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ORIGINAL PAPER

A Study on the Effectiveness of Various Geophysical Methods in Detecting Naturally Formed Cavities in Lateritic Deposit

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Abstract Timely identifying unknown cavities below ground can minimize associated consequences, but there is no straightforward method to detect cavities. This paper aims to study the effectiveness of the application of different geophysical methods for detecting naturally formed subsurface cavities in lateritic deposits. A comparative summary of the effectiveness of various geophysical survey techniques used to identify the cavities is presented. There are multiple reasons for subsurface cavity formation, and the physical properties of the materials change when these voids are filled with air, water, or other geologic materials. The anomalies due to changes in physical properties between cavity space and surrounding medium can be easily detected by geophysical techniques. The main three geophysical methods, ground penetrating radar, electrical resistivity survey and multichannel analysis of surface wave, are studied on their advantages and limitations in detecting subsurface cavities. A typical field study is presented from the soil piping-affected region of Kerala, India. Geophysical surveys were conducted in the study area, and the size and depth of the cavity were mapped by the integrated geophysical method.

Keywords Geophysical study · Cavity · GPR · Electrical resistivity · MASW · Laterite Soil

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Introduction

The presence of underground cavities, whether caused by subsurface erosion or abandoned mine tunnels, can pose a significant threat to the stability of man-made structures such as highways, dams, and buildings. Subsurface cavities and anomalies can damage the ground strata, resulting in ground subsidence and excessive settlement that can affect the structures built above them. These anomalies can be caused by the cavity space itself, secondary effects around the cavity, or materials within the cavity [1]. There are several reasons for the formation of subsurface cavities, including abandoned mines, natural dissolution of rock material, underground faults, erosion of limestone, sewage line defects, poor backfill compaction, underground excavations, and dewatering [2–4]. Subsurface cavities are not easily detectable unless there is a surface opening or subsidence; hence, they act as an active source of property damage and a potential cause of personal injuries. Therefore, detecting subsurface cavities at the initial stage is crucial to stabilize the ground and prevent undesired damages and failures, especially since they can impair the bearing capacity of the foundation and water-retention structures such as earth dams, which can lead to piping failure if not adequately treated. While it may not be possible to detect every cavity during site investigation, gaining enough information to make reasonable evaluations of the extent of the problem at a given site and make reasonable estimates of the cost of dealing with it is desirable.

Detection of cavities traditionally involves examining aerial photographs, satellite images, conducting geotechnical and geomorphologic field inspections, and gathering data through interviews with locals and farmers. However, these conventional methods are often expensive and have several limitations in collecting accurate subsurface details.

Geophysical methods have emerged as satisfactory solutions for detecting underground voids to overcome these issues. Various geophysical methods which find helpful in detecting subsurface cavities are ground penetrating radar (GPR) [2, 4–7], electrical resistivity tomography (ERT) [4–6, 8], gravity survey [7, 9–11], surface wave methods such as Multichannel Analysis of Surface Wave (MASW) [5, 12, 13], very low-frequency electromagnetic method [4, 14], seismic methods [4, 15–17], electromagnetic methods [4, 17] and self-potential methods [4, 16]. Non-destructive testing or geophysical methods are being widely used to identify subsurface features critical for geotechnical site characterization, such as the thickness of soil/rock layers, stiffness of soil layers, physical properties, and shallow subsurface objects/anomalies.

Geophysical techniques are highly effective in assessing the risk of cavities in a specific site, as they can detect near-surface cavities and overcome the limitations of traditional probing methods. These techniques offer several advantages, such as flexibility, speed, and the ability to investigate a large area quickly. Unlike classical methods, geophysical techniques are non-invasive and provide detailed information on the internal structure of soil or rock masses. They are also suitable for various site conditions and can quickly and cost-effectively provide valuable information for engineering applications. Consequently, geophysical methods are ideal for developing appropriate hazard mitigation plans and implementing engineering designs for cavity-related hazards in the region.

Geophysics involves gathering physical measurements to derive physical parameters. Anomalies, such as subsurface cavities, can be detected due to their contrast with the surrounding geological conditions. There are various geophysical techniques available to measure the differences in physical properties between the concealed subsurface structures, such as cavities, and the surrounding lithology [3]. However, cavities can be filled with air, water, collapse material or a combination of these, making it challenging to identify contrasts in physical properties. Experience and appropriate geophysical methods are necessary to overcome these challenges. The use of geophysical methods for investigating underground voids can be traced back to the 1670s [17], and the U.S. Government's efforts to locate tunnels in Vietnam in the 1960s marked a peak in this area [4]. Geophysical methods are classified into three types: electrical, potential field, and seismic methods, and each relies on contrasts in different physical properties in the subsurface. In this paper, the effectiveness of identifying naturally formed cavities in a lateritic terrain using the above-mentioned geophysical methods is discussed with typical field survey. In the literature, the geophysical survey has been successfully applied in different soil conditions to get the dimensions of subsurface cavities, but limited references are available on lateritic soil deposits. This study intends to discuss the challenges faced in the geophysical survey of lateritic deposits and get the exact dimensions of cavity space using the integrated geophysical technique.

Study Area

Lateritic deposits in the Western Ghats are known for naturally formed cavities. Furthermore, the phenomenon of the formation of these natural cavities due to subsurface erosion is called soil piping [18]. Soil piping is a natural phenomenon which leads to the development of micro and macro air or mud-filled cavities in the soil. They may lie close to the ground or may be found at great depth. Initially, it is seen as minute pores, but in the course of time, it grows bigger and even causes land subsidence. This subsurface erosion is difficult to detect and is more rapidly occurring. These cavity formations do not occur suddenly but take time and depend on the nature of the soil, subsurface water flow, presence of vegetation and topography. Soil pipes are classified into juvenile pipes, younger pipes, typical pipes, and oversized pipes. Juvenile pipes are micro pipes which are usually seen in laterite cuttings [19], and it is the initial stage of piping. Younger pipes are small pipes that indicate the secondary stage of soil piping. Its diameter ranges from 5 to 30 cm. Typical pipes are mature pipes; an outlet will be visible in the lower region of such piping formations. Oversized pipes are huge pipes which cause land subsidence in most cases [19]. Huge pipes frequently occur in hilly regions, and in a few instances, these pipes pass under houses or other infrastructure, threatening their stability and safety. One common feature observed in these locations is hard lateritic soil in the top layers with an underlying saprolitic clayey layer. During monsoons, these layers will be subjected to hydraulic instability, leading to tunnel formation. This kind of huge natural cavity is observed in the Nelliyadukkam locality, Karindalam panchayath, Kinanur village, Vellarikundu taluk of Kasaragod district, Kerala (Fig. 1). Soil piping incident in this area occurred on 2014 August 2, the subsided area is located adjacent to the foundation of a house under construction. The cavity was noticed only in a later stage of construction, and the construction was stopped and relocated to a nearby area to prevent future structural failures. The Kerala State Disaster Management Authority (KSDMA) has done a field investigation in this area to map this cavity using an ERT survey, and the results are included in their report titled "Studies on land disturbances due to soil piping affecting the critical zones in Western Ghats of Kerala" in 2020 [19]. The cavity dimensions increase due to the subsurface flows during monsoon season, and resistivity surveys have limitations in getting the subsurface profile of a wide area. In some locations, ERT has space constraints,

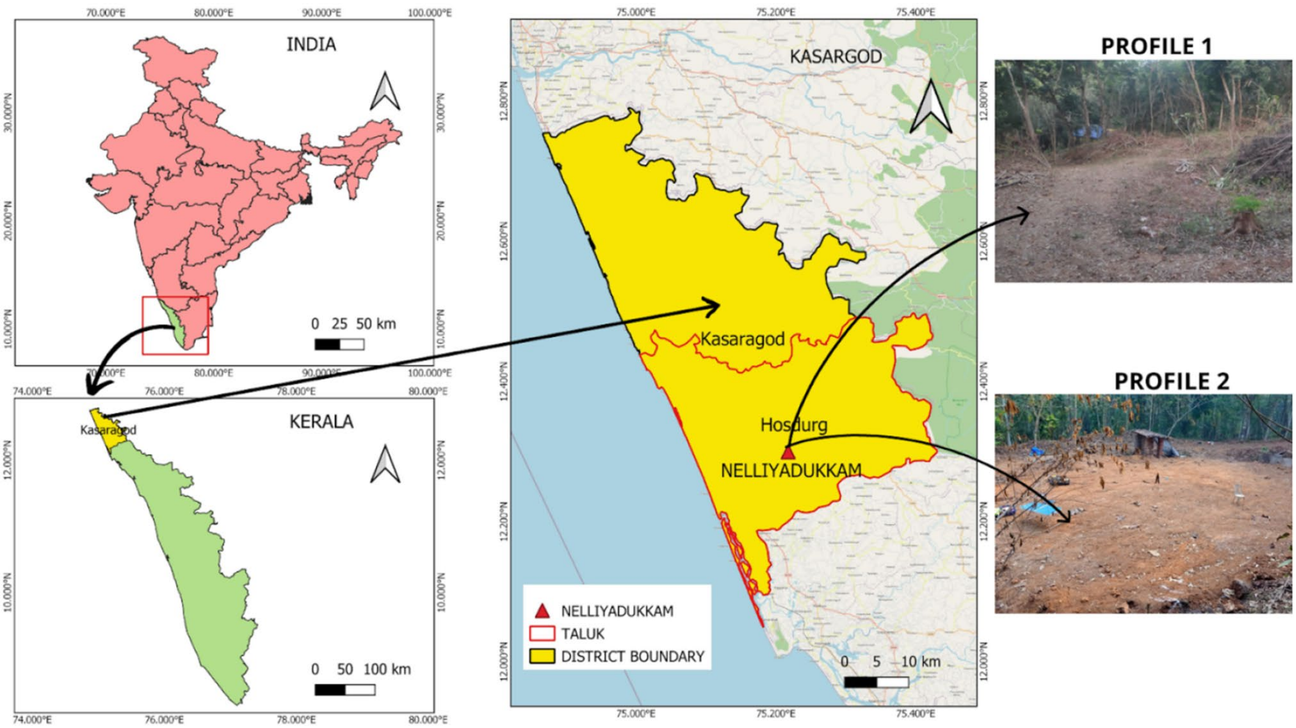


Fig. 1 Study area, Nelliyadukkam, Kasaragod district, Kerala, India

and we will have to rely on other geophysical methods. In the present study, ERT was conducted on the same location and alignment where results are available in the KSDMA report with the intention of checking the cavity propagation after monsoons and the same was compared with the results of the KSDMA report. Other methods, such as GPR and MASW, were also conducted in the area to check the effectiveness of getting cavity dimensions. The entire cavity outline in the selected study area is shown in Fig. 2, and this is a sloppy terrain with three different plains: the top road area, middle cavity plain and lower cavity plain. The elevation difference between three different plains is recorded using the dumpy level, which is marked in Fig. 2. The cavity space at the lower plain was huge at around 3 m wide, and people can stand in these caves. The survey details and results obtained for the lower cavity plain are discussed in detail in this paper.

The cavity in the study area is found to be oriented, as shown in Fig. 2. Since the cavity was visible from the sides and inside entry, it was possible to take the inner measurements for validation; the survey was conducted at the lower cavity plain, and the same is presented here. The house at the bottom plain was relocated into a safer area after the cavity was identified in the subsurface, and it was a bare area at the time of the field survey. The condition of the site during 2014 and present site conditions are shown in Fig. 3, and the inner view of the cavity is depicted in Fig. 4. The stratigraphy of the area consists of top hard lateritic soil followed by a normal clayey layer and soft saprolite clayey layer, and weathered rock as shown in Fig. 5. Samples were collected from different layers as marked in Figs. 3, 4 and 5, and the index properties were evaluated as given in Table 1. It is observed that the soil in the terrain consists a major portion of fines, especially clay. Samples from location 1 and location 2 came under the classification of silty soil because most of the clay fines gets washed out with erosion.

Methodology

Survey parameters for various geophysical methods such as GPR, ERT and MASW are fixed based on the inferences obtained from the literature. Applications of different methods in different geological conditions are studied in detail, and suitable survey parameters are selected for the study area. The number of studies available in lateritic terrain is very low, and the challenges are high in the effectiveness of the survey for such bigger subsurface cavities. Hard lateritic rock on the surface for a depth of around 2 m again makes the situation complicated, and we really need to check the effectiveness of the normal geophysical survey technique as well as data processing steps in this study area. Survey details implemented in the study area are given below.

Fig. 2 Cavity map of the study area

Ground Penetrating Radar in Cavity Detection

GPR is a geophysical technique used to obtain information about subsurface features. The GPR surveys involve moving an antenna across the ground surface to send high-frequency electromagnetic waves into the soil. By measuring the reflected waves, the GPR instrument can generate qualitative and quantitative subsurface details [20]. When an electromagnetic pulse is transmitted from the antenna, it travels through the subsoil at a speed that is determined by the dielectric properties and conductivity of the materials [2]. Suppose the radiated energy encounters an anomaly with different electrical properties in the subsurface. In that case, only a part of the incident energy will be reflected back to the antenna, and the rest will be transmitted through inhomogeneity [4]. The reflected pulses are received by the antenna's receiver, which helps to measure the travel time. The time delay between the transmit time and the signal receiver time can provide an indication of the target depth.

The amplitude and travel time of reflected pulses in GPR are primarily determined by the electrical properties of geological materials, which are influenced by factors such as the degree of saturation, ionic strength of pore fluids, and porosity [20]. GPR surveys can be conducted using either a monostatic or bistatic mode. The former uses a single antenna for both transmission and reception, while the latter employs separate transmitting and receiving antennas. Although a single-antenna system is less expensive and easier to use, a dual-antenna array is more effective in detecting minor vertical fractures in the subsurface and minimizing

Fig. 3 **a** Damaged foundation in the study area during 2014 [19] **b** Site Condition at 2022

unwanted surface noise [2]. The choice of antenna frequency in GPR systems is determined by the resolution or depth of penetration required for the survey, and antennas ranging in frequency from 20 to 3 GHz are commonly used. A high-frequency pulse produces a greater resolution but has limited penetration depth, while a low-frequency pulse contains more energy and penetrates farther into the subsurface but has reduced reflection from smaller targets. The penetration depth of GPR is inversely related to clay content due to the high adsorptive capacity of clays for water and exchangeable cations, which increases the dissipation of electromagnetic energy. GPR data processing involves removing time delay, applying a time-varying gain and a bandpass filter, and migrating and correcting for topography. Many commercial software packages are available for processing GPR data, and Reflexw, a computer-based software package for seismic, electrical, and GPR data processing, modeling, and interpretation, is a useful tool [21]. GPR has been widely used in geological engineering and environmental management for mapping shallow targets. GPR surveys encountered various logistical and instrumentation constraints over 40 years ago, resulting in many engineers holding a negative view of their effectiveness. However, with the significant advancements in computer equipment, GPR capabilities have significantly improved. The ability to utilize post-survey filters on stacked wave traces saved in a computer offers a significant advantage to the investigator. Engineers can apply filters such as gain and noise

Fig. 4 Inside view of the cavity space in the survey location

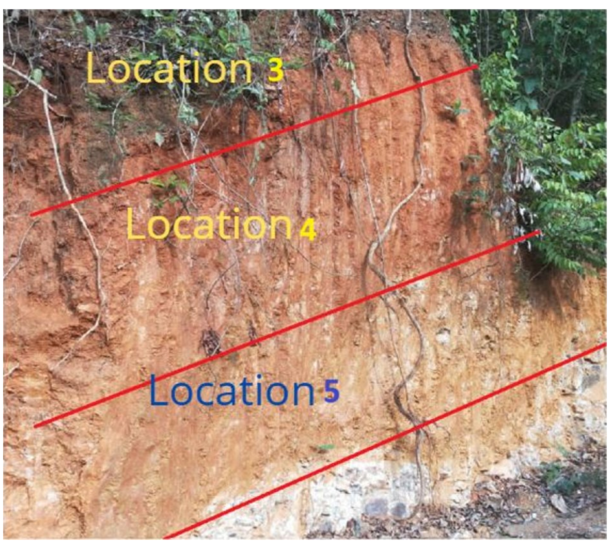


Fig. 5 Sample collection locations of study area

(frequency, background removal, etc.) to enhance the survey data and detect less visible subsurface characteristics.

