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ORIGINAL ARTICLE

# Implication of Electrical Resistivity Tomography for Precise Demarcation of Pothole Subsidence Potential Zone Over Shallow Depth Coal Mine Workings

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## ABSTRACT

**Pothole, an undesirable catastrophic consequence, is a common phenomenon in old coal mine workings, especially at shallow depth endangering habitats and surface structures. Precise identification of pothole potential zone is vital to prevent any major setbacks. Limited sub-surface information leads to branching out from the realistic ground conditions resulting in improper inferences. Resistivity imaging system is a favourable tool for gathering and strengthening technical information to demarcate the potential areas of pothole occurrence as it has proven ability to translate the characteristic of strata. Geological disturbance, one of the causes for pothole, has been located precisely by electrical resistivity survey at the study site. The overlying rock type has been correlated with resistivity range and validated with borehole lithology. Considering influencing parameters for pothole i.e. position of underground workings, geological disturbance and nature of near surface strata potential locations of the pothole likely to occur has been demarcated based on resistivity characteristics. Two potholes occurred in the past also helped in strengthening in interpretation.**

## INTRODUCTION

Subsidence has been observed above abandoned mines where overburden ranges in thickness from few meters to as much as 135m (Prakash, et al., 2010). Coal mining particularly at shallow depth with saturated weak overburden and geological discontinuities poses serious threat of pothole subsidence (Whittaker and Reddish, 1989; Singh, 2007). Pothole subsidence, a collapse of mine roof with a formation of cavity in the overlying strata results in an abrupt depression in the ground surface, damages the topography which cannot be reinstated. Constraint of accessibility in old workings results in inadequate knowledge of ground conditions. Limitation of prior indication of pothole occurrence causes paroxysm of panic especially if hitting human habitat. It leads to severe damage to surface structures causing collapse of houses with development of crevices on walls and floors. The openings of potholes are hazardous to social life in the form of risk of falling, inflow of surface run off into the mine, outflow of mine water at the surface and emission of huge amount of mine gases. Breathing of air through pothole deteriorates underground mining conditions (Lokhande et al., 2014). In order to root out the fear of such incidence it is vital to widen the scope of investigation for precise demarcation of stable and unstable ground conditions over old coal mine workings.

In-situ geophysical techniques are able to measure physical parameters directly or indirectly linked with the lithological, hydrological and geotechnical characteristics of the terrains related to the movement (Hack, 2000; Jongmans and Garambois, 2007). Electrical Resistivity Tomography, a geophysical technique for imaging sub-surface structures from electrical resistivity measurements, is a versatile, fast and cost-effective technique for mapping the shallow subsurface anomaly (Kumar, 2012). Contrast in resistivity is due to variation in lithology, water content, presence of cavity, geological discontinuity etc. helps in interpretation and identification of such existence.

The study was conducted at Khandra colliery of Raniganj coalfield. Decades back mine workings were developed by bord and pillar method at shallow depth, presently being enveloped by habitats. The depth of investigation, determined by a combination of the spacing between the electrodes, the number of electrodes used in the specific type of array, geological strata architecture and heterogeneity of the sub-surface formation, was sufficient enough to cover the depth of top seam ranging up to 25 m.

## CAUSES OF POTHOLE

Potholes are caused by various mechanisms, including water seepage, rainfall, earthquakes and underground excavations, among other factors (Yejin et al., 2015). The occurrence of subsidence events in various geological settings is an increasing hazard (Carminati and Martinelli, 2002). Geological discontinuities, particularly closely spaced joints and faults, play a very important role in the formation of potholes (Peele, 1961; pp.519-533). When a roof is formed from blocks bounded by joints or cracks, it may fail by shearing along planes of weakness when the vertical stress exceeds the shear resistance along the joints. Sinkholes may form as a result of lowering the water table by excessive pumping of water for human use (Karfakis et al., 1988). The causes of pothole subsidence thus can be broadly categorized as shown in Fig. 1.

