



Assessment of hydrological condition in strata associated with old mine working during and post-monsoon using electrical resistivity tomography: a case study

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Abstract

Water management is a strategic factor in old coal mine working areas due to disturbance in the aquifer caused by subsidence resulting in drying of wells and streams. Cavity formation due to underground mining leads to roof fall, heaving of clay floors and collapse of coal pillars in soft clay floors. Logging of water in old mine workings is a common phenomenon especially during rainy season. Mine water is extensively used in various mining activities, and hence, a study has been conducted in part of Jamadoba 6 and 7 Pits, Jharia coalfield, India, to assess the hydrological condition during and post-monsoon. Initially, a conceptual model has been prepared to identify the possible sources of water including its path entering into old mine workings. Electrical resistivity tomography (ERT) i.e. Wenner-Schlumberger configuration with quality factor 5 has been adopted as it is effectual and reliable in detecting subsurface cavities at shallow depth and the possible path of transmission of subsurface water into the mine void with season variation. The study helped in identification of abandoned incline, porous and permeable strata conditions. The correlation of the resistivity variations is observed to be in close approximation with working plans and available borehole lithology. This technique proved to be suitable for adopting such studies.

Keywords 2D ERT · Wenner-Schlumberger · Old mine workings · Water-filled cavity

Introduction

Scarcity of groundwater in coal mining areas is due to disturbance in aquifer zone. Outflow of groundwater at shallow depth affects in logging of water in underground workings. Geological disturbances help in leading the path for the flow of such water bodies. The surface and groundwater are a part of mining section in a catchment area (Salonen et al. 2014). Land subsidence in mining area could have a great influence on the available surface water system and groundwater storage and can cause an impact on water environment (Xu et al. 2014; Zha 2008; Zhang et al. 2014; Jinhai et al. 2018). Mine water is used for mineral processing, dust suppression and slurry transportation and hence is an extremely important resource for the mining industry. Therefore, the approachability

of water is one of the key sources for the entire mining and mineral processing industry.

The geophysical prospecting method is extensively adopted in delineation of boundary of old and abandoned underground workings and accumulation of water because of its high proficiency and non-destructive characteristics (Roy 1996; Anbazhagan and Sitharam 2008; Coles and Morgan 2010; Plati et al. 2010; Peng et al. 2016). There are several geophysical techniques, and each of them has certain advantages and limitations. For instance, (i) ground penetrating radar (GPR) possesses strong resolution but restricted to depth of investigations and topographic variation are the influencing radar signal (Davis and Annan 1989; Daniels 2005) and (ii) seismic and Rayleigh wave-layering ability is strong, but the justification to water filling is not noticeable (Yang et al. 2010); and (iii) the transient electromagnetic method (TEM), being slightly affected by topography, detects accumulation of water in underground voids prominently. It has no clear response to high-resistance anomaly (Danielsen et al. 2003; Jørgensen et al. 2003; Jiang et al. 2007; Yu et al. 2008). In previous studies, various geophysical techniques are generally used to hydrogeological conditions, landslides and

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groundwater exploration and environmental and near-surface problems. Nevertheless, there are few researches on the investigation of goaf and water-bearing areas in coal mines.

ERT method has extensive use in field of environmental, complex subsurface geology and shallow subsurface investigations. Amongst geophysical techniques, ERT has been demonstrated to be very operative and appropriate technique for detection of subsurface cavities (Abu-Shariah 2009; Pánek et al. 2010; Martínez-Moreno et al. 2014; Martínez-Pagán et al. 2013; Metwaly and AlFouzan 2013; Bharti et al. 2016a, b). Contrast resistivity, which is achieved by imagery method, helps in better detection of subsurface cavities, geological disturbances, solid bedrock, sediments, air and water-filled conditions.

A few studies were carried out in recent past years over Raniganj and Jharia coalfield for identification and delineation of mine workings. Maillol et al. (1999) studied resistivity imaging method for detection of uncharted mine galleries in Raniganj coalfield, West Bengal, India. The water-logged area in abandoned old workings at Hingir Rampur colliery was delineated by Singh (2013) using 2D resistivity imaging system by single array approach. Bharti et al. (2019) detection of old mine working over Jharia coalfield by electrical resistivity tomography technique in which coal pillars has been identified with relatively high resistivity anomaly whereas galleries and goaf have been delineated with relatively low resistivity anomaly. Krishnamurthy et al. (2009) delineated coal seam barrier thickness and demarcated water-filled voids through electrical resistivity method. Das et al. (2017) carried out investigation on abandoned coal mine galleries in Jharia coalfield, India, by resistivity imaging technique. They used Wenner, Schlumberger, dipole-dipole and gradient arrays, and the outcomes showed the existence of subsurface water and air-filled cavity due to resistivity anomaly distinction with respect to surroundings. Bharti et al. (2016a, b) studied detection of subsurface voids associated with illegal mine using electrical tomography technique over Raniganj coalfield, West Bengal, India.

Several shallow old/abandoned mine working situated in Jharia coalfield and their current status is indistinct. Thus, a state-of-art technique is required for mapping of unidentified water-logged zone due to old mine workings. The present study was conducted in the Jamadoba 6 and 7 Pit colliery, which falls in northern part of Jharia coalfield in Dhanbad District, Jharkhand, India. The key objective of the study is to delineate and map subsurface hydrological condition in strata associated with old and unapproachable mine workings using Wenner-Schlumberger configuration. Pazdirek and Blaha (1996) stated that Wenner-Schlumberger configuration is a combination of Wenner and Schlumberger arrays which is sensitive in both horizontal and vertical directions. Wenner and the dipole-dipole array combination are best suited for investigation of multiple oriented geological structures

(Loke 1999). The depth of investigation can be enhanced by 10% and a better horizontal coverage can be achieved using this combination than done only by Wenner array for the same stretch of survey (Loke 1999).