GPR is a quick and highly responsive method to soil properties [2, 4, 21–23], especially in the karst environment [14, 20, 21, 24], where long surveys with small trace spacing can be conducted. However, the effectiveness of GPR can be limited in damp or saturated soils and shaly environments [5, 23, 25], and it may not be effective in detecting cavities in coastal areas [25]. The GPR method is highly dependent on the electrical properties of the ground and may have limited application in highly conductive materials. In contrast, low conductivity sandy soils and limestone terrain can be explored to greater depths using GPR [4, 6, 14, 20–22]. Various studies highlight the advantages of using GPR due to its ease of data collection and ability to efficiently detect and map shallow subsurface cavities in areas with resistive terrain. GPR's high-frequency operation allows for excellent resolution of anomalous features, producing clear images of shallow subsurface features [2, 4, 14, 20, 26]. However, the presence of high levels of clay in soils in the shallow subsurface can make GPR ineffective [14, 23]. Additionally, it may be challenging to detect small-sized cavities or accurately measure their dimensions using GPR [22, 23, 26]. The size of cavities may also be overestimated in some studies.

In the present study, the equipment used was Mala ProEx GPR manufactured by Mala Geoscience consisting of 250 MHz and 500 MHz ground coupled, shielded bistatic antenna with RAMAC control unit, RAMAC XV11 GPR acquisition system, interconnecting cables and an odometer. Calibration of the distance and electromagnetic wave velocity, i.e., depth, was done in the field before carrying out a detailed survey. Distance calibration is done by laying a 10-m-long measuring tape along a flat surface and then selecting the 10-m-length odometer calibration option on the GPR system. Measured distance in GPR by sampling intervals of electromagnetic pulses emitted every 10 cm is compared with the field values, and the associated metadata is updated. Similarly, the depth of the subsurface layer

Table 1 Index properties of soil at different layers

Property	Location 1	Location 2	Location 3	Location 4	Location 5
Moisture content (%)	19.51	11.94	11.11	14.03	9.76
Specific gravity	2.64	2.68	2.85	2.65	2.85
Gravel (%)	4	20	4	0	0
Sand (%)	30	57	28	26	21
Fine (%)	66	22	68	74	79
Liquid limit (%)	40	24	33	49	52
Plasticity index (%)	11	NP	9	26	24
IS classification	MI	ML	CL	CI	CH

or object below the ground was identified and electromagnetic velocities are varied in GPR to match with the same. Matched GPR electromagnetic velocity confirms that data obtained from GPR is reliable and these site calibrations are followed in every site GPR survey to ensure reliable GPR signal and interpretation. In some cases, the dielectric permittivity of the soil terrain was measured using the time-domain reflectometry (TDR) test and the electromagnetic velocity in the soil was calculated and compared with field values. The maximum penetration depth of Mala ProEx250 and 500 MHz antennas is around 10 and 5 m, which depends on the ground conditions such as soil type, moisture content, and salt content. The survey was carried out along the six lines of the lower cavity plain in the study area as shown in Fig. 6. The acquisition was performed using wheel mode, and the speed of acquisition was a normal walking pace. The site consisted of rough ground, and thus, the surface required smoothening with an earthmover to allow good contact between the base of the antenna and the ground surface.

Electrical Resistivity Survey in Cavity Detection

The ERT is a method used for mapping the geoelectric structure of the subsurface of the earth. To induce an electrical field in the earth, a direct electric current is injected into the ground, or a very low-frequency current is used. The current electrodes are used to inject the current, and the potential electrodes are used to measure the earth's response, which is recorded as a potential drop or voltage [27]. Depending on the depth of penetration and resolution required, various electrode configurations can be used. Resistivity measurements are utilized to detect changes in subsurface resistivity, and these measurements are reported as apparent resistivity. The measured voltage is used to represent resistivity, assuming the subsurface has invariant electrical properties throughout and the depth of exploration is homogenous [28]. True resistivity and apparent resistivity are equivalent only if the subsurface is perfectly homogeneous to a depth equal to the depth of exploration.

Fig. 6 Survey line details of GPR and MASW

Different electrical methods employ varying methodologies and frequencies of the electrical field. Low-frequency techniques utilize an electric field that changes slowly, whereas high-frequency methods employ a rapidly changing electric field. The effectiveness of each electrical method depends on a range of factors, such as the electrical properties of the anomaly in comparison with its surrounding environment, as well as the size and depth of the anomaly. Electrode spacing is adjusted to study resistivity variation with depth. Increasing the electrode spacing allows for a greater depth of penetration. A fixed electrode separation is maintained along a profile line to determine lateral variations. To detect shallow targets, small electrode spacing is required. However, ambient noise levels resulting from natural fluctuations of earth resistivity, cultural interference, and lateral variations in the subsurface may limit the recognition of these anomalies. Nonetheless, the electrical responses are strong enough to justify further investigation [4].

During electric resistivity surveys, several configurations, such as Wenner, Schlumberger, pole–dipole (Bristowbate) and dipole–dipole, are commonly utilized in the field for cavity mapping. Research studies by Orlando et al. [29] and Carbonel et al. [6] suggest that the dipole–dipole configuration is known to yield more significant responses to a given anomaly. Additionally, this configuration has been found to be highly sensitive to horizontal resistivity changes, making it ideal for mapping vertical structures such as dikes and cavities [30]. On the other hand, the pole–dipole method has been proven more effective for cavity mapping, as per the findings of Lowry [28] and Samyn et al. [31]. The Bristow method, which employs a pole–dipole configuration, can accurately determine the size and location of subsurface cavities by approximating a monopolar current source and moving the current electrode an effectively infinite distance from its counterpart, typically five to ten times the distance to be surveyed [28].

The primary distinguishing feature of a cave is the difference in electrical resistance between the air-filled cavity and the surrounding limestone or other materials. As a result, the resistivity method is the most commonly used technique for cave detection [16, 32–34]. When an air or water-filled cavity is encountered, the current distribution is disturbed, leading to an abnormal rise or fall in the electrical resistance value. Low-resistivity anomalies usually indicate water-filled or sediment-filled cavities [3, 4, 6, 9–11, 14, 16, 26, 30–32, 34], while high-resistivity anomalies generally suggest air-filled cavities [4, 8–11, 22, 24, 30, 32, 33]. Regions with resistivity less than 0.5 Ωm may be associated with salt deposits [24], while those with resistivity less than 125 Ωm can be identified as moist soil and those with resistivity greater than 125 Ωm as dry soil [8]. Carbonate rocks are typically associated with very high resistivity values [14, 34]. These findings are based on several studies using the resistivity method to detect caves. The resistivity method has been the most widely used for cave detection because of the difference in resistance between an air-filled cavity and the surrounding limestone or other materials. However, the ERT survey cannot discern cylindrical cavities beyond the depth to the top, approximately equal to the diameter of the cavity [28]. While ERT has greater depth capabilities than GPR [14, 26, 28], its results may vary with the presence of water, making it less reliable in certain situations.

An ERT survey was conducted in the area with an ABEM Terrameter instrument with all three arrays of Wenner, Schlumberger and dipole–dipole in the same alignment as conducted in the KSDMA report 2020. The receiver had 24 channels with a precision of 0.1% and an accuracy of 0.2%. A resolution of 3 nV at 1-s integration can be achieved. The transmitter is a constant-current transmitter with a maximum output of 2500 mA. The precision and accuracy are 0.1% and 0.2%, respectively. A total of 80 m stretch was surveyed with 1 m electrode spacing, as shown in Fig. 7, with anticipated cavity space at the middle of the survey line. The sampling frequency was set as 50 Hz. The data was inverted using Res2Dinv software to get the subsurface resistivity image.

Seismic Methods in Cavity Detection

MASW is a technique for exploring seismic activity that was first introduced in the field of Geophysics by Park et al. [12].

Fig. 7 Typical ERT survey alignment in the field

This technique involves analyzing the changes or dispersion of surface waves as they travel across a particular site and, specifically, how the energy of these waves changes as they pass through a group of geophones. Unlike other seismic waves, surface or Rayleigh waves are helpful for obtaining accurate dispersion patterns, as they are highly correlated with the shear wave velocity (Vs) profile of the medium being studied [15]. Additionally, Rayleigh waves are unable to travel through voids filled with air or water, as the shear modulus of these materials is zero, making anomalies easy to detect. MASW is a valuable tool for determining ground stiffness, as it measures the shear wave velocity of the subsurface in one, two, or three dimensions, making it ideal for a range of geotechnical engineering projects, typically at depths of 0–30 m. The shear modulus, which is a critical engineering parameter, is directly related to a material's stiffness, and Vs is the most reliable indicator of this parameter from a seismic perspective.

Previous research indicates that two common techniques used to study surface waves are the spectral analysis of surface waves (SASW) and the MASW [12]. The SASW method involves using two receivers placed at different distances to analyze the properties of different depths. However, this method is typically time-consuming. On the other hand, the MASW method uses multiple receivers to gather synthetic seismic data. This allows for extracting the dispersion curve of Rayleigh waves by considering all of the receivers. The shear velocity profile can then be estimated by applying the inversion process to the obtained dispersion curve. Overall, the MASW method is more accurate and efficient than the SASW method [13].

The MASW method involves recording frequencies ranging from a few to tens of hertz (e.g., 1–30 Hz) using a multichannel recording system with a receiver array over a distance range of a few to a few hundred meters (e.g., 2–200 m). Two types of MASW methods are available: active and passive. The active method is the most common and can produce a 2D Vs profile with an investigation depth of up to 30 m. In contrast, the passive method can investigate a few hundred meters. Seismic waves generated by a large energy source travel into the ground and reflect, refract, and diffract due to differences in seismic wave velocity among various earth materials [27]. Sensitive vibration detectors, called geophones, measure the response of the waves upon returning to the surface. Large-wavelength surface waves require a substantial energy source to create [27].

The MASW method is used to identify underground anomalies by measuring the time taken for a seismic wave to travel from the source to geophones, reflecting off geological discontinuities along the way. The different seismic velocities of earth materials cause the reflection, and by moving the geophones and source, the properties of the anomaly can be determined. Typically, an array of geophones spaced 2 to 5 m apart is used with multiple source locations to collect travel time information. Precise geophone and source locations are necessary to locate the anomaly accurately. Filtering is necessary to eliminate unwanted signals and improve the signal-to-noise ratio, which is essential for obtaining the shear wave velocity profile of the stratum. Without filtering, the phase-frequency domain reveals no anomaly, even if the void is present. As the shear wave velocity typically increases with depth [22] and inverted S-wave velocity profiles can indicate the presence of voids at depths where the shear wave velocity drops present [5, 31]. However, these profiles represent only the average velocities of the subsurface layers. Studies by various researchers have shown this to be the case.

Seismic surveys are a more reliable method as they can pass through different kinds of soils, but as the depth increases, the waves can be attenuated, affecting the results. The seismic survey uses Rayleigh waves, which can detect anomalies filled with air or water quickly with the MASW survey. Seismic refraction surveys cannot detect dissolution cavities at the bottom of the salt layer when they are filled with water or sediments with a primary wave velocity lower than the salt layer [24]. The MASW survey may not be effective in some Karst cavity areas because of the large dimensions of the cavity, and the reflected seismic waves could not reach the geophones. Various methods are available for cavity detection. One such method, proposed by Nasseri-Moghaddam et al. in 2005 [35], is called the analytical procedure based on attenuation analysis of Rayleigh waves (AARW). This approach utilizes seismic data's frequency spectrum to compute the spectral energy, which is dependent on the size and depth of the void [15, 36]. As a result, an energy concentration above the void can be observed. Passive and active MASW surveys are capable of detecting subsurface cavities at large and near-surface depths, respectively. However, accurately detecting the dimensions of the cavities can be challenging and requires a complete understanding of seismic wave propagation in the study area.

A seismic survey of MASW was performed in the study areas using 24-channel Geometrics Geode seismograph with 4.5 Hz geophones. The seismic wave for this survey was generated from an active source by hitting a 7-kg sledgehammer on a 300 mm × 300 mm size metal plate with three shots. A typical field photograph of the MASW survey conducted at the site is shown in Fig. 8. These waves were recorded by geode with 12 receivers placed at an offset of 0.5 m. The shot offset distance for each line was kept at 3 m. The wave traces recorded were processed using Surfseis 6 software to get the 2D subsurface Vs profile.

Fig. 8 Typical line 5 of MASW 2D survey

Results and discussion

The resistivity profile obtained from the ERT survey is shown in Fig. 9. The resistivity values change from 35 to 2500 Ωm. The suspected cavity space was located at a distance of 30 m from the starting point, and from the resistivity diagram, a high conductive passage is observed within a depth of 2.5 m from the surface and which was validated from the site with the presence of saturated subsided soil sediments in the cavity space. The presence of a high resistive zone vertically below the central electrode is strengthened by the geoelectrical sections of the profile. The tunnel roof was observed at a depth of about 2.5 m from the surface in both Schlumberger (Fig. 9a) and Wenner (Fig. 9b) electrode configurations. But the dipole–dipole survey was not effective in the region because of the hard lateritic rock on the surface as well as extremely dry soil conditions. The high-resistivity zone was found to extend at a depth of 2.5 to 8.5 m in both configurations. The data generated by Schlumberger configuration was more accurate than Wenner array mode. The survey line 1 of Nelliyadukkam locality given in the report of KSDMA 2020 [19] shows the similar test