There is a strong possibility of occurrence of pothole when the ratio of overburden thickness (h) to mining height (m) is less than 5. Statham and Trharne (1991) reported that 90% of total potholes occurred when the h/m ratio was less than 6. Caving of 10-15m of a weak rock formation with an equal amount of sub-soil led to pothole

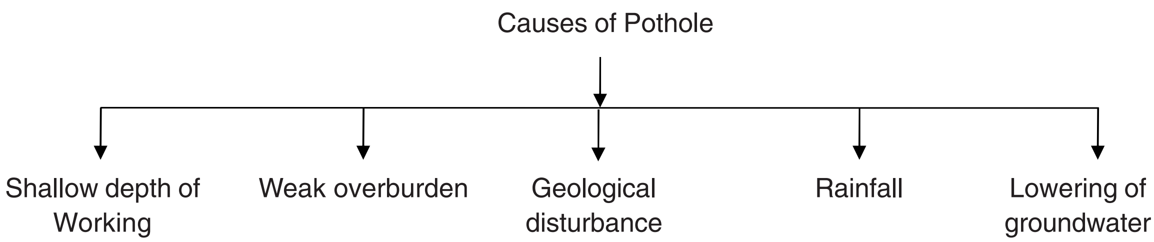



**Fig. 1.** Causes of occurrence of pothole

formation (Singh and Dhar, 1997). Rainfall aggravates subsidence over old workings (Prakash et al., 2010).

Considering the complexity of varied influencing parameters, the inclusion of electrical resistivity survey would be beneficial in identifying some of them. An improved interpretation can be drawn by interwining the parameters of geo-mining conditions through plan and characteristics of near surface strata through resistivity imaging system. It will help in unfolding technical information leading to arrive at intriguing result.

## ELECTRICAL RESISTIVITY TOMOGRAPHY

### Applicability

The applicability of the electrical resistivity tomography (ERT) is gaining attention due to faster acquisition systems and advanced software for data processing and the creation of 2D and 3D tomographic images for interpretation. The advantages of ERT survey are to interpret the sub-surface anomaly quantitatively from 2D resistivity models of the sub-surface geological formations, extract the range of true resistivity from the inverted resistivity models, large density data coverage for better resolution and less time for data acquisition etc. Electrical resistivity surveys have been used in environmental and engineering studies (Loke, 1999), landslide investigations (Lapenna et al., 2003; Gelislil and Ersoy, 2017), contamination from the landfill (Onojasun, 2015), civil engineering (Omowumi, 2014), bedrock structure identification (Hsu et al., 2010; Chambers et al., 2012), slope stability (Abidin et al., 2012; Perrone et al., 2014), bridge foundation (Arjwech et al., 2013; Tucker et al., 2014) and geological settings (Kie³basiñski and Mieszkowski, 2008).

The resistivity imaging technique has been widely used in mining domain. The coal bearing formation could be delineated with distinctive resistivity characteristics (Singh et al., 2004; Rao et al., 2015). It was also used for delineation of gold mineralisation (Abdullahi et al., 2018). Schoor (2002) and Farooq et al. (2012) applied ERT technique for the mapping of potholes, cavities and other disruptive features. According to Farooq et al. (2012) low resistivity image was identified due to weak rock and clay filled cavities. The existence of cavity was also proven by drill hole. Voids caused due to illegal mining activities were detected by ERT approach (Bharti et al., 2016) and abandoned mine galleries were also determined (Das et al., 2017).

Keeping in view the causes of pothole, depth of working, weak overburden and geological disturbance, as briefed in Fig.1, are the parameters that could be identified by the ERT survey. The depth of working comprise cavity formed due to extraction of coal in the seam. Cavity may be dry or water logged. This can be identified by resistivity contrast. Weak overburden can be identified by typical high/low resistivity depending up on strata saturation condition. Contrast change in resistivity can be observed in case of geologically disturbed area like existence of fault.

### Methodology

ERT survey was carried out using multi-electrode system, here comprising of 96 electrodes. The electrodes are anchored on the ground in a straight line with constant spacing. Each electrode is connected to multicore cable. Salt water is poured on electrode to minimise the influence of contact resistance. The direct current, supplied through 12V external battery, is forced through two electrodes and the potential difference is measured on the other electrodes.

Standard electrode configurations used for 2D ERT surveys are Wenner, dipole-dipole, Wenner-Schlumberger, pole-pole, pole-dipole, and equatorial dipole-dipole (Telford et al., 1990, p.744; Dahlin and Zhou, 2004). A general "thumb rule" for electrical resistivity surveying is that grounded structures be at least half of the maximum electrode spacing away from the axis of the electrode array (Middleton, 1974). Lateral electrical resistivity contrasts, such as lithologic contacts, can best be mapped in the profiling mode.

The Wenner and Schlumberger arrays are generally known to have good signal strength, because the electric potential measurement, electrodes are located between the current injection electrodes, where C1 & C2 are current electrodes and P1 & P2 are potential electrodes. With the Wenner-Schlumberger array, the inner potential probes remain fixed while the outer current probes are moved. The geometric factor of the array is expressed as:

$$k = \pi n\,(n + 1)\,a \qquad (1)$$

Where, a = dipole length (m), n = dipole separation factor and k = geometric factor.

The Wenner-Schlumberger array is ideally suited for distinguishing lateral from vertical variations in resistivity (Wightman et al., 2003) and hence this technique was considered for the study.

## FIELD INVESTIGATION AND INTERPRETATION

ERT data-acquisition field setup using 10-channel resistivity meter Syscal-Pro (IRIS INSTRUMENTS, France) with 96 electrodes was used in the study. Being a multi-channel data acquisition system, it has two current electrodes and 94 potential electrodes. Lithological formations can be distinguished based on the electrical resistivity range and taking into account existing drilling information available from the area. Coal being a sedimentary deposit, the scale of resistivity of a few rock types in sedimentary formation developed based on the study conducted by Palacky (1987) and Telford et al. (1990), was used as a guideline for identification of rock as shown in Fig.2. A wide range of resistivity values is primarily due to heterogeneous nature of rock. The resistivity values are largely dependent on the porosity of the rocks.

A total of six numbers of 2D ERT profiles viz., AA', BB', CC', DD', EE' and FF' were selected over old and shallow depth of workings of Khandra colliery located in the Bankola area of Eastern Coalfields Limited (ECL) in the state of West Bengal. The study layout covering the water stream, water tank, surface structures and area of potholes occurred in the past were taken into account in order to assess the impact or influence, if any (Fig. 3). The details of each profile are deciphered in Table 1. All profiles were in line with the strike of the coal seam with an exception of FF'. The depth of the seam remains constant along the strike of the seam and hence all the profiles were