Study area

Hydrological condition in strata associated with old mine working was assessed at Jamadoba 6 and 7 Pit colliery of Jharia coalfield, India (Fig. 1). The stratigraphy of Jharia coalfield is unconformable overlying Archean basement. The rock formation belongs to the Lower Gondwana group rocks of Permian age comprising Talchir, Barakar, Barren measures and Raniganj formations, from bottom to top (Chandra 1992). After completion of development in coal seam in chess board pattern, coal is extracted in the form of panels. These panels are generally maintained in subcritical dimension to prevent structural damages by minimising subsidence magnitude. The available borehole section located in the vicinity of the study area is shown in Fig. 2.

A concept of water entering in old mine out area

As a general concept water inundates goaf area by the various geological activities, and natural process is shown in Fig. 3. In most mining operations, water is pursued from groundwater, streams, rivers and lakes, heavy rain fall, or through commercial water service suppliers. Old mine workings at shallow depth are subjected to inrush of water mostly from the drainage basin and hydraulic connections. The amount of free water accumulated in the pore space is nearly washed out. It is mainly depending on rainfall infiltration into the rock mass, and the inflow time is flexible and depends on the route through which the water wanders. Subsidence caused by underground mining operation affects surface water due to change in topography and also affects groundwater due to disturbance of strata.

Methodology

ERT technique is a non-conventional geophysical method experienced in the form of profiling and sounding to interpret respectively lateral and vertical structures of subsurface characterizations. The application of ERT technique is related to current scattering of the subsurface. The information related to geological disturbances which are concealed from the surface can be uncovered by resistivity method (Keller and Frischknecht 1966; Telford et al. 1976). Sedimentary rock is typically characterized by porosity, bearing high water content. In general, resistivity of coal range in 50 to $10^5 \Omega \text{ m}$ (Verma and Bhui 1979; Singh et al. 2004) while sandstone, shale, clay, water and limestone have resistivity range of 8–4

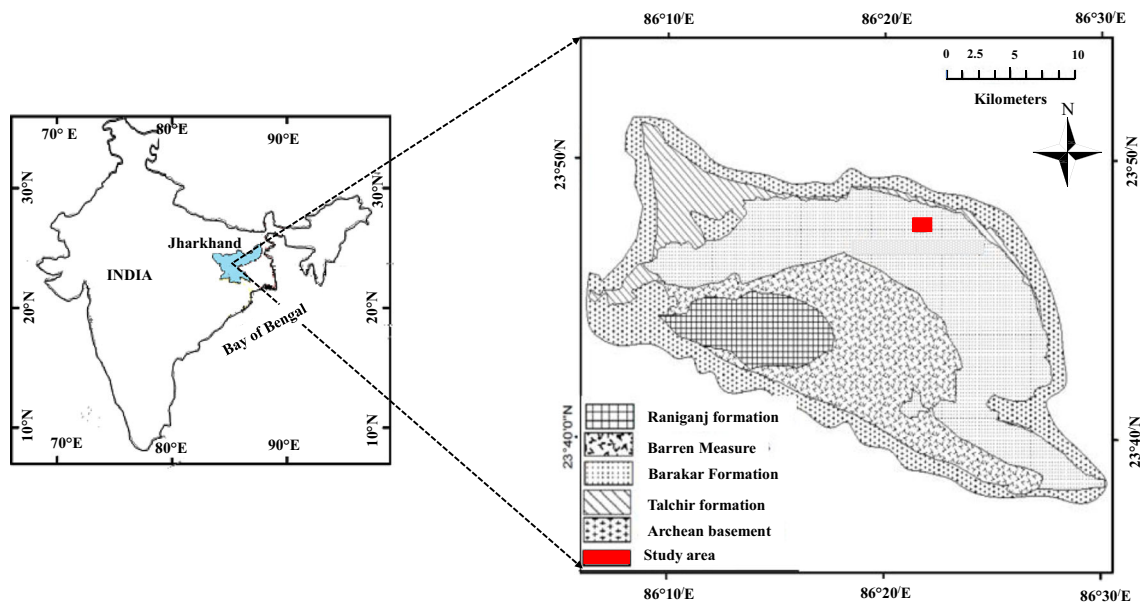


Fig. 1 Location map the study area along with generalized map of the Jharia coal field

$\times 10^3$, $20-2 \times 10^3$, $1-100$, $10-100$ and $50-4 \times 10^2 \Omega$ m, respectively (Keller and Frischknecht 1966).

Electrodes are fixed firmly on the ground surface at equal interval, and direct current is transmitted in the ground

through current electrodes, and potential difference is measured via potential electrodes. A suitable configuration for the current and potential electrodes is adopted based on the objective of the study.

Field measurements were made using a state-of-the-art Syscal Pro 96 Standard and Switch (IRIS Instrument system multi-electrode resistivity meter) which can be connected to 96 electrodes simultaneously, and 10 channels of resistivity meter for resistivity and chargeability measurements over the possible old mine working in a Jamadoba 6 and 7 Pit colliery as shown in Fig. 4. Based on the availability of space in the field area for water condition in strata due to old mine working, ERT survey was carried out using appropriate configuration i.e. Wenner-Schlumberger arrangement, with 5-m electrode spacing for prospecting purpose during and post-monsoon. Total length of survey profile was 480 m.