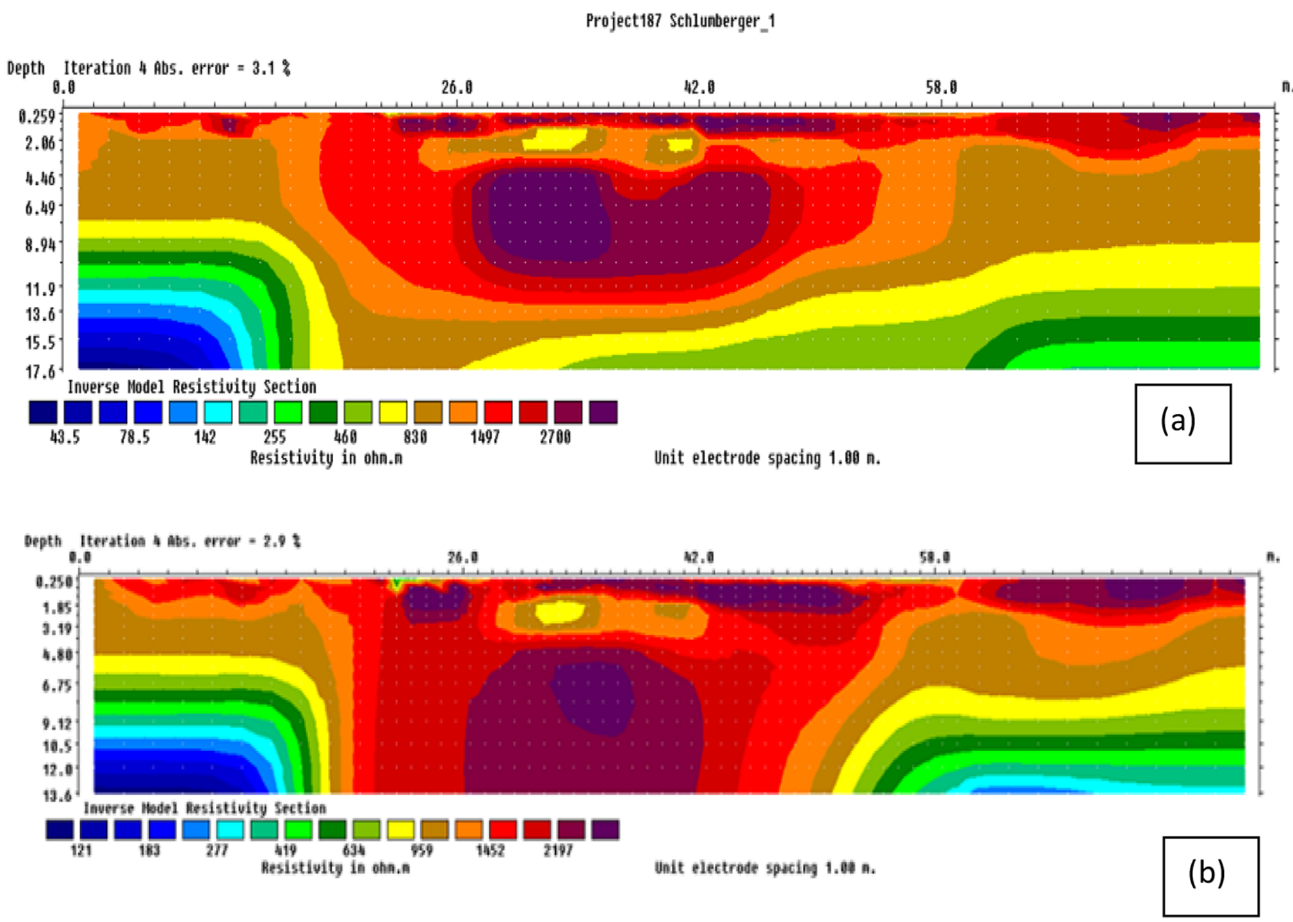


Fig. 9 Resistivity tomography obtained for the study location **a** Schlumberger **b** Wenner

results; the only change noticed from the report is the roof of the cavity starts at 3.98 m and extended to 10 m at the bottom. The comparison of the results indicates that the roof of the cavity collapsed more with the passage of subsurface water in the course of time, and more sediment was deposited at the bottom of the cavity. ERT survey was successful in the survey alignment, but it was unable to get the lateral spread of the cavity area using this survey technique. Moreover, in such situations, GPR and MASW play a great role.

Typical raw GPR data obtained for line 1 is shown in Fig. 10, and the Wiggle form of reflected electromagnetic waves with distance is shown in Fig. 11. The interpretation is difficult from raw data because of the noise in the signal. GPR data were processed using Reflexw software by applying the time zero correction, Dewow correction and signal gain. Data processing steps are depicted in Fig. 12. Processed GPR profiles across the cavity in the bottom plain are shown in Fig. 13, line 1 to line 6. The average depth of pipe development is found to be 2 m. Figure 6 shows the lines along which the GPR equipment was dragged. The total stretch of the survey line was 13 m, and the center part of the cavity space was found to be filled with suspended sediments, which are clearly visible in the radargrams and validated visually from the site as well with ERT results. The cavity space started at a depth of 2 m from the radargram, which was checked visually at the survey area and validated with ERT results also. The multiple reflections at the starting and end of the survey lines show the presence of a cavity. If