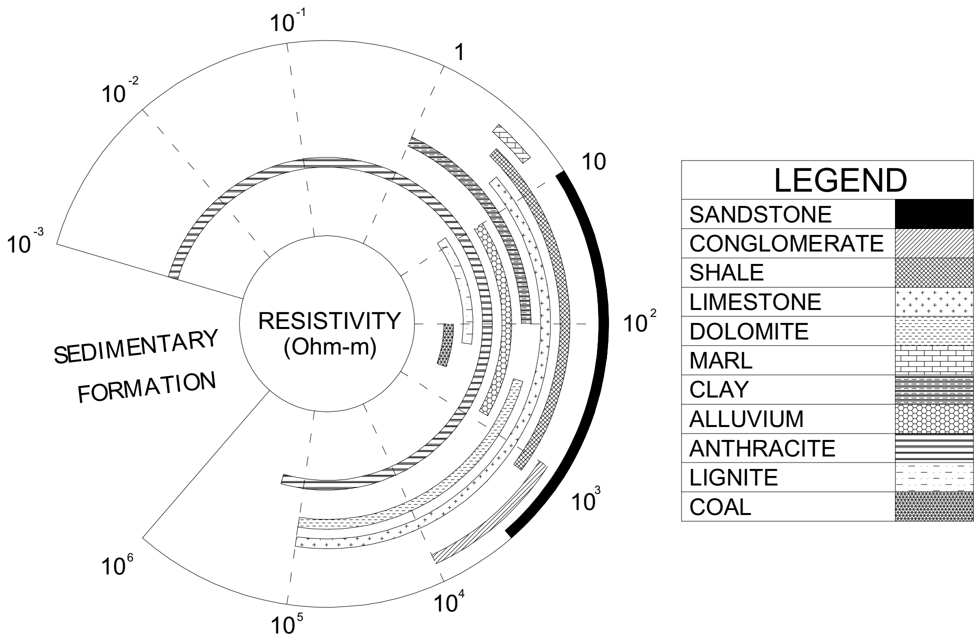



**Fig. 2.** Range of resistivity in sedimentary formation (Telford et al., 1990; Palacky, 1987)

preferred along it for better interpretation. Owing to space hindrance the length of the profile CC' was restricted to 285 m. Profiles AA', BB', CC', DD' and EE' were parallel at an offset of 11 m, 73 m, 30 m and 30 m respectively. The width of the study area was 144 m covering the shallow depth of working to locate the potential zone of pothole occurrence.

The ambient noise was eliminated. The data sets have been inverted based on the regularized algorithm i.e. least square optimisation technique through RES2DINV software (Loke, M.H. and Barker, R.D., 1996). The inverted geo-electrical sections were interpreted based on the variation of anomalous high and low resistivity values. The 2D ERT section of profiles AA', BB', CC', DD', EE' and FF' of 5 quality factor i.e. standard deviation in percentage, generated using Wenner-Schlumberger array are shown in Figs. 4a-4f respectively. The total data generated for the full depth of survey was 2385. The resistivity range observed in all the profiles was interpreted with reference to Fig. 2 to arrive at the rock type. Four boreholes namely, SD-20, SD-21, SD-25 and SD-26 were located in the vicinity of the study area but only SD-20 and SD-21 (Fig. 5a and Fig. 5b) were considered for interpretation and validation. Other boreholes were located beyond the faults which may mislead in interpretation. The location and orientation of the faults were as per the geological plan provided by the mine management. Comparatively low resistivity was observed at an average depth of around 10-12 m over the study area. Key observations of each profile are briefed in Table 2.

The bending signature accentuates quirky genre of the strata. In this study, a fault was detected in three profiles by ERT survey as shown in Fig. 4. The existence of three faults in close proximities indicates the region to be geologically disturbed. This may lead to the possibilities of folding of strata. Such anomaly is a conspicuous manifestation of geological disturbance. Folds result from the displacement variations on fault segments (Khaliland McClay, 2002). According to Suppe (1983) map-scale folds in sedimentary sequences are formed by the bending of fault blocks as they ride over non-planar fault surfaces. Flow of material through geological disturbances like

**Table 1.** Details of ERT profiles

| Sl. No. | Profile | Profile length (m) | Electrode spacing (m) | Profile orientation with respect to inclination of the seam |
|---|---|---|---|---|
| 1 | AA' | 475 | 5 | Along strike |
| 2 | BB' | 475 | 5 | Along strike |
| 3 | CC' | 285 | 3 | Along strike |
| 4 | DD' | 475 | 5 | Along strike |
| 5 | EE' | 475 | 5 | Along strike |
| 6 | FF' | 475 | 5 | Apparent dip |

