surface variation noise, it provides high resolution than Wenner–Schlumberger array. It also delineates maximum number of resistivity anomalies resulting from different possible old mine voids/galleries. Under such situations, the Wenner–Schlumberger configuration is less effective substitute. Academically, each type of array has its merits and demerits because the investigation of subsurface geological characteristics with more than one array at the same location and it may provide the different geoelectrical inverse models because of their inconsistent conceptual and applied advantages and disadvantages (Athanasίου 2004; Athanasίου *et al.* 2007).

Based on resistivity imaging survey, borehole was drilled in the survey area at a lateral distance of about 100 m along profile AA' generated by dipole–dipole array as shown in figure 7. The drilling location was selected based on the strength of the anomalies, i.e., high resistivity contrast zone. Continuous core samples were collected from the borehole to probe the composition of soils and rocks. The interpretation was consistent with borehole data which demonstrated that cavity/void occurs approximately at the same depth of around 30 m (figure 7) where possible old mine workings consisting of hard rock and alternative coal pillars interconnected cavities and mining galleries were found from profile AA'. This is validated based on the outcomes of borehole. From the above measurement, it is established that a 1-m thick cavity uniformly at a depth of 30 m could not be delineated distinctly, which shows that the existing electrical resistivity contrast over void is not sufficient for demarcation. Therefore, these models display that the cavities/voids associated with old mine workings, which are of small size compared to the depth of their occurrence do not show clear cut anomalies in the inverted sections, it is confirmed through a forward modelling (figures 2 and 3), whether they are formed. The study was conducted on an investigational basis, and this shows that the resistivity imaging technique could not discriminate the cavities/voids formed due to

quarry of coal seams in underground mines, but could discriminate the water-filled cavities/voids from the surrounding rocks in such mining areas. It is also confirmed through a forward modelling.

8. Conclusions

This study has shown how ERT can be used effectively to assess subsurface concealed voids/cavities/galleries associated with abandoned/old underground mine workings for evaluation of ground stabilization and any potential subsidence hazards in Chinchuria railway station at part of the Salanpur colliery, Raniganjh coalfield in India.

The inverted sections of ERT results based on the synthetic model show that the accuracy of the mapping of cavities in mining environment with Wenner–Schlumberger and dipole–dipole arrays. Dipole–dipole array has higher vertical and lateral resolution and due to this, the apparent resistivity anomaly is highly matched to the location of subsurface old mine workings (abandoned galleries) with their location, extension and dimension.

Further, the field study was carried out along two profiles using Wenner–Schlumberger and dipole–dipole arrays. A possible old mine workings consisting of hard rock and alternative coal pillars interconnected cavities and mining galleries was delineated from profile AA' of dipole–dipole array. It is considered as a high resistivity contrast zone, i.e., ranging from 400 to 800 Ωm juxtaposed with the neighbouring rocks, whereas water-filled voids combined with the neighbouring rocks relatively show low resistivity value, which seemed towards south of the profiles. The obtained results were also correlated and matched well with the borehole log along the profile AA' over the study area. Subsequently, the improvements in ERT performance used statistical analysis of calculated apparent resistivity, observed apparent resistivity, true resistivity and measured resistivity data set for measurement errors. Such approaches may help us, a necessary step towards obtaining more quantitative information from geophysical methods across a range of disciplines and applications.

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Author statement

Abhay Kumar Bharti: Contribution in data acquisition, processing and interpretation and preparation of the paper. KKK Singh and CN Ghosh: Contributed in data interpretation and analysis. Kanhaiya Mishra: Contributed in field investigation.