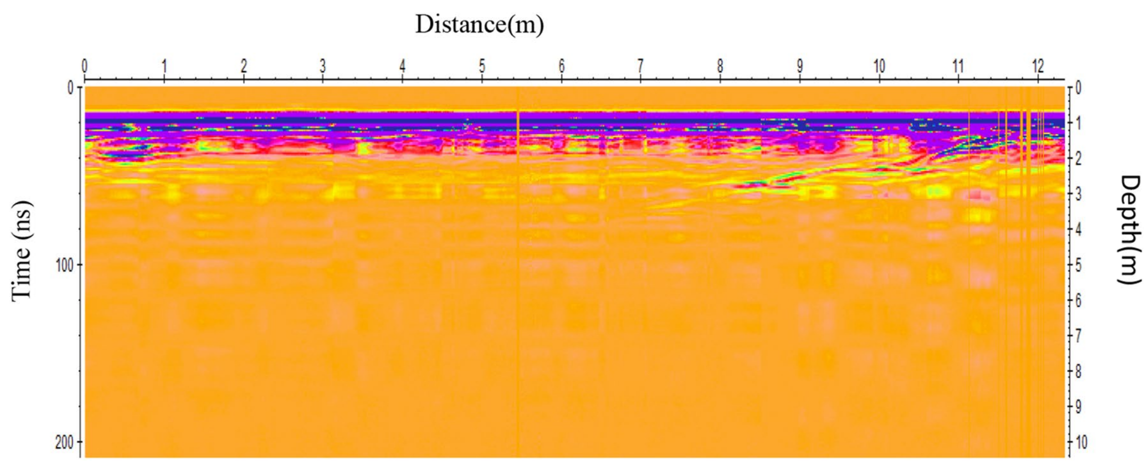


Fig. 10 Raw radargram obtained for line 1

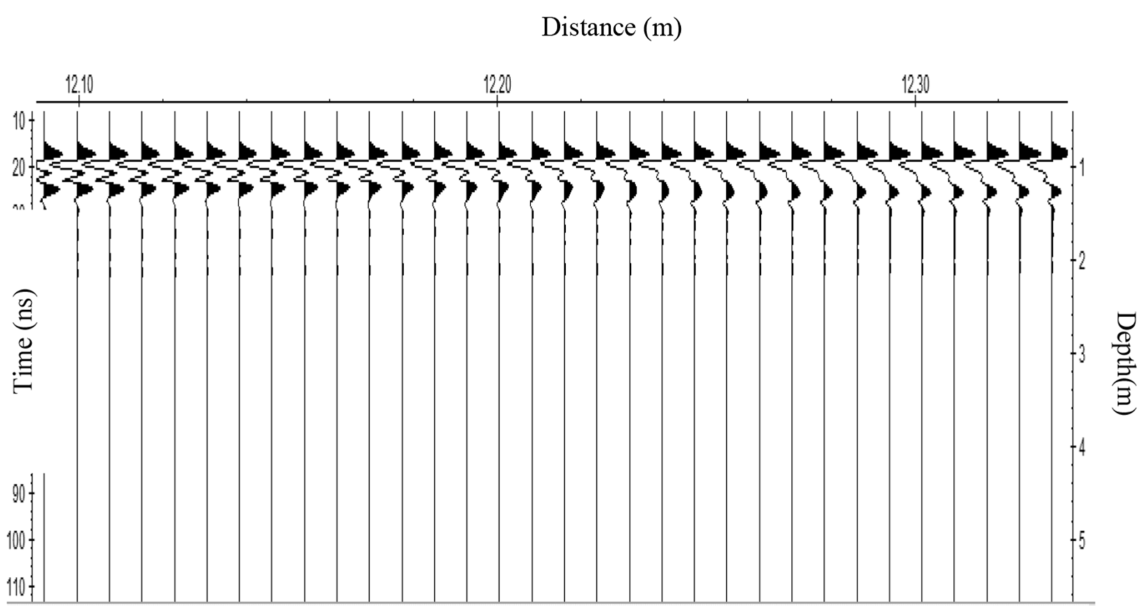


Fig. 11 Wiggleform reflected electromagnetic waves of line 1

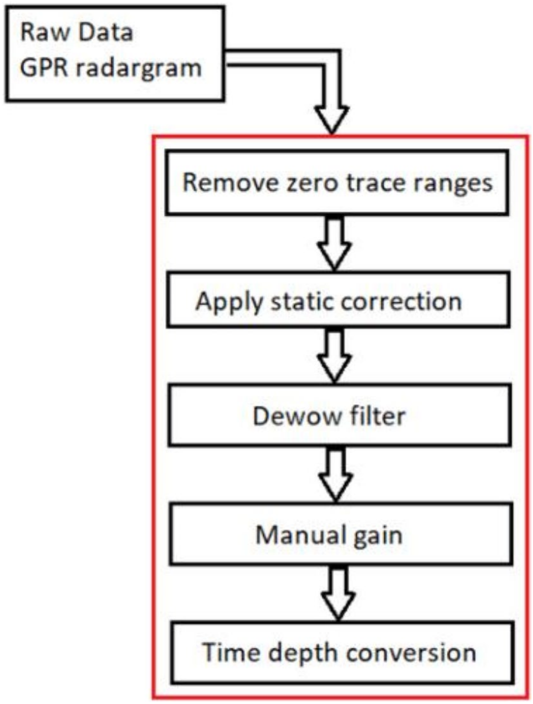


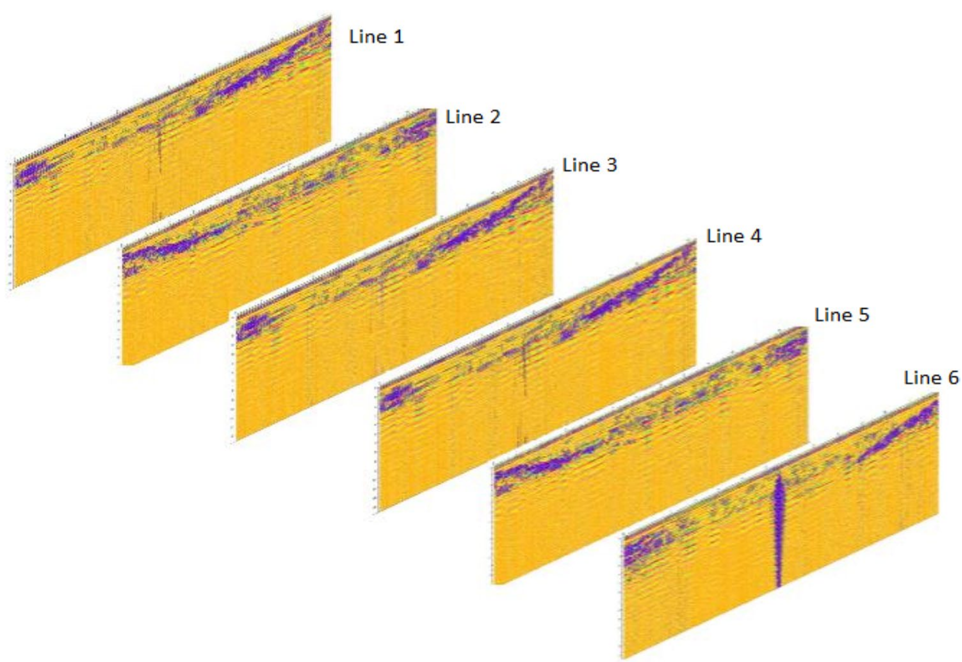
Fig. 12 Data processing steps of GPR radargram

there is any cavity space present in the subsurface, the electromagnetic waves will undergo multiple reflections from the cavity wall and, which is noticed in the radargrams. The middle portion of the cavity space is filled with suspended sediments which are high in clay. Electromagnetic waves attenuate very fast in clay, and the same trend is observed in this case as well. Detailed processed data of the GPR radargram is shown in Fig. 14, and different interfaces are marked clearly. Reflections from the air–laterite surface interface, cavity space filled with subsided saturated soil sediments and cavity–soil bottom interface are clear from the radargram. The same is visible in the wiggle form as well. Reflections from the air cavity will be in phase with the transmitted wave, which is shown in Fig. 14.

The top surface of the study area contains strong laterite soils having an S-wave velocity of 500 m/s. When hit on the plate with a sledgehammer, seismic waves are produced, and these waves pass through the ground and reach after being refracted and reflected by subsurface features. Geophones of 4.5 Hz were used in the survey, and a 2 D MASW survey was conducted. Recorded data were processed using Surfseis software version 6 to prepare the 2D shear wave velocity profile. Typical seismic wave records obtained from the instrument are shown in Fig. 15. Dispersion curves (Fig. 16) are prepared initially, and this is inverted to get the 1 D shear wave velocity profile (Fig. 17). Several 1D shear wave velocity profiles combined to get the 2D shear wave velocity profile of the study area, and the same is presented in Fig. 18. The top hard layer of laterite stone for a depth of 2.5 m and bottom cavity space filled with subsided saturated soil materials 4 m is clearly visible from the 2 D shear wave velocity profile, which matches with the field conditions in Fig. 19 as well as ERT and GPR results.

It is seen from the above results that we cannot rely on a single method in obtaining cavity dimension, and it is better to go with an integrated profile approach developed by Anbazhagan et al. [5, 37]. The cavity dimensions obtained