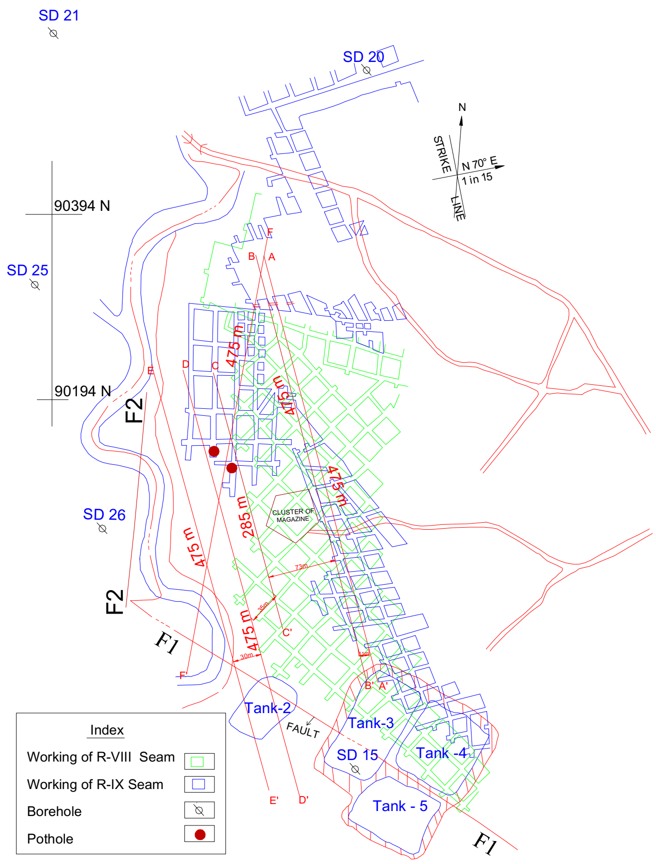



**Fig. 3.** Layout of survey profiles over workings of Khandra