References

- Athanasiou E 2004 Combined inversion of geoelectrical data by the use of contact electrodes; M.Sc. Thesis, Aristotle University of Thessaloniki.
- Athanasiou E N, Tsourlos P I, Papazachos C B and Tsokas G N 2007 Combined weighted inversion of electrical resistivity data arising from different array types; *J. Appl. Geophys.* **62** 124–140.
- Balkaya Ç, Göktürkler G, Erhan Z and Ekinçi Y L 2012 Exploration for a cave by magnetic and electrical resistivity surveys: Ayvacık Sinkhole example, Bozdağ, İzmir, western (Turkey); *Geophysics* **77** B135–B146.
- Bharti A K, Pal S K, Priyam P, Narayan S, Pathak V K and Sahoo S D 2015 Detection of illegal mining over Raniganj Coalfield using electrical resistivity tomography; *Engineering Geology in New Millennium*, New Delhi.
- Bharti A K, Pal S K, Priam P, Kumar S, Shalivahan S and Yadav P K 2016a Subsurface cavity detection over Patherdih colliery, Jharia Coalfield, India using electrical resistivity tomography; *Environ. Earth. Sci.* **75**(5) 1–17.
- Bharti A K, Pal S K, Priam P, Pathak V K, Kumar R and Ranjan S K 2016b Detection of illegal mine voids using electrical resistivity tomography: The case study of Raniganj coalfield (India); *Eng. Geol.* **213** 120–132.
- Bharti A K, Pal S K, Ranjan S K, Priyam P and Pathak V K 2016c Coal mine cavity detection using electrical resistivity tomography: A joint inversion of multi array data; *22nd European Meeting of Environmental and Engineering Geophysics, EAGE*, Barcelona, Spain, <https://doi.org/10.3997/2214-4609.201602084>.
- Bharti A K, Pal S K, Saurabh Kumar S, Mondal S, Singh K K K and Singh P K 2019 Detection of old mine workings over a part of Jharia Coal Field, India using electrical resistivity tomography; *J. Geol. Soc. India* **94**(3) 290–296.
- Bharti A K, Prakash A, Verma A and Singh K K K 2021 Assessment of hydrological condition in strata associated with old mine working during and post-monsoon using electrical resistivity tomography: A case study; *Bull. Eng. Geol. Environ.* **80** 5159–5166.
- Barbosa M K, Braga M A, Gama M F P, Paula R G, Brandi L V and Dias L S D O 2020 Electrical resistivity contrast in the geotechnical assessment of iron caves, N4EN mine, Carajas, Brazil; *Geophysics* **85** B1–B7.
- Cardarelli E, Di Filippo G and Tuccinardi E 2006 Electrical resistivity tomography to detect buried cavities in Rome: A case study; *Near. Surf. Geophys.* **4** 387–392.
- Cardarelli E, Cercato M, Cerreto A and Di Filippo G 2010 Electrical resistivity and seismic refraction tomography to detect buried cavities; *Geophys. Prospect.* **58** 685–695.
- Chalikakis K, Plagnes V, Guerin R, Bosch F and Valois R 2011 Contribution of geophysical methods to karst-system exploration: An overview; *Hydrogeol. J.* **19**(6) 1169–1180, <https://doi.org/10.1007/s10040-011-0746-x>.
- Clairbout J F and Muir F 1973 Robust modeling with erratic data; *Geophysics* **38** 826–844.
- Coggon J H 1971 Electromagnetic and electrical modelling by the finite element method; *Geophysics* **36** 132–155.
- Dahlin T and Zhou B 2004 A numerical comparison of 2D resistivity imaging with 10 electrode arrays; *Geophys. Prospect.* **52** 379–398, <https://doi.org/10.1111/j.1365-2478.2004.00423.x>.
- Dahlin T and Zhou B 2006 Multiple-gradient array measurements for multichannel 2D resistivity imaging; *Near Surf. Geophys.* **4** 113–123.
- Das P, Pal S K, Mohanty P R, Priyam P, Bharti A K and Kumar R 2017 Abandoned mine galleries detection using electrical resistivity tomography method over Jharia coal field, India; *J. Geol. Soc. India* **90**2 169–174.
- Dey A and Morrison H F 1979 Resistivity modelling for arbitrarily shaped two-dimensional structures; *Geophys. Prospect.* **27** 106–136.
- Ezersky M 2008 Geoelectric structure of the Ein Gedi sinkhole occurrence site at the Dead Sea shore in Israel; *J. Appl. Geophys.* **64** 56–69.
- Guha A and Vinod K 2012 Structural controls on coal fire distribution – remote sensing-based investigation in the Raniganj coalfield, West Bengal; *J. Geol. Soc. India* **7** 467–475.
- Gupta A 1999 Early Permian Palaeo-environment in Damodar Valley coalfields, India: An overview; *Gondwana Res.* **2**(2) 149–165.
- GSI 2003 Bulletin of the Geological Survey of India; *Coalfields of India Series* **45**(A) 128–137.
- Hutchinson D J, Phillips C and Cascante G 2002 Risk considerations for crown pillar stability assessment for mine closure planning; *J. Geotech. Geol. Eng.* **20** 41–64.
- Johnson W J, Snow R E and Clark J C 2002 Surface geophysical methods for detection of underground mine workings; Abstract of Symposium on Geotechnical Methods for Mine Mapping Verifications, Charleston, West Virginia.
- Loke M H 1999 Electrical imaging surveys for environmental and engineering studies a practical guide to 2-D and 3-D surveys 63.
- Loke M H 1997 Electrical imaging surveys for environmental and engineering studies; Unpublished report, pp. 1–8.
- Loke M H and Barker R D 1996 Rapid least-squares inversion of apparent resistivity pseudo sections using a quasi-Newton method; *Geophys. Prospect.* **44** 131–152.
- Loke M H, Acworth I and Dahlin T 2003 A comparison of smooth and blocky inversion methods in 2D electrical imaging surveys; *Explor. Geophys.* **34** 182–187.
- Martínez-Pagán P, Gómez-Ortiz D, Martín-Crespo T, Manteca J I and Rosique M 2013 The electrical resistivity tomography method in the detection of shallow mining cavities. A case study on the Victoria Cave, Cartagena (SE Spain); *Eng. Geol.* **156** 1–10.
- Martínez-Moreno F J, Pedrera A, Ruano P, Galindo-Zaldívar J, Martos-Rosillo S, González-Castillo L, Sánchez-Úbeda J P and Marín-Lechado C 2014 Combined microgravity, electrical resistivity tomography and induced polarization