Fig. 13 Radargrams obtained for GPR lines



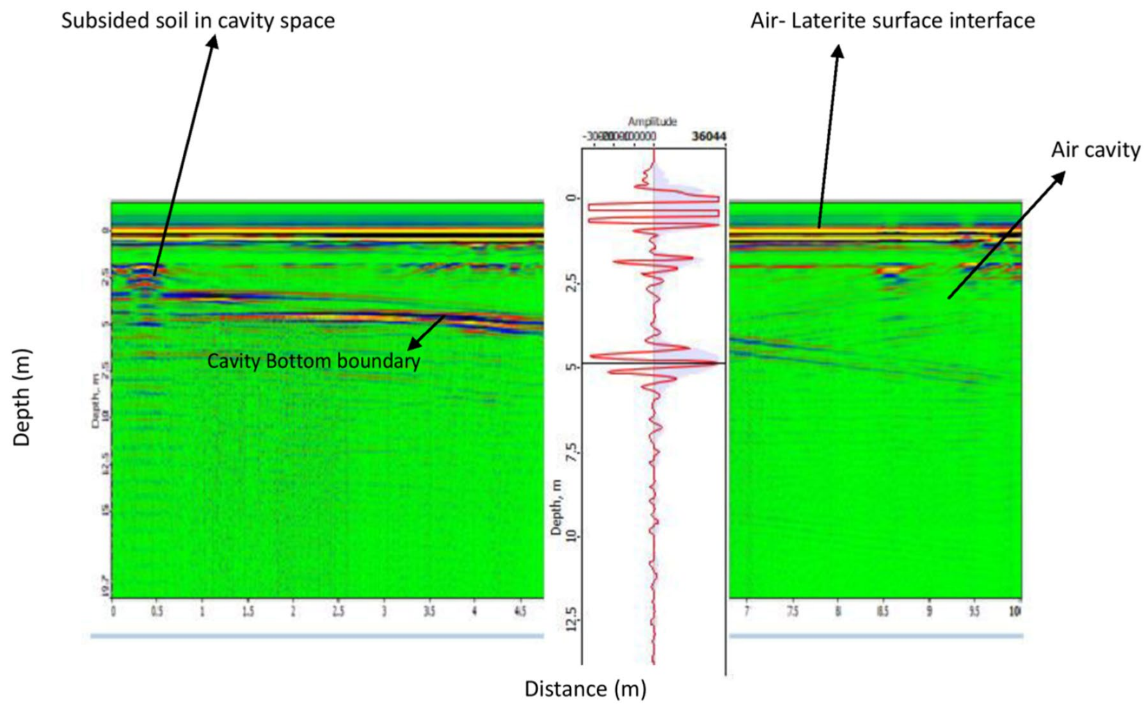


Fig. 14 Processed radargram of the study area line 1 with 250 MHz antenna

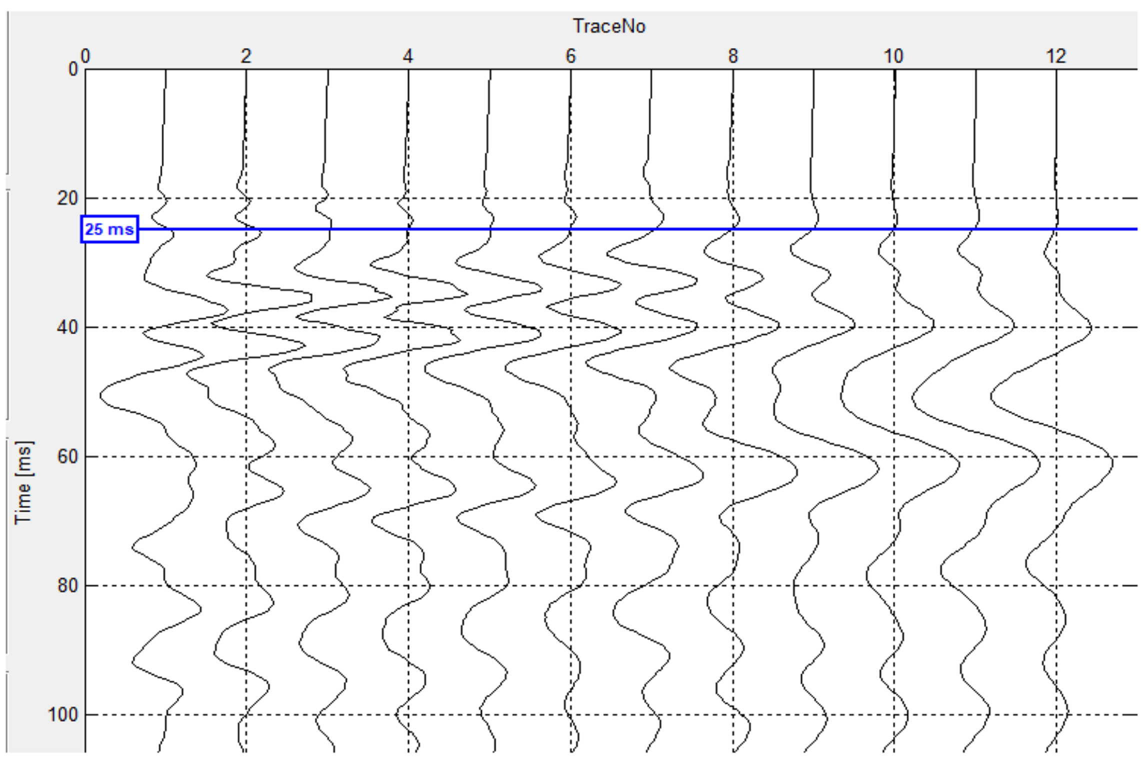


Fig. 15 Seismic wave record of study area

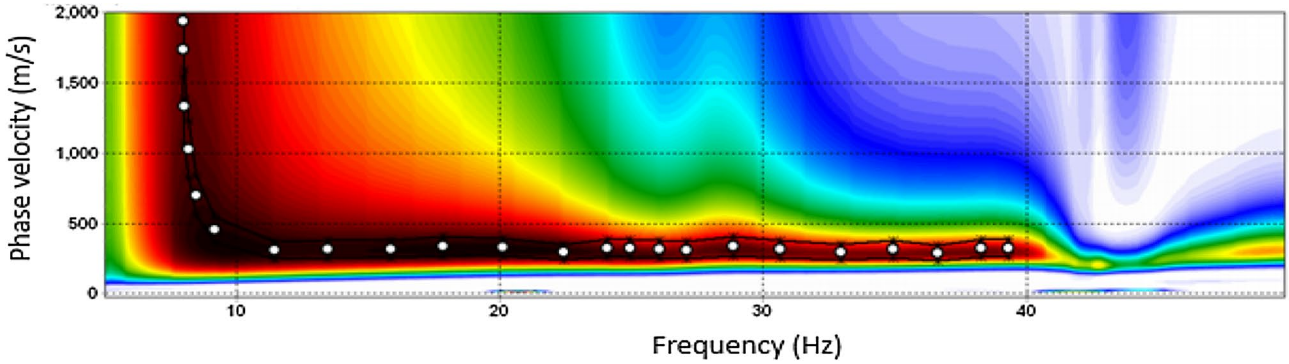


Fig. 16 Typical dispersion curve of MASW survey over lateritic terrain

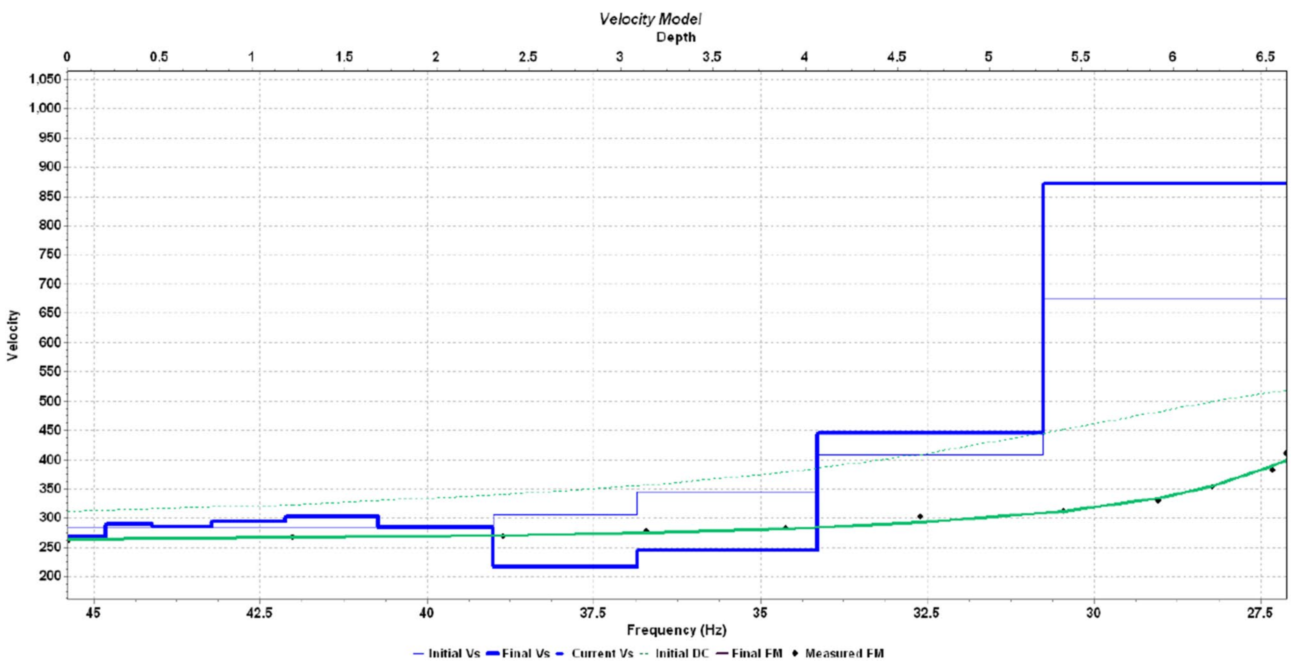


Fig. 17 Typical 1D shear wave velocity profile

from the ERT survey were the roof of the cavity started at 2.5 m and had a diameter of around 6 m at the particular survey alignment. But it was difficult to obtain the lateral spread of the cavity. In the GPR survey, the cavity roof was found to start at a depth of 2 m, and the diameter was around 2 m at the starting point and around 6 m at the end point closer to the ERT survey alignment. In the MASW survey, the roof of the cavity was found to be started at 2.5 m, and the diameter changed from 2 m at the inlet portion to a value of 6 m at the end of the survey location closer to ERT alignment. Integrating all three geophysical methods, such as GPR, MASW and ERT survey, the depth and dimensions of the cavity in the entire area were tried to map, and the results are shown in Figs. 20 and 21.