colliery, ECL

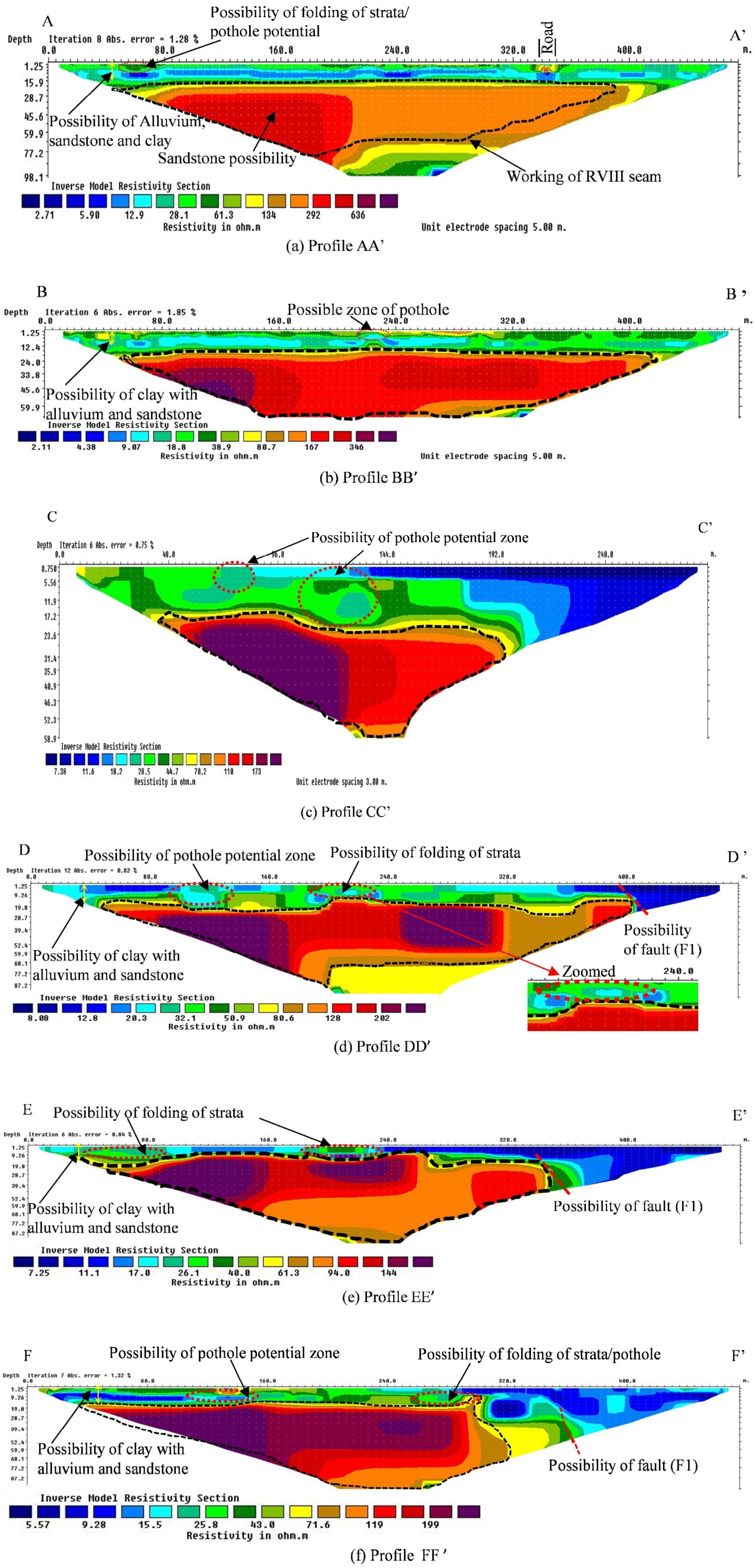
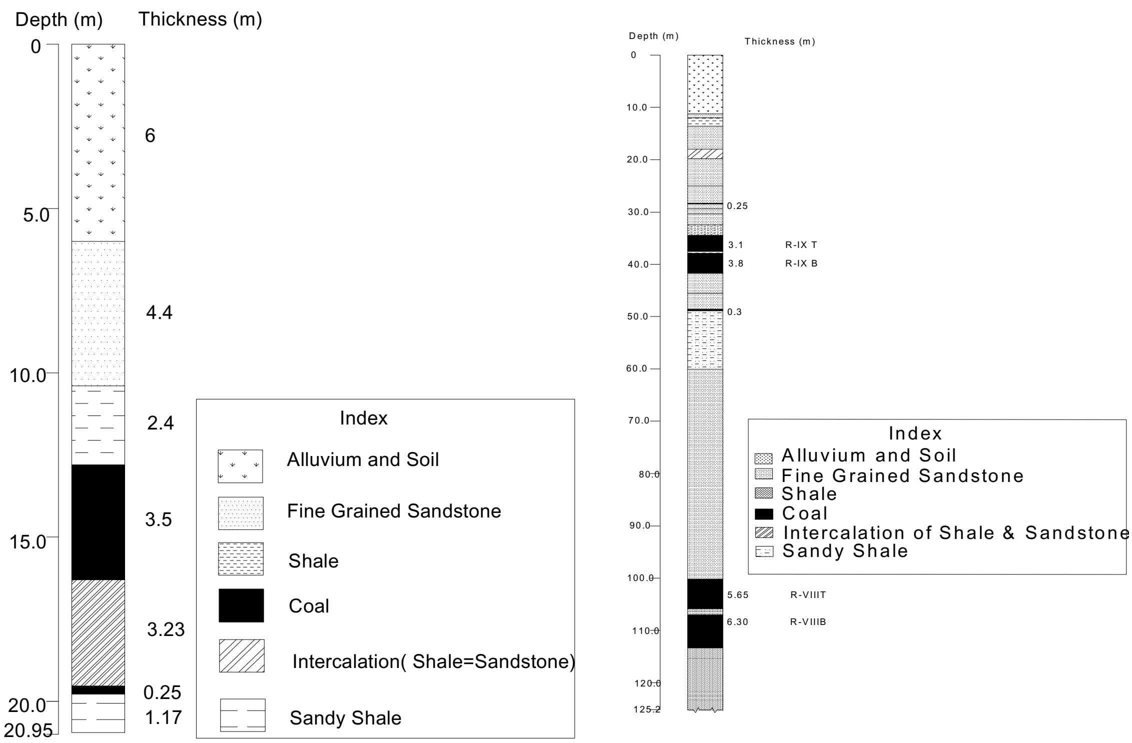



**Fig. 4.** 2D ERT section by Wenner-Schlumberger array along different profiles

**Table 2.** Key observations of resistivity survey

| Profile | Depth (m) | Inverted true resistivity (Ωm) | Rock type based on resistivity range | Validation through boreholes | Key observations | Ground condition |
|---|---|---|---|---|---|---|
| AA' | 0-15<br><br><br><br>90 | 2.71-61.3<br><br><br><br>Up to 636 | Mainly alluvium with possibility of existence of sandstone and clay<br><br>Sandstone | Alluvium, sandstone and shale<br><br>Sandstone | • Anomaly between 345 and 355 m<br>• Folding of strata between 65 and 90 m<br>• No anomaly observed | • Road between 345 and 355 m.<br>• Weak ground condition from 65to 90 m and possibility of pothole<br>• Possibility of water logging in RVIII seam |
| BB' | 0-15 | 2.11-38.9 | Mainly clay with alluvium and sandstone | Alluvium, soil and sandstone | • Folding of strata between 210 and 240 m | • Possible zone of pothole |
| CC' | 0-17 | 7.38-44.7 | Mainly clay with alluvium and sandstone | Alluvium, soil and sandstone | • Folding of strata between 102 and 150 m<br>• Anomaly from 120 to 138 m | • Possible zone of pothole.<br><br>• Pothole occurred in its vicinity |
| DD' | 0-13 | 8.08-50.9 | Mainly clay with alluvium and sandstone | Alluvium, soil and sandstone | • Folding of strata from 95 to 135 m, 185 to 210 m and 220 to 230 m with anomalies.<br>• Abrupt change in resistivity at 405 m | • Pothole occurred between 100 and 130 m.<br>• No working at other locations<br>• Possibility of fault |
| EE' | 0-8 | 7.25-40 | Mainly clay with alluvium and sandstone | Alluvium, soil and sandstone | • Folding of strata from 30 to 110 m, 185 to 240 m with anomaly.<br>• Abrupt change in resistivity at 340 m | • No working.<br>• High conductivity from 240 m onwards due to nala and tank<br>• Possibility of fault |
| FF' | 0-18 | 5.57-43 | Mainly clay with alluvium and sandstone | Alluvium, soil and sandstone | • Folding of strata from 130 to 155 m and from 285 to 320 m.<br>• Anomaly from 125 to 140 m and from 250 to 290 m. of 250 to 290 m. | • Possible zone of pothole from 130 to 155 m.<br>• No working between 285 and 320 m.<br>• Pothole occurred in the vicinity |