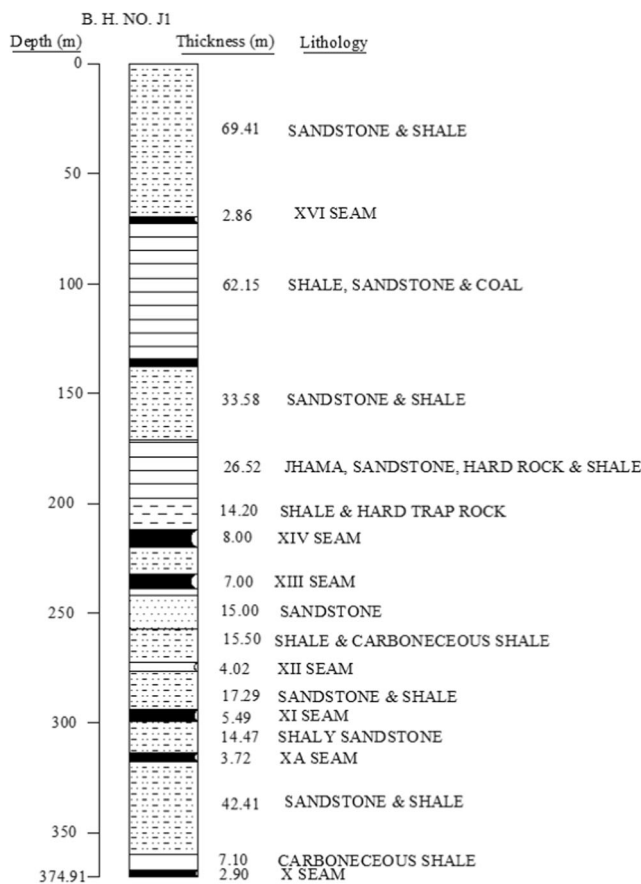
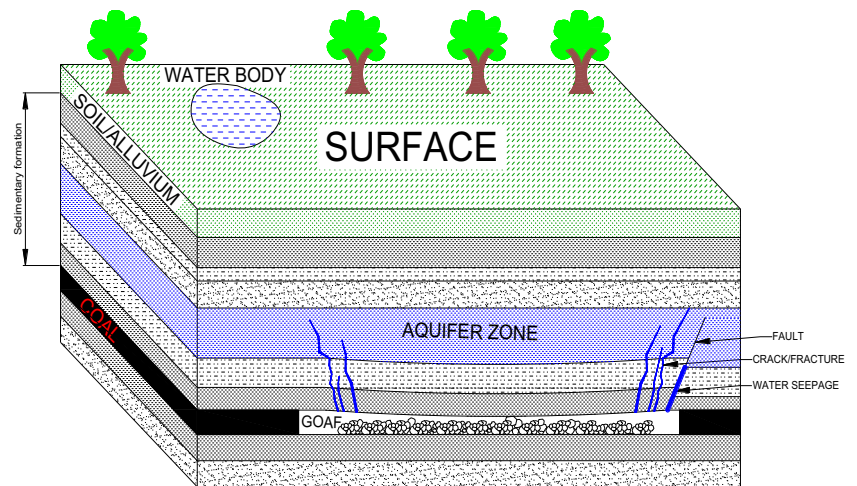


Fig. 2 Available borehole section of nearby area

Result analysis

2D ERT data was obtained along profile AA' during two seasonal phases, i.e. during monsoon and post-monsoon using Wenner-Schlumberger configuration. The acquired data was imported in the Prosys-II data user software. The Prosys II software allows to run an automatic filtering by data processing. This option allows to filter the data in a classical way (it contains, by default, some rejection threshold for the main parameters, and some lateral data smoothing). So, this filtering can be used in most of any standard cases. This automatic filter technique was also used by other researchers for near-surface in homogeneities, leading to over-smooth tomograms aimed at analysing specific features at depth, or they focused only on spike noise, which are singular anomalous values within the measured resistivity pseudo-section (Ritz et al.

