Revised Version (Clean)

Unknown Urban Cavities – Formation, Problem & Possible Mapping

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Unedited version published online on 18/10/2023

ABSTRACT

Urban living exerts a magnetic pull on the younger generation due to its wealth of prospects and attractive lifestyles. However, it is important to acknowledge that many familiar and unforeseen challenges accompany urban living.This paper discusses the most pressing issue of the collapse of urban roads due to the formation of Cavities/sinkholesin the subsurface with the scientific reason and advanced approach to mapping such cavities to reduce urban risk. Sinkhole formations are very common incidents in many cities in India, and several such incidents are being reported. Naturally formed sinkholes in Lateritic deposits and urban cavities due to improper handling of subsurface soil. Typical reason behind urban cavities are summarized with scientific explanations on density of filling and subsurface water flow. Further, scientific methods available for identifying such cavities in advanced geophysical methods and the usual procedure followed for closing the cavities are presented. Regular inspection to focus onformation science,understanding of the formation reason and technically designed treatment based on site soil can help avoid cavities collapsing and subsequent disasters.

Keywords: *Urban cavities, soil density, subsurface flow, mapping of cavities, GPR and MASW*

INTRODUCTION

Urban roads are known for smooth and quality rides; sometimes, undesirables potholes and problems on the surface/subsurface cause disaster. Even though road taxes are heavily collected, there is no relation between the quality of the road, riding quality, and road conditions with taxes. Apart from surface road conditions defects, many urban roads have recently been caved and collapsed suddenly, and many vehicles and people have sunken. Likely these are not due to the separation of tectonic plates happening in Africa[1] but due to poor engineering practices on the soil. Increased urban infrastructure development on the surface and subsurface induce enough soil pressure, which also changes motherly Earth's nature and causes problems for living organisms on the Earth.Improper soil excavation and refilling lead to instability, and rearranging soil will lead to more displacement and less soil strength, which exceeds the allowable limit and causes the collapse of the surface/subsurface layer,forming cavities.

The formation of Cavities/Sinkholes is a well-known problem in some geological formations, such as Lateritic deposits in western ghats (Kerala and some parts of Karnataka). These cavities mustbe mapped and treated before commencing infrastructure works[2]. However, there is no understanding of when and how cavities are formed; people living in these regions are aware of such cavