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# Joint geomorphological and geophysical (electrical resistivity) investigation for the configuration of soil pipe

Ujjal K. BORAH[1,2,*], Alka GOND[1], Prasobh P. RAJAN[1], Rajappan SIVAN[1], Nandakumar VIVEKANANDAN[1]

[1] ESSO – National Centre for Earth Science Studies, Ulloor – Akkulam road, Akkulam, Thiruvananthapuram, Kerala, India 695011

[2] Gauhati University, Gopinath Bordoloi Nagar, Jalukbari, Guwahati, Assam, India 781014

**Abstract:** Soil piping is a complex mechanism of subsurface soil erosion, which results underground conduits (cave/tunnel) of varying dimensions. Soil piping associates with severe consequences, such as land subsidence and land slide. Therefore, the investigation of soil pipe is crucial. However, the study of soil pipe is challenging unless characteristic surficial evidences of the pipe are available. Based on the surficial evidences, soil pipe can be configured with geophysical techniques which in-turn aid in designing precursory measures. Therefore, in the present study, we carried out a combined geomorphological and geophysical investigation to configure the soil pipe at Kinanoor village, Kasaragod, Kerala, India. Based on the vital geomorphological information, we carried out resistivity survey and configured an underground soil pipe of diameter $\sim$6.5 to 7 m that is seated $\sim$3 m beneath the surface. This hollow pipe is underlain by the only accessible road of that locality which makes the road vulnerable for transportation. Therefore, a bridge like structure is recommended to construct at the pipe location to stabilize the risk factor. Since the study area is situated on a fringe-slope, the geomorphological investigation points out that the disturbance in natural course of the drainage system and the accumulation of water in the up-slope area due to the man-made activities might act as potential causes for the piping in the area. Therefore, it is suggested not to disturb the natural course of the drainage which may lead to subsidence of the area in future.

**Key words:** near-surface, geo-hazard, soil piping, electrical resistivity tomography (ERT)

## 1. Introduction

The phenomenon of soil piping is basically referred to the formation of subsurface linear voids (underground cave or tunnel like structures) by concen-

*corresponding author, e-mail: ujjal.borah6@gmail.com

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trated running water either in soils or in unconsolidated/poorly consolidated sediments (*Jones, 2004*). Soil pipe acts as a good conduit for water, solutes, dissolved gases and sediments through it. The formation mechanism of soil pipe is complex (*Bryan, 2000; Bryan and Jones, 1997; Jones, 2004*) and related to various processes; such as seepage erosion, sapping, heave, tunnel erosion and backwards erosion (*Bryan and Jones, 1997; Dunne, 1990*). The soil piping phenomenon is associated with several factors, such as topography, lithology, climate, vegetation, land management etc. However, water plays a crucial role in the development of soil pipes. Groundwater table fluctuation (*Vannoppen et al., 2017*) and subsurface flow obstruction due to mass movement (*Verachtert et al., 2013*) controls the soil piping. The infiltration of water and percolation into deeper soil horizons depends on the characteristics physical properties of the soil which controls the erosion rate and piping mechanism (*Bernatek-Jakiel et al., 2016; Nadal-Romero et al., 2011*). Presence of clay in the formation, specially swelling clay (e.g. smectite), absorbs water and gets swell which facilitates the erosion rate (*Faulkner, 2013; Faulkner et al., 2000*). The initial development of soil pipe depends on the desiccation period of the soils which determines the soil cracking (*Barendregt and Ongley, 1977; Gilman and Newson, 1980*). Cracks provide more pathways for the fluid to flow and aid the piping activity.

The soil piping phenomenon affects the landscape in various aspects, either as depositional features or as erosional landforms, due to the combined effect of hydrological and geomorphological processes involved into it. The collapse of pipe roof develops the sinkholes and the development of several sinkholes within the same pipe leads to the formation of blind gullies (*Bernatek-Jakiel and Kondracka, 2016*). Soil piping has a strong effect on soil erosion, slope stability and channel network development (*Bernatek-Jakiel and Poesen, 2018*). Soil piping may affect the slope stability by accelerating the rate of soil drainage and reducing the development of perched ground water conditions (*Pierson, 1983; Uchida et al., 2001*). On the other hand, embankment dam failures can also be caused by soil piping (*Foster et al., 2000; Richards and Reddy, 2007*).

The detection of soil pipes is bit methodologically difficult (*Grellier et al., 2012*). Evidence of soil pipes through geomorphological mapping, the most commonly used method, becomes possible only when the roof of a pipe collapses, or the inlet or outlet of a pipe has been detected (*Bernatek-Jakiel and Kondracka, 2016; Bernatek-Jakiel et al., 2016*). Aerial photography in areas with no forestation, such as badlands (*Farifteh and Soeters, 1999*) or grasslands and pastures (*Grellier et al., 2012*), and high resolution digital elevation models (*Bernatek-Jakiel and Poesen, 2018*) would be useful for surface mapping. The direct methods (e.g. digging, trenching, dyeing, smoke bomb) are associated with point or area-specific information (*Anderson et al., 2009; Carbonel et al., 2014; Jones and Crane, 1984; Smart and Wilson, 1984; Zhu, 1997*) and sometimes provide piping connectivity. Though the surface mapping and direct methods aid in the detection of soil pipes, however, these approaches are not capable to bring out the subsurface piping configurations (*Cappadonia et al., 2015*) and network densities (*Holden et al., 2002; Got et al., 2014*). In this regard geophysical investigations, such as Ground Penetrating Radar (GPR); Electrical Resistivity Tomography (ERT); Seismic Refraction (SR); Self Potential (SP); Induced Polarization (IP), play an important role to configure the piping system. Among them GPR (*Bernatek-Jakiel and Kondracka, 2016; Got et al., 2014; Holden, 2004, 2006; Holden et al., 2002*) and ERT (*Ahmed and Carpenter, 2003; Bernatek-Jakiel and Kondracka, 2016; Giampaolo et al., 2016; Leslie and Heinse, 2013; Sajinkumar et al., 2015*) are used widely in soil piping investigation. The ERT technique measures the potential difference generated by the current inserted in the ground; therefore, the method responses well in case of a loamy as well as relatively wet subsurface (*Schrott and Sass, 2008*).

In the present study we carried out a combined geomorphological and ERT investigation to configure a soil pipe near the Kinanoor village of Kasaragod district, Kerala, India (Fig. 1). The study area falls in the northern part of Kerala, India (Fig. 1) and situated on the flank of Western Ghats (a NS elevated escarpment parallel to west cost of India, Fig. 1). The Kerala region, especially central to north Kerala, is prone to soil piping and several piping activity have been reported every year (*Joshi et al., 2021; Sajinkumar et al., 2015*). The reported piping activities are associated with lateritic environment and intensity of occurrence is intense during the monsoon seasons (*Joshi et al., 2021*). The present study aims to configure the reported pipe in electrical sense, understand the probable cause and most importantly study the societal consequences of the underground pipe.

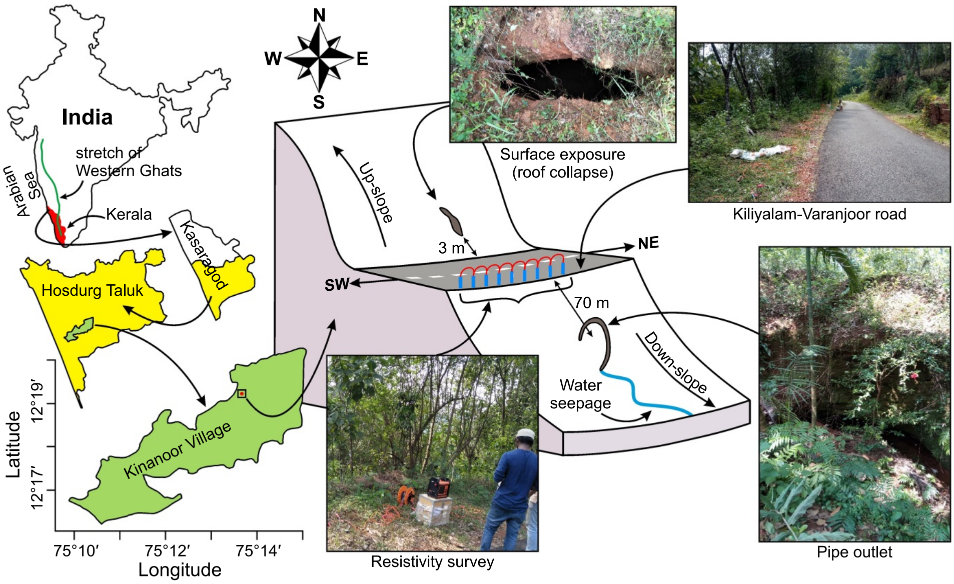


Fig. 1. Location map of the soil piping investigation site. A schematic diagram of the site provides a realization of the surrounding topographic settings. The site is located on the fringe-slope having high up-slope ($>25°$) and down-slope ($\sim 19°$). A subsided pipe outlet and a small roof collapse of the pipe are observed from geomorphological investigation and both are following a NW–SE trend. This site is run by only accessible Kiliyalam-Varanjoor road along which the resistivity survey is carried out to configure the pipe.

## 2. The study area

Physiographically the Kerala region, India consists of three distinct landforms namely the coastal plains (narrow alluvial deposits of elevation $<10$ m running parallel to the coast), the midlands (to the east of coastal plain with elevation $10-300$ m) and the eastern highland regions (elevation $>300$ m). The midland region is comprised of discrete lateritic hillocks separated by colluvium and alluvium covered deep cut valleys; which exhibits a rugged topography.

The study area, Kinanoor village, Kasaragod, Kerala, India (Fig. 1), is situated in the midland region and has a variable elevation of $\sim 20$ m to $\sim 80$ m. The soil piping affected site in Kinanoor village (12° 19′ 12.4″ N, 75° 13′ 40.0″ E) falls on the fringe-slope at $\sim 30$ m elevation and run by the Kiliyalam-Varanjoor road (Fig. 1). The up-slope of the affected locality is characterized by high slopes (>25°) whereas the down-slope is ∼ 19° (Fig. 1). Both the up-slope and down-slope sides are occupied by mixed forest. The study area is characterised by clay rich loamy soil cover directly seated over the Charnockite dominated Precambrian crystalline basement.

The study area falls in a humid climate having relative humidity ∼ 70.8% to ∼ 92.6% at a monthly average temperature range of ∼ 22.4° to ∼ 31.3° and experiences average annual rainfall of ∼ 3500 mm whose 85.3% is contributed by the southwest monsoon (according to data from Central Ground Water Board, India). The depth to the ground water table in the study area varies from ∼ 5 m to ∼ 24 m during pre-monsoon and ∼ 4 m to ∼ 22 m during post monsoon periods with a water table fluctuation from ∼ 0.3 m to ∼ 4.35 m (according to data from Central Ground Water Board, India) which certainly aids the piping activity in the region.

## 3. Methodology

To get a comprehensive configuration of the piping system in the study area, first we carried out geomorphological investigation in and around the affected locality. Based on the critical information obtained from the geomorphological study we carried out the site specific two dimensional (2D) ERT survey to understand the scenario of soil piping on the basis of subsurface electrical signatures.

### 3.1. Geomorphological investigation

Geomorphological investigation carried out in the study area primarily focuses the identification of pipe inlets-outlets and probable locations for pipe collapses such as depression (subsidence), sinkholes, blind gullies etc. To the down-slope side, around 70 m from the road, we found the tunnel opening (outlet) as a narrow stretch (Fig. 1) which is emerged at that location because of land subsidence. The dimension of the subsided location is approximately $1.5 \times 4.2$ m$^2$ and the pipe outlet formed due to the subsidence partly filled with subsided earth material. We observed the seepage of water through the tunnel bottom (Fig. 1) which flows 100 m down-slope and then connected to a tributary stream. On the other hand, towards the up-slope side, around 3 m from the road, we found a surface exposure (a small roof collapse) of the underground tunnel (Fig. 1). These both, the pipe outlet to the down-slope and the small roof collapse to the up-slope follow a NW–SE trend which is crossed by the NE–SW running Kiliyalam-Varanjoor road (Fig. 1). No other surficial evidence of the pipe has been observed. Based on the identified crucial inputs of the pipe we decided to carry out resistivity investigation orthogonal to the pipe trend to bring out the pipe configuration. However, to the up-slope and down-slope directions we didn't find any desirable space (because of the rugged topography and forestation) to carry out the resistivity survey. Since, the study area is located on the fringe-slope; therefore, the only possible way was to carry out the ERT survey along the road side. Therefore, we arranged the resistivity layout along the road side to carry out the 2D ERT survey for the pipe configuration.

### 3.2. 2D ERT investigation

#### 3.2.1. Data Acquisition

Resistivity data is acquired across the underground tunnel along a $\sim 95$ m long traverse that runs along the road side (NE–SW, see Fig. 1). ABEM Terrameter LS instrument (*ABEM, 2012*) is used to collect the full waveform 2D resistivity data at different depth points corresponding to a specific set up of electrode configuration. In the present study, 64 electrodes and 4 cables (with 16 take-outs in each cable) are used as $4 \times 16$ spread configuration. Both sounding (Schlumberger configuration) and profiling (Wenner configuration) are carried out to get the output with enhanced resolution in vertical and horizontal directions respectively. For both the configuration unit electrode spacing was 1.5 m. A total number of 1307 and 651 apparent resistivity full waveform data points are recorded for Schlumberger and Wenner configuration respectively. Number of stacking of the signal was 4 with 1% error at each depth point recording.

#### 3.2.2. 2D inversion

The collected data was processed and inverted using smoothness-constrained Gauss-Newton least-squares inversion algorithm (*Loke 1997; Loke et al, 2010; Sasaki 1992*) with the help of Res2DInv software package. The 2D inversion scheme tries to reduce the misfit in a least square sense. For that, the inversion program tries to determine the resistivities of subsurface in an iterative manner, whose responses will agree the data. The limit up to which the measured data is agreed by the model responses of the inversion output is expressed numerically in terms of root-mean-square (rms) error. Therefore, the rms error is a measure of accuracy of the model obtained after inversion.

#### 3.2.2.1. 2D inversion for Schlumberger array

The data collected using Schlumberger array is inverted and final model is obtained after 10 iterations. The final model yields an rms error of 0.81%. Figure 2a shows the final inverted 2D model along the $\sim$95 m long traverse for Schlumberger array.

To have a detailed view of the data misfit, the observed data and computed response at each electrode position along the profile is plotted as a function of pseudo depth. Figure 2b shows these pseudo sections representing the fit to the measured data. By utilizing these data misfit pseudo sections, it is seen that the data and the model responses are well correlated, which establishes the reliability and accurateness of the inversion output along the profile.

#### 3.2.2.2. 2D inversion for Wenner array

The 2D inversion is carried out on the data collected using Wenner array and the inversion is run for 10 iterations. The final model, obtained after 10 iterations, yields an rms error of 0.82%. Figure 3a shows the final inverted 2D model along the profile for Wenner array.

The pseudo sections representing the inversion responses and the measured data are shown in Fig. 3b to get an overview of the data misfit as a function of pseudo depth. The pseudo sections for model response and data show clear correlation which proves the dependability of the model obtained after inversion.

## 4. Results and discussions

The inversion outputs for sounding (Schlumberger array) and profiling (Wenner array) are studied together (Fig. 4) to get the vertical and horizontal

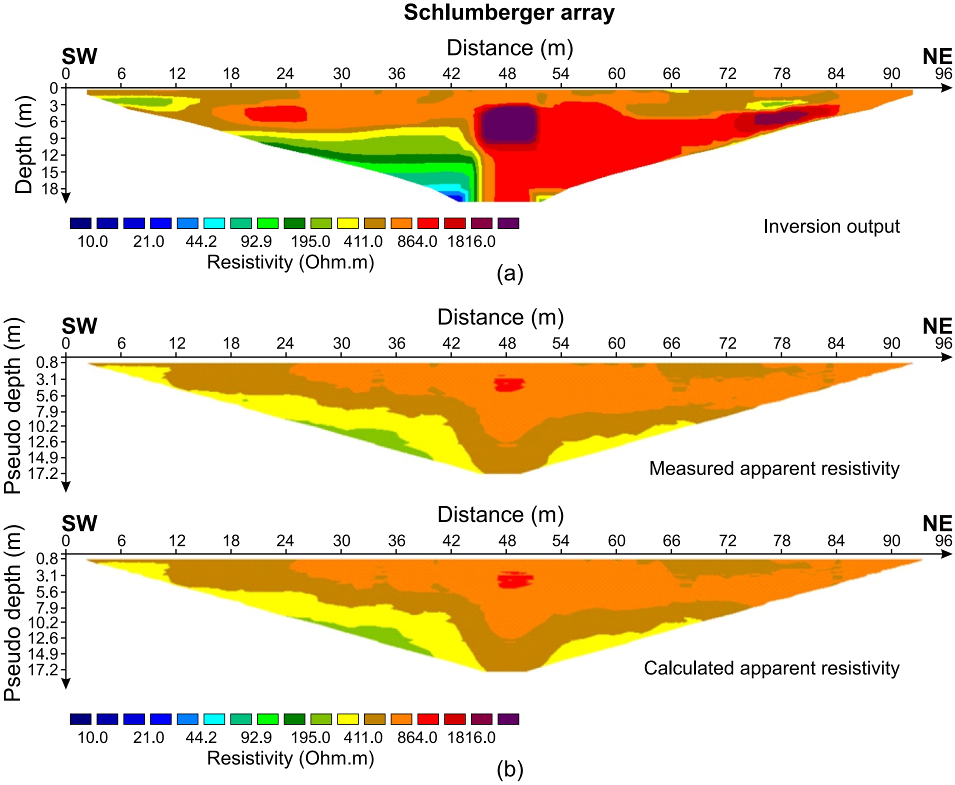


Fig. 2. Inversion result along with pseudo sections for data misfit estimation as obtained from Schlumberger array. (a) The 2D resistivity section obtained from the inversion of 1307 resistivity data points along the ∼95 m long profile down to ∼20 m depth. (b) Realization of the data misfit through the pseudo sections of observed and computed responses of the data along the profile.

structural variations beneath the surface. The 2D inversions provide us the resistivity sections down to ∼20 m and ∼18 m depth for Schlumberger and Wenner arrays respectively. From the combined section (Fig. 4), it is observed that the study area is anisotropic in terms of resistivity and can be divided into four distinct parts namely A, B, C and P ($P_1$ and $P_2$).

The top portion (A) having an average resistivity of ∼600 Ωm, represents the lateritic soil cover in the study region (Fig. 4). Within the top layer of average resistivity ∼600 Ωm, we have seen patches of low resistive (∼200 – 400 Ωm) zones at the extreme left and extreme right of the resis-

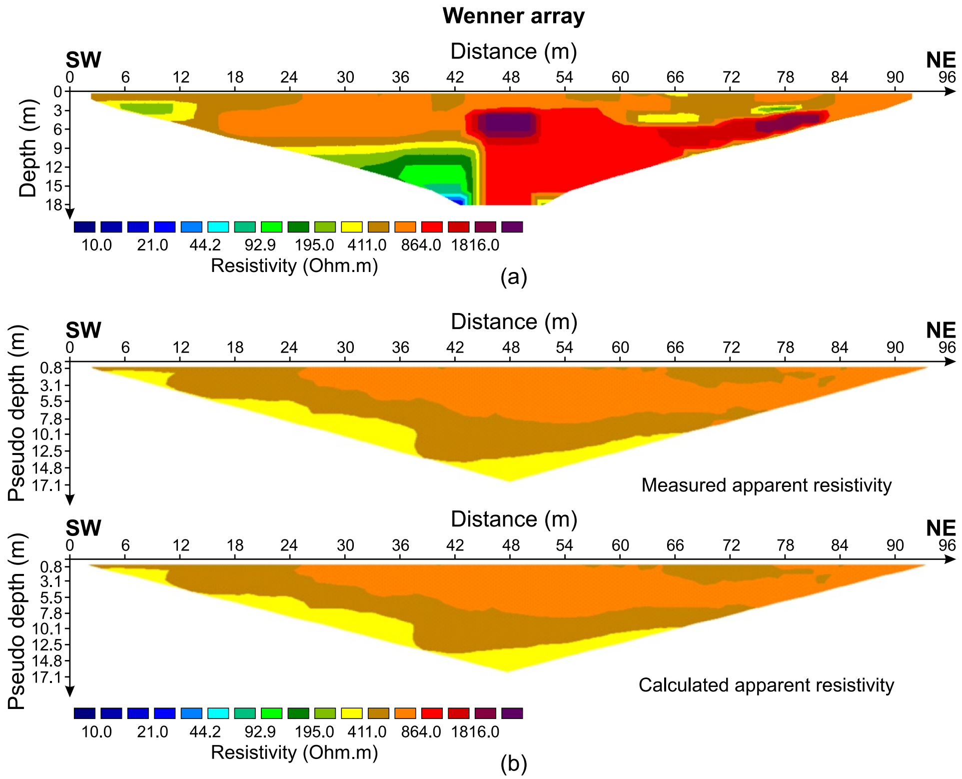


Fig. 3. Inversion output and data misfit pseudo sections for Wenner array. (a) The 2D resistivity section obtained after inversion of 651 data points along the ∼ 95 m long profile down to ∼ 18 m depth. (b) Pseudo sections represent the comparison between observed and computed responses of the data along the profile.

tivity sections (Fig. 4). These low resistive pockets of average resistivity of ∼ 300 Ωm might be appear due to the presence of local clayey sand /sandy clay near to the surface. The variation of the lateritic soil base (black horizontal solid line, $I_1$ in Fig. 4a) is demarcated utilizing the inversion output of Schlumberger array, since this array provides better vertical resolution. Below the lateritic soil layer there is a considerable amount of horizontal resistivity variation. The right portion of the bottom part (B) of the resistivity sections is more resistive (∼ 1500 Ωm) than the left part (C) (Fig. 4). The high resistivity (∼ 1500 Ωm) of the right part (B) is associated with the probable presence of either hard compact lateritic sandy soil or dry sand.

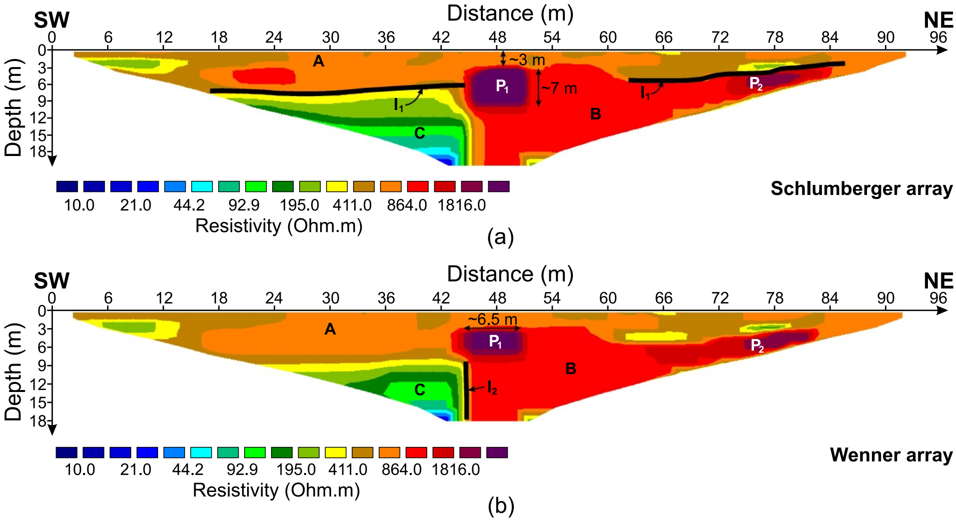


Fig. 4. Combined analysis of the inversion outputs of Schlumberger array (a) and Wenner array (b) show the detailed electrical signatures of the subsurface. It is observed that the resistivity variation in both the sections is inhomogeneous and based on that the subsurface is divided into four distinct parts – A, B, C and P ($P_1$, $P_2$). The solid black lines $I_1$ (a) and $I_2$ (b) demarcate the interfaces between different types of soil formation. The anomalous very high resistive zone ($P_1$) at the central part of both the sections signifies the hollow cave formed due to the soil piping. $P_2$ represents the probable presence of either a pipe or a hard rock boulder.

The resistivity of the left side (C) varies from $\sim 20 - 200$ Ωm with an average of $\sim 100 - 150$ Ωm. Therefore, this part (C) probably consists of clay material or mudstone and has high water saturation than the surrounding formation. The boundary between the high resistive part (B) and low resistive part (C) (black vertical solid line, $I_2$ in Fig. 4b) is demarcated from the inversion output of Wenner array as this array provides better horizontal resolution.

For both the resistivity sections (Schlumberger and Wenner), an anomalous very high resistive zone of resistivity $> 4000$ Ωm ($P_1$ in Fig. 4) is observed in the central portion of the sections. The appearance of this very high resistive zone in the resistivity sections ($P_1$, Fig. 4) signifies the presence of an air filled hollow structure beneath the surface. This signature of hollow structure might be occurring due to the presence of underground soil pipe; intrusion of air into which makes it highly resistive in nature. The detailed configuration of the hollow structure ($P_1$) is delineated based on the resistivity outputs (Fig. 4) of Schlumberger array (for vertical configuration) and Wenner array (for lateral configuration). It is derived from the resistivity section of Schlumberger array that the depth to the top of the hollow structure from the surface is $\sim 3$ m and the distance from the top to the bottom of the hollow structure is $\sim 7$ m (Fig. 4a). Horizontal extent of the hollow structure is $\sim 6.5$ m as derived from the resistivity section of Wenner array (Fig. 4b). This hollow structure ($P_1$, Fig. 4), lies along the same directional trend (NW–SE) of the observed pipe outlet and roof collapse (Fig. 1). Therefore, it can be suggest that all these three signatures might be associated with the same cave like structure formed due to the soil piping. We try to correlate these three inputs in systematic order and configure the probable outline of the pipe. Figure 5 shows the schematic diagram of the suggested hollow cave (formed due to the soil piping) of diameter $6.5-7$ m which is located $\sim 3$ m beneath the surface.

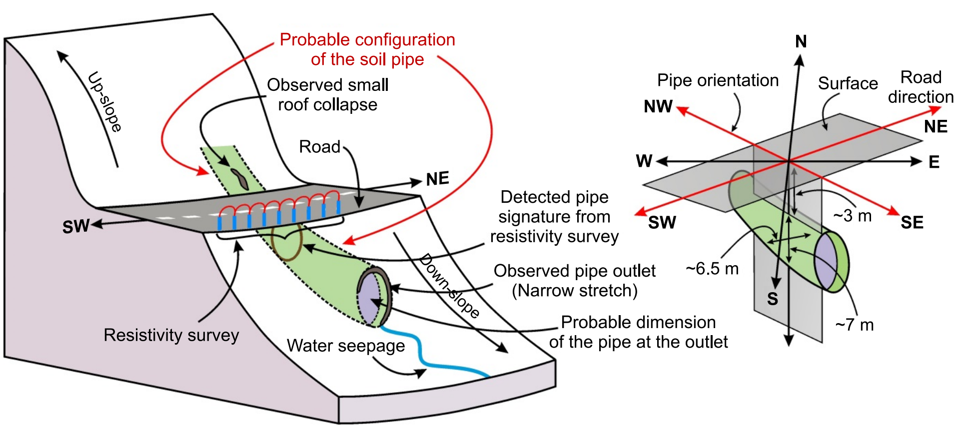


Fig. 5. Schematic diagram shows the probable configuration of the soil pipe beneath the study area.

Another probable signature of soil pipe ($P_2$, Fig. 4) of $\sim 2 \times 7$ m$^2$ dimension at a depth $\sim 5$ m with resistivity $> 2000$ Ωm is observed at the extreme right end of the resistivity sections. Though the resistivity analysis brings this probable pipe signature ($P_2$) into the picture, during geomorphological investigation we didn't find any characteristics of the pipe in the up-slope direction and could not find any surficial signature of the pipe due to the inaccessible down-slope area at that portion. Therefore, the resistive signature $P_2$ thought to be occurred in the inversion outputs because of the presence of either a probable pipe or a hard rock boulder.

To examine the reliability of the derived pipe configuration, we have carried out a synthetic study. For the study, we consider a 2D synthetic initial model (Fig. 6a) which resembles similar subsurface scenario of the study

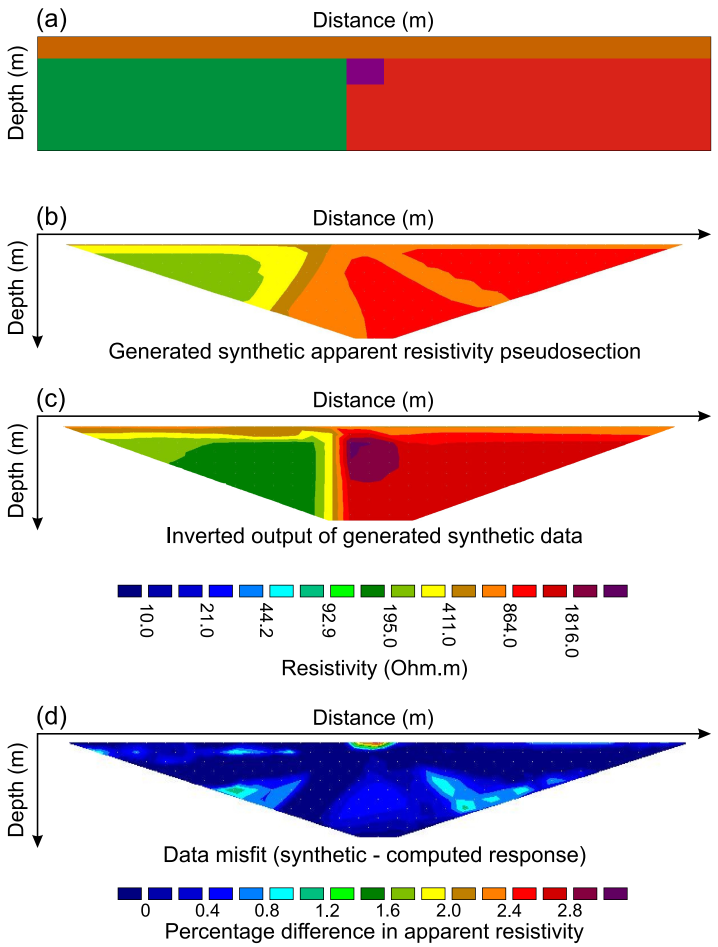


Fig. 6. Synthetic test to study the reliability of the derived configuration of the pipe. (a) The initial 2D synthetic model considered for the test (b) Generated forward synthetic responses (c) Inverted model of the synthetic forward responses. (d) Data misfit stands for a reliable output.

area. The initial resistivities are assigned based on the inverted models (Fig. 4). The forward resistivity responses for the synthetic initial model is generated (Fig. 6b) with an electrode spacing of 1 m. The inversion of the generated synthetic data brings the signature of the pipe (Fig. 6c). A low data misfit (Fig. 6d) stands for the reliability of the derived configuration of the pipe.

## 5. Concluding remarks

We carried out an integrated geomorphological and electrical resistivity investigation to configure the subsurface tunnel developed due to the soil piping in Kinanoor village, Kasaragod, Kerala, India. The salient conclusions made from the current study are:

1) Based on the critical input from geomorphological study the electrical resistivity investigation brings out the inhomogeneous nature of the subsurface. A lateritic soil cover of resistivity $\sim 600\ \Omega$m is seated on the formation having lateral resistivity variation of $\sim 100 - 150\ \Omega$m to the SW direction (mainly composed of clay or mudstone) to $\sim 1500\ \Omega$m to the NE direction (primarily consists of compact lateritic sandy soil/ dry sand).
2) A hollow tunnel (formed due to the soil piping) of diameter $\sim 6.5$ to 7 m is detected $\sim 3$ m below the surface through resistivity investigation. The tunnel depicts itself as a very high resistive ($> 4000\ \Omega$m) zone (because of the presence of air) at the central part of the resistivity sections.
3) The tunnel beneath the surface developed due to the soil piping orients in NW–SE direction and crosses by the Kiliyalam-Varanjoor road (only accessible road in the locality that runs NE–SW direction) almost orthogonally. From the investigation it is observed that the road is prone to collapse as the thickness of the tunnel roof is only $\sim 3$ m. Therefore, this thin soil cover above the tunnel makes the road vulnerable for transportation.
4) A bridge like structure with proper drainage facility at the location of the pipe is highly recommended to prevent the collapse of the road and any related unwanted circumstances. Therefore, the local administration is suggested to take proper precursory measures in this aspect.

5) Another signature of a probable pipe is also observed at the extreme NE end of the resistivity sections. However, there is a lack of supporting surficial evidences and the signature is thought to be related to a hard rock boulder. Therefore, the proper source of this signature needs to be investigated further in detail.
6) As the site is located on the fringe-slope, numerous first order streams originate from the up-slope constitute a radial drainage pattern in and around the affected site. However, the modification of the up-slope land for rubber plantation hinders the natural drainage system which aids the intense rain water to get accumulated in the top soil layers. Similarly, trenches made for rainwater harvesting in the up-slope direction facilitate the percolation of water. These activities might act as potential source factors for soil piping which lead to collapse of land. Therefore, it is suggested that the natural course of the drainage system in the up-slope area should not be disturbed/blocked because this may lead to subsidence of the area in future.

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