Fig. 3 A conceptual model of entering water in old mine working



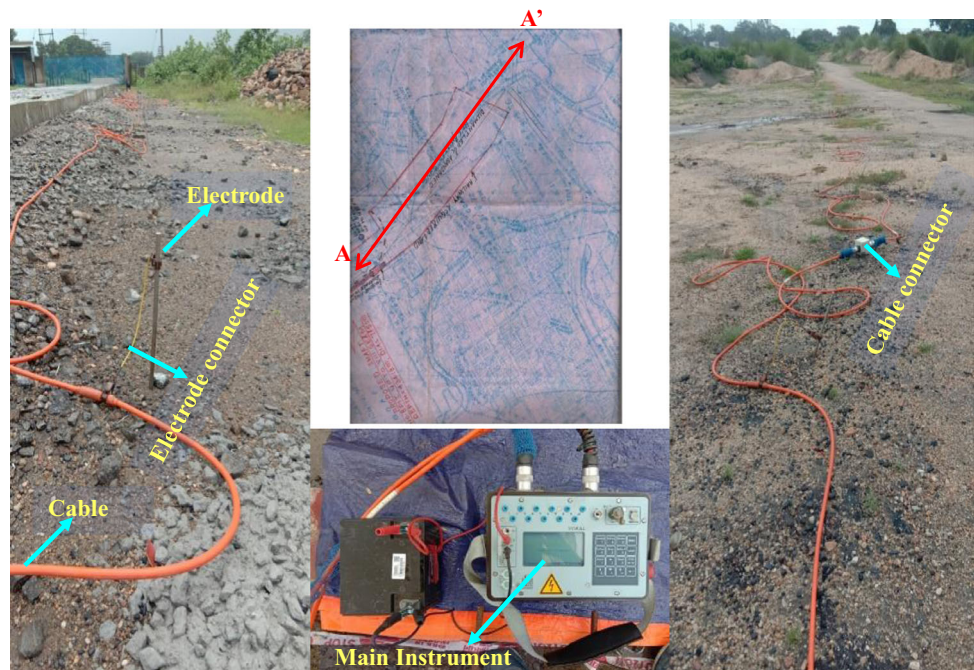
1999; Ferathia et al. 2009, 2012; Rosset et al. 2013). After filtering, the number of data reduced to 70 from 84 at a depth of 10.38-m level as shown in Fig. 5. A total of 3841 raw data were generated in the field during the monsoon, and the amount reduced to 2134 after filtering resulting in 44% reduction in data, imparting higher noise formation during rainy season due to improper current flow at greater depth causing distortion at the conducting near surface. However, generally, geophysical survey is avoided during rainy season, but study was conducted to understand the objective of the research. The percentage of data reduction after filtering during the measurement conducted in post-monsoon was 33%. This imparts a clear indication of large noise generation during monsoon period. The processed data was exported to RES2DINV software for inversion of apparent resistivity to true resistivity

distribution in the ground. Spicks and noises were also removed by least square optimization technique using RES2DINV (Loke and Barker 1996). Inconsistency in the resistivity values was observed in the sections. The 2D geoelectric sections of profile AA' estimated using Wenner-Schlumberger configuration with sensitivity analysis are shown in Figs. 6, 7, and 8, respectively.

During monsoon

The inverted data of the geoelectric section of profile AA' (Fig. 6a) measured during monsoon revealed heterogeneity of the subsurface strata. The topmost layer up to a depth of 10 m was anticipated as possibility of soil/alluvium due to relatively low resistivities in the range of 2–50 Ω m. A

Fig. 4 Layout of the instrument over study area along with surface mine plan



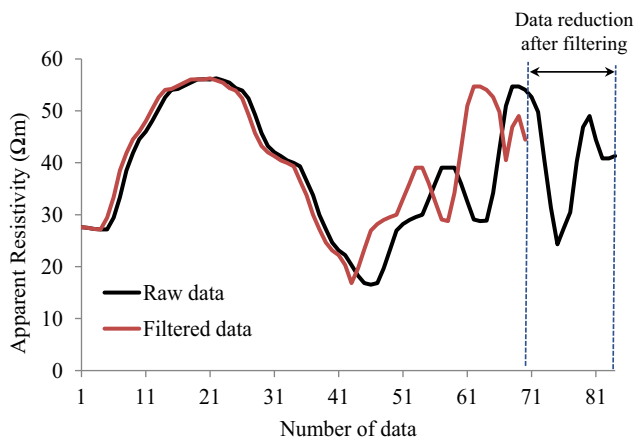


Fig. 5 Data reduction after filtering for the measurement conducted during monsoon at a depth of 10.38-m level

possibility of moist weathered sedimentary formation was observed at the centre of the profile with medium resistivity range of 50–120 Ω m. Samouelian et al. (2005) and Palacky (1987) classified resistivity range of soil and weathered sedimentary formations. Model represents a horizontal layer of hard rock/bed rock/floor rock along the complete length of the profile at a depth below 10 m with relatively high resistivities of the order of 120–380 Ω m. Additionally, the three prominent feasibility of water body was indicated at a depth of about 14 to 30 m (marked zone A), 10 to 32 m (marked zone B) and 70 to 187 m (marked zone C), with electrical resistivity variation ranging from 2 to 9 Ω m.

The 2D ERT inverted data set was accordingly checked for sensitivity distribution in which sensitivity ranged between 0.075 and 4.65 (Fig. 6b). The average model sensitivity in relative sensitivity section was found to be high

ranging from 1.43 to 4.6 at shallow depth and low sensitive values (0.075 to 0.791) in medium depths (35 to 60 m). Low value of sensitivity (0.075 to 0.791) was up to a depth of 85 m with respect to the centre of the profile where the high resistivity zone was delineated (Fig. 6a). A plot was made between sensitivity and depth to define low and high sensitivity along with range of depth as shown in Fig. 7.

Post-monsoon

2D ERT section of the inverse model of post-monsoon (Fig. 8a) that the upper ~10-m thick layer comprised of soil/alluvium with relatively low resistivity of 2–50 Ω m throughout the profile. A possibility of moist weathered sedimentary formation was expected at the centre of the profile due to medium resistivity range of 50–120 Ω m. An anomalous high resistivity of more than 240 Ω m was observed beneath the layer indicating horizontal layer of hard rock/bed rock/floor rock along the whole length of the profile and extending up to the depth of study i.e. 85 m. In addition, two low resistivity signatures (marked zone B and zone C) of about 2 to 12 Ω m water body between reduced distance (RD) of about 345 to 380 m and 200 to 260 m and depth of about 24 and 70 m were also identified.