Summary and Conclusions

The use of geophysical techniques to characterize or identify locations of subsurface voids was investigated through literature reviews of theory and practical applications and field investigations. The three main geophysical methods, namely ground penetrating radar, electrical resistivity survey and multichannel analysis of surface wave, are analyzed in detail on their applications and limitations in detecting subsurface cavities. A field study is presented from soil piping-affected regions of Kerala, India, with the identification of naturally formed huge cavities with GPR, MASW and ERT. The survey results of ERT were compared with the field report of KSDMA, 2020, and it

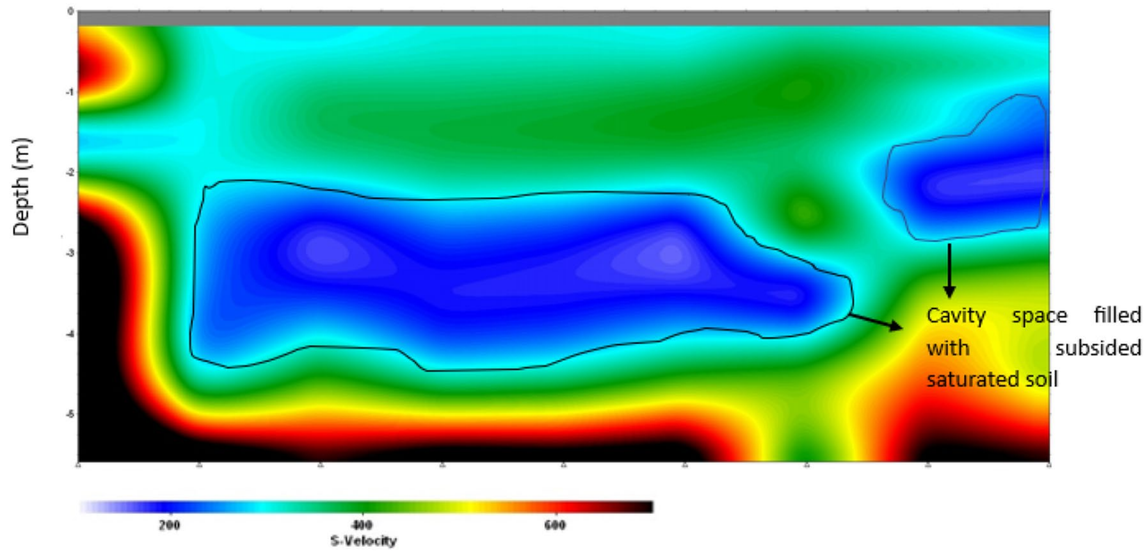


Fig. 18 Typical 2D shear wave velocity profile

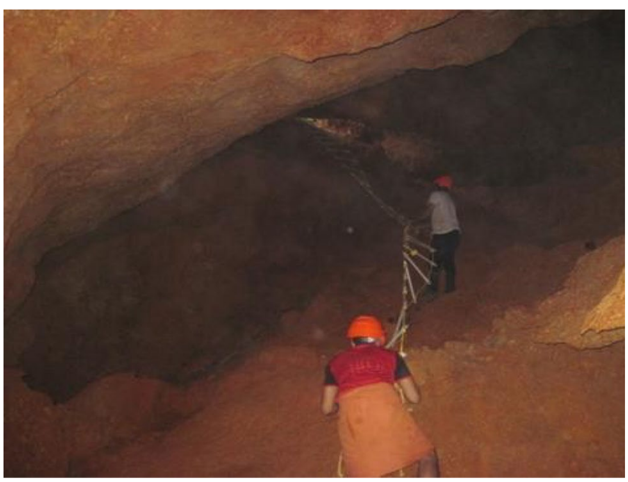


Fig. 19 Inside view of the cavity space with filled subsided saturated sediments [19]

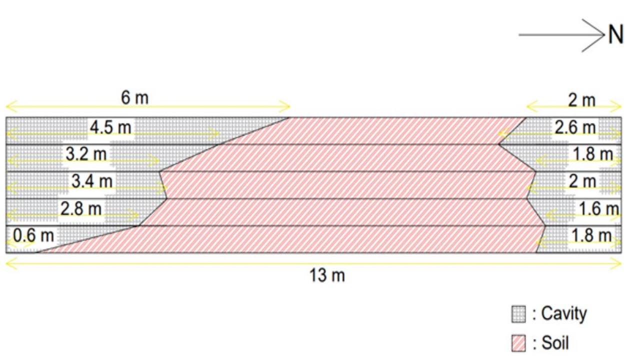


Fig. 20 Mapped cavity (plan view) in the location in the site using integrated survey

was noticed that the roof of the cavity collapsed more with the passage of subsurface water in due course of time and at the bottom of the cavity, more sediment was deposited. The cavity dimensions obtained from the ERT survey were the roof of the cavity started at 2.5 m and had a diameter of around 6 m at the particular survey alignment. But, it was difficult to obtain the lateral spread of the cavity. In the GPR survey, the cavity roof was found to start at a depth of 2 m and the diameter was around 2 m at the starting point and around 6 m at the end point closer to ERT survey alignment. In the MASW survey, the roof of the cavity was found to be started at 2.5 m, and the diameter changed from 2 m at the inlet. It is seen from the results that dimensions are almost match in all three surveys still we cannot rely on a single method in obtaining cavity dimensions and better to go with an integrated profile approach. Huge cavities at a depth of 2.5 m from the stiffer laterite surface were successfully identified in the study area, and a detailed subsurface profile was prepared using an integrated geophysical approach. The development of an integrated profile of one particular section is presented in this paper. To survey different stretches in the entire locality to prepare the outline of cavity propagation and identify the infrastructures under the threat of subsidence is the ultimate goal of this work. Data processing using conventional methods is time-consuming considering the huge dataset, and future studies are planned to prepare the three-dimensional orientation of the cavity with the help of advanced artificial intelligence tools in data filtering

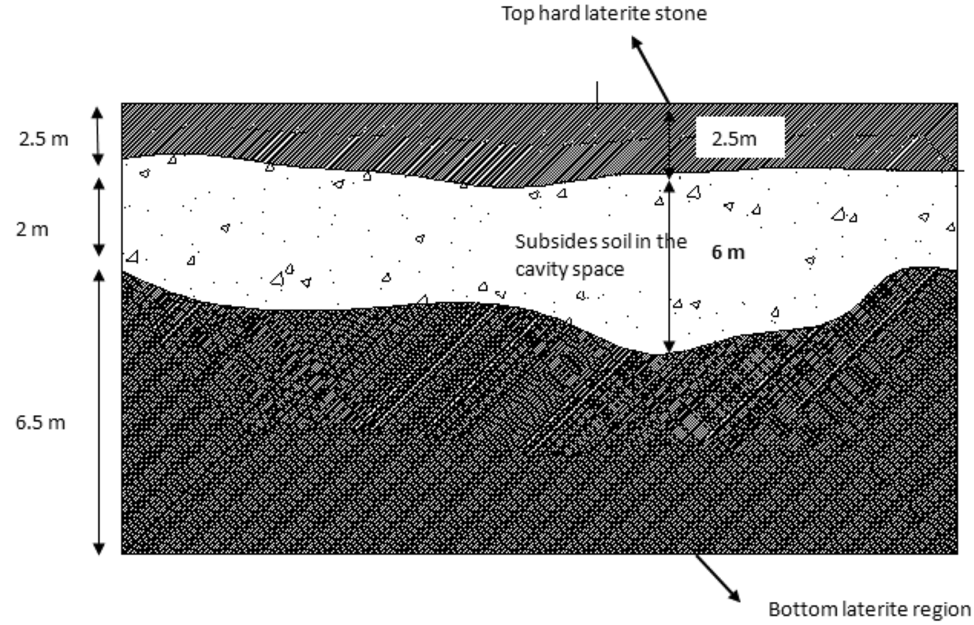


Fig. 21 Mapped cavity (section view) in the location in the site using integrated survey

and processing. The data collected in this study will be used for training purposes in artificial intelligence.

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Declarations

Conflict of interest The authors have not disclosed any competing interests.

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