- to detect deeply buried caves: Algaidilla cave (Southern Spain); *Eng. Geol.* **162** 67–78.
- Metwaly M and AlFouzan F 2013 Application of 2-D geoelectrical resistivity tomography for subsurface cavity detection in the eastern part of Saudi Arabia; *Geosci. Front.* **4** 469–476.
- Riddle G I, Hickey C J and Schmitt D R 2010 Subsurface tunnel detection using electrical resistivity tomography and seismic refraction tomography: A case study; Symposium on the Application of Geophysics to Engineering and Environmental Problems, pp. 552–562.
- Sasaki Y 1992 Resolution of resistivity tomography inferred from numerical simulation; *Geophys. Prospect.* **40** 453–464.
- Saurabh S, Pal S K and Kumar R 2020 A time-lapse study using self-potential and electrical resistivity tomography methods for mapping of old mine working across railway-tracks in a part of Raniganj coalfield, India; *Environ. Earth. Sci.* **79** 332.
- Singh K K K, Bharti A K, Pal S K, Prakash A, Saurabh, Kumar R and Singh P K 2019 Delineation of fracture zone for groundwater using combined inversion technique; *Environ. Earth. Sci.* **78** 110.
- Wolke R and Schwetlick H 1988 Iteratively reweighted least-squares algorithms, convergence analysis, and numerical comparisons; *SIAM J. Sci. Stat. Comput.* **9** 907–921.
- Van Schoor M 2005 The application of in-mine electrical resistance tomography (ERT) for mapping potholes and other disruptive features ahead of mining; *J. South African Inst. Min. Metall.* **105(6)** 447.
- Zhou W, Beck B F and Adams A L 2002 Effective electrode array in mapping karst hazards in electrical resistivity tomography; *Environ. Geol.* **42** 922–928.

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