The geoelectric inverted data set was subsequently analysed for sensitivity spreading in which the minimum and maximum values were 0.052 and 5.36, respectively (Fig. 8b). A moderately low sensitivity zone (0.380 to 0.737) was estimated at the centre of profile up to a depth of 85 m, where a relatively low resistivity zone was demarcated (Fig. 8a).

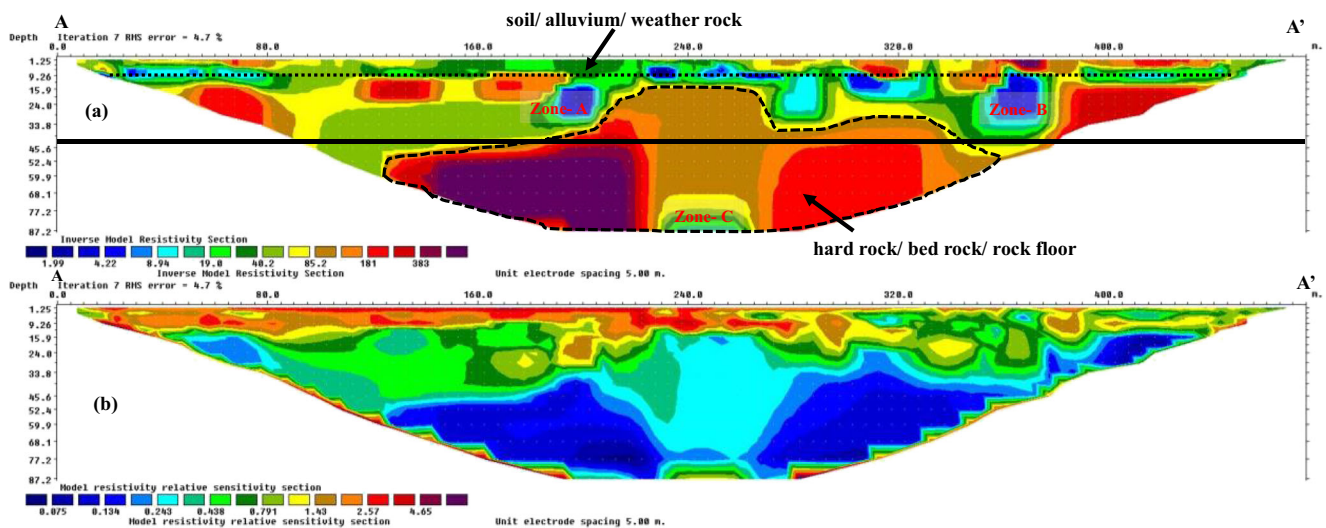
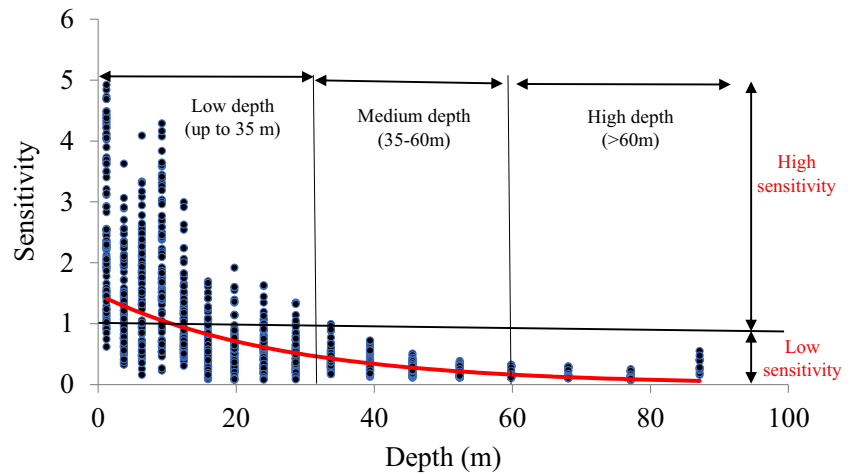


Fig. 6 2D ERT section along profile AA' over study area during monsoon **a** Wenner-Schlumberger array, **b** model resistivity relative sensitivity section of profile

Fig. 7 Sensitivity distribution with depth over study area during monsoon



Interpretation

The geoelectrical section of this array indicated presence of soil/alluvium up to a depth of around 10 m from the surface. The topmost seam is at an average depth of 40 m, having a gradient of 1 in 7.2 dipping towards south-west, as shown in Fig. 9. The interpretation of the resistivity section of the ERT profile was drawn from the resistivity variations and the lithology determined through borehole section (Fig. 2) and underground working plan. Range of resistivity was categorised quantitatively as low, medium and high with the support of range defined by Verma and Bhuiin (1979) and Verma et al. (1982). A high resistivity contrast was observed near surface from RD of 320 to 425 m indicating old mine workings. Location was identified as abandoned incline as per the plan, although there is no sign of incline at the surface. High resistivity indicated air-filled cavity near the depth of about 18 m.

This zone is unsafe for erection of any structure from stability point of view. It is also a possible source for inflow of surface water to the underground workings as shown in Fig. 9.