**(a)** SD-20 **(b)** SD-21

**Fig. 5.** Lithological section of boreholes in the vicinity of the study area

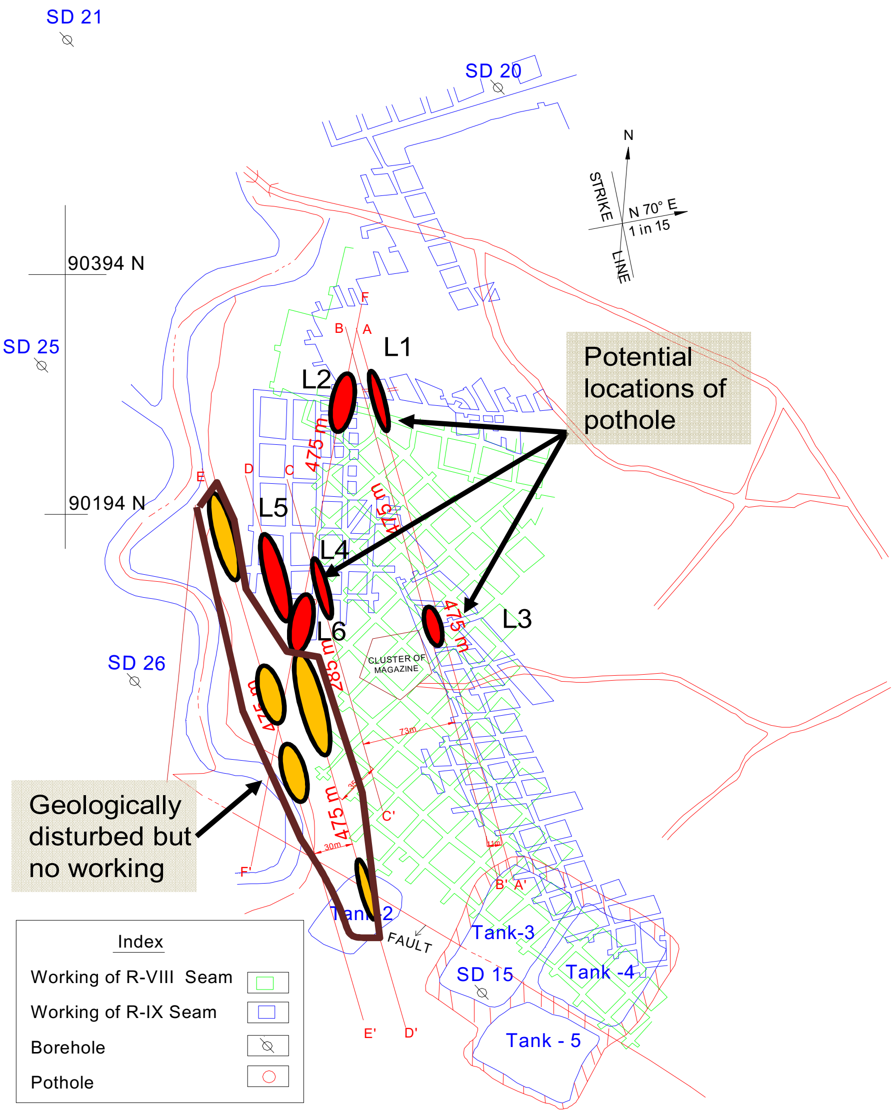



**Fig. 6.** Demarcated potential zones of pothole

fault in the presence of water is one of the causes for pothole formation. The rocks are weak at the folding region and hence such areas are considered as risk to pothole occurrence in future.

In addition, gallery junctions become more vulnerable to pothole owing to large underground opening. The potential zone of pothole has been demarcated in Fig. 6 based on key observations of six profiles. Six locations (L1-L6), shown in red shade, are prone to pothole occurrence. The evidences of potholes that occurred in the past at two places (L5 and L6) are geologically disturbed zones. These potholes occurred long back. It was difficult to demarcate the potholes in the field with present topography. However, as per the information collected from the mine management, the potholes were approximately of 2 m diameter and the depth of potholes was around 1.5 m. No surface structures should be built at these locations. Few places are geological disturbed with no underground working in the top R-IX seam (yellow shade) and hence such areas are safe but not advisable for underground mining. Identification of rock types based on resistivity range was found to be in close approximation with the lithology of the boreholes. The sub-surface anomalies observed in lines CC', DD' and FF' in the form of abrupt sharp and a strong resistivity contrast in vertical orientation indicating the filled-up pothole enhanced the degree of confidence in interpretation. This variation is primarily due to less compactness of ground compared to *in-situ* condition.

## CONCLUSION

Pothole is the key attribute to mining at shallow depth and hence there is always a quest to isolate unstable ground to prevent risk of any injury. ERT has immense potential to unearth subsurface geotechnical evidence and address gap information like geological disturbance. The interpretation of resistivity images of the study conducted over shallow coal mine workings helped in locating geologically disturbed strata and verified by comparing against available geological information through borehole lithology. The evidence of potholes in geologically disturbed area supported in validation and in turn demarcation of zones potential to pothole occurrence. Thus, ERT survey is invaluable and should be undertaken to demarcate pothole risk potential zones.

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