During monsoon, high resistivity of about $\sim 180 \Omega \text{ m}$ was observed up to a stretch of 190 m from the starting point indicating no cavity at 40 m depth (Fig. 9a). There is no underground working up to 190-m length on correlating with the status of old workings which validated with the surface plan as shown in Fig. 9. The developed underground working was observed at RD of 190 to 480 m as per plan. Expected water-logged zone was identified at RD from 190 to 275 m (85-m stretch) with relatively low resistivity of about $02 \text{ to } 19 \Omega \text{ m}$ near the depth of about 30 m (zone A). High resistivity beyond 300 m indicated air cavity, i.e. free from water logging. Strata at the depth range from 9 to 30 m for RD of about 190 to 470 m appeared to be permeable. The source of rain water (surface water) appeared to percolate from 235 to 255 m RD. Low resistivity of $20 \Omega \text{ m}$ was observed in this

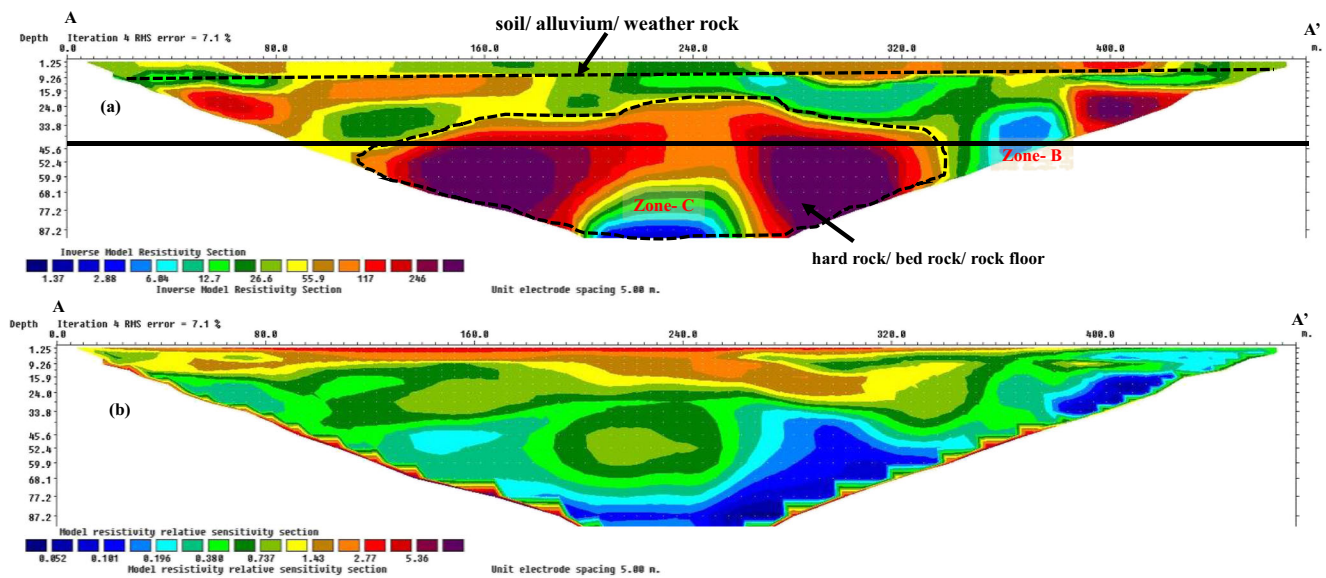


Fig. 8 2D ERT section along profile AA' over study area during post-monsoon **a** Wenner-Schlumberger array, **b** model resistivity relative sensitivity section of profile

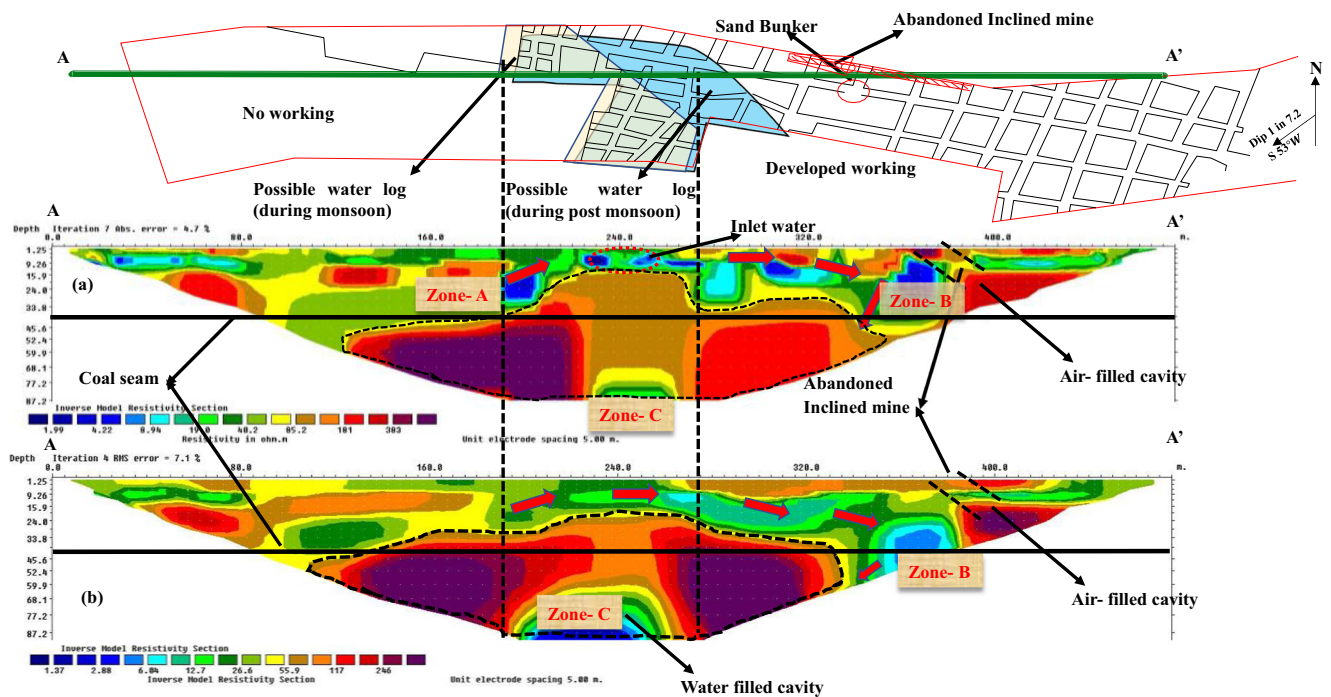


Fig. 9 2D electrical resistivity profile (a) during monsoon and (b) post-monsoon showing the general conditions of subsurface encountered around a section of 6 and 7 pit mine

zone indicating the inflow of surface water to the mine, indicated from zone A to zone B.

Water-filled (marked as zone C) was found to enhance during post-monsoon measurement as shown in Fig. 9b. The extent of water increased from 85 to 125 m was indicated by relatively low resistivity of about 09Ω to 16Ω m. However, high resistivity was found in the permeable zone indicating the complete percolation of rain water to the mine. The water appeared to ingress from the rise side of the developed working, i.e. at zone A and that was found to flow towards zone B supported by the seam inclination. This consequently led to enhanced accumulation of water in zone C as interpreted through resistivity tomography anomalies.

Conclusions

2D ERT technique, one of the vital tools for delineation and mapping of water logging in cavity associated with old mine working, was carried out at Jamadoba 6 and 7 Pits, Jharia coalfield, India, during and post-monsoon using Wenner-Schlumberger configuration. Higher noise formation was observed during monsoon as indicated by data reduction by 44% after filtering. Distortion of current flow near surface led to improper current flow at greater depth. The percentage of reduction in post-monsoon data was 33% after filtering. This imparted a clear indication of large noise generation during monsoon period. The enhancement of resistivity ranges from 4 to 26Ω m at around 10-m depth during monsoon and post-

monsoon, respectively, assisted in distinct demarcation of porous and permeable strata. The possible location of inlet of rain water from surface to the mine was identified through resistivity contrast. Unknown cavity at shallow depth like abandoned incline was also identified with high resistivity $\sim 300 \Omega$ m near the depth of about 18 m. Accumulation of water in abandoned old workings was observed after post-monsoon. The estimated range of resistivity variation of study area was well corroborated with the field investigation results of previous research conducted in Raniganj Coalfield and Jharia coalfield, India, as well as borehole lithological section and working mine plan. The result supports the application of Wenner-Schlumberger configuration for better understanding of old and unapproachable mine workings.

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References

- Abu-Shariah MII (2009) Determination of cave geometry by using a geoelectrical resistivity inverse model. *Eng Geol* 105:239–244
- Anbazhagan P, Sitharam T G (2008) Site Characterization of Bangalore using geophysical method. Civil Engineering, Indian Institute of Science, Bengaluru, Karnataka
- Bharti AK, Pal SK, Priam P, Kumar S, Shalivahan, Yadav PK (2016a) Subsurface cavity detection over Patherdih colliery, Jharia

- Coalfield, India using electrical resistivity tomography. *Environ Earth Sci* 75(5):1–17
- Bharti AK, Pal SK, Priam P, Pathak VK, Kumar R, Ranjan SK (2016b) Detection of illegal mine voids using electrical resistivity tomography: the case-study of Raniganj coalfield (India). *Eng Geol* 213:120–132
- Bharti AK, Pal SK, Saurabh, Kumar S, Mondal S, Singh KKK, Singh PK (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
- Chandra D (1992) Jharia coal fields. Geological Society of India, Bangalore, p 149
- Coles DA, Morgan FD (2010) A method of fast, sequential experimental design for linearized geophysical inverse problems. *Geophys J Int* 178(1):145–158
- Daniels DJ (2005) Ground penetrating radar, in *Encyclopedia of RF and Microwave Engineering*. Wiley, Hoboken
- Danielsen JE, Auken E, Jørgensen F, Søndergaard V, Sørensen KI (2003) The application of the transient electromagnetic method in hydrogeophysical surveys. *J Appl Geophys* 53(4):181–198
- Das P, Pal SK, Mohanty PR, Priyam P, Bharti AK, 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
- Davis JL, Annan AP (1989) Ground-penetrating radar for high-resolution mapping of soil and rock stratigraphy. *Geophys Prospect* 37(5):531–551
- Ferahtia J, Djarfour N, Baddari K, Kheldoun A (2012) A fuzzy logic-based filter for the removal of spike noise from 2D electrical resistivity data. *J Appl Geophys* 87:19–27
- Ferathia J, Djarfour N, Baddari K, Guerin R (2009) Application of signal dependent rank-order mean filter to the removal of noise spikes from 2D electrical resistivity imaging data. *Near Surf Geophys* 7:159–169
- Jiang ZH, Yue JH, Liu SC (2007) Prediction technology of buried water-bearing structures in coal mines using transient electromagnetic method. *J China Univ Mining Tech* 17(2):164–167
- Jinhai Z, Ning J, Liming Y, Liyang B (2018) The effects of mining subsidence and drainage improvements on a waterlogged area. *Bull Eng Geol Environ*. <https://doi.org/10.1007/s10064-018-1356-9>
- Jørgensen F, Sandersen PBE, Auken E (2003) Imaging buried quaternary valleys using the transient electromagnetic method. *J Appl Geophys* 53(4):199–213
- Keller GV, Frischknecht FC (1966) *Electrical methods in geophysical prospecting*. Pergamon Press Inc, Oxford
- Krishnamurthy NS, Rao VA, Kumar D, Singh KKK, Ahmed S (2009) Electrical resistivity imaging technique to delineate coal seam barrier thickness and demarcate water filled voids. *J Geol Soc India* 73:639–650
- Loke MH (1999) *Electrical imaging surveys for environmental and engineering studies. A practical guide for 2D and 3D surveys*
- Loke MH, Barker RD (1996) Rapid least-squares inversion of apparent resistivity pseudosections by a quasi-Newton method. *Geophys Prospect* 44:131–152
- Maillol JM, Seguin MK, Gupta OP, Akhauri HM, Sen N (1999) Electrical resistivity tomography survey for delineating uncharted mine galleries in West Bengal, India. *Geophys Prospect* 47:103–116. <https://doi.org/10.1046/j.1365-2478.1999.00126.x>
- Martínez-Moreno FJ, Pedrera A, Ruano P, Galindo-Zaldívar J, Martos-Rosillo S, Gonzalez-Castillo L, Sánchez-Úbeda JP, Marín-Lechado C (2014) Combined microgravity, electrical resistivity tomography and induced polarization to detect deeply buried caves: Algaiddilla cave (Southern Spain). *Eng Geol* 162:67–78
- Martínez-Pagán P, Gomez-Ortiz D, Martín-Crespo T, Manteca JI, 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
- Metwaly M, 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
- Palacky GJ (1987) Clay mapping using electromagnetic methods. *First Break* 5:295–306
- Pánek T, Margielewski W, Tábořík P, Urban J, Hradecký J, Szura C (2010) Gravitationally induced caves and other discontinuities detected by 2D electrical resistivity tomography: case studies from the Polish Flysch Carpathians. *Geomorphology* 123:165–180
- Pazdirek O, Blaha V (1996) Examples of resistivity imaging using ME-100 resistivity field acquisition system. EAGE 58th Conference and Technical Exhibition Extended Abstracts, Amsterdam.
- Peng C, Xue LF, Liu ZH, Liu HY (2016) Application of the non-seismic geophysical method in the deep geological structure study of Benxi-Huanren area. *Arab J Geosci* 9(4):310
- Plati C, Loizos A, Papavasiliou V (2010) Inspection of railroad ballast using geophysical method. *Int J Pavement Eng* 11(4):309–317
- Ritz M, Robain H, Pervago E, Albouy Y, Camerlynck C, Desclotres M, Mariko A (1999) Improvement to resistivity pseudosection modeling by removal of near-surface inhomogeneity effects: Application to a soil system in south Cameroon. *Geophys Prospect* 47:85–101
- Rosset E, Hilbich C, Schneider S, Hauck C (2013) Automatic filtering of ERT monitoring data in mountain permafrost. *Near Surf Geophys* 11:423–433
- Roy A (1996) The method of continuation in mining geophysical interpretation. *Geoexpl* 4(2):65–83
- Salonen VP, Korkka-Niemi K, Moreau J, Rautio A (2014) Kaivokset ja vesi – esimerkinä Hannukaisen hanke. (in Finnish). *Geolog* 66:8–19
- Samouelian A, Cousin I, Tabbagh A, Bruand A, Richard G (2005) Electrical resistivity survey in soil science: a review. *Soil Tillage Res* 83(2):173–193
- Singh KKK (2013) Delineation of waterlogged area in inaccessible underground workings at Hingir Rampur Colliery using 2D resistivity imaging: a case study. *Bull Eng Geol Environ* 72(1):115–118
- Singh KKK, Singh KB, Lokhande RD, Prakash A (2004) Multielectrode resistivity imaging technique for the study of coal seam. *J Sci Ind Res* 63:927–930
- Telford WM, Geldart LP, Sheriff RE, Keys DA (1976) *Applied geophysics*: Cambridge University Press
- Verma RK, Bhuin NC (1979) Use of electrical resistivity methods for study of coal seams in parts of the Jharia Coalfields, India. *Geoexpl* 17:163–176
- Verma RK, Bandopadhyay TK, Bhuin NC (1982) Use of electrical resistivity methods for study of coal seams in parts of the Raniganj coalfield (India). *Geophys Prospect* 30:115–126
- Xu H, Liu B, Fang Z (2014) New grey prediction model and its application in forecasting land subsidence in coal mine. *Nat Hazards* 71(2):1181–1194
- Yang Y, Zheng Y, Chen J et al (2010) Rayleigh wave phase velocity maps of Tibet and the surrounding regions from ambient seismic noise tomography. *Geochem Geophys Geosyst* 11(8):1020–1029
- Yu JC, Wang YZ, Liu J, Zeng XB (2008) Time-depth conversion of transient electromagnetic method used in coal mines. *J China Univ Mining Tech* 18(4):546–550
- Zha JF (2008) Study on the foundational problems of mining subsidence controlled in waste stow. Ph.D. Thesis, China University of Mining and Technology (in Chinese)
- Zhang J, Jiang H, Deng X, Ju F (2014) Prediction of the height of the water-conducting zone above the mined panel in solid backfill mining. *Mine Water Environ* 33(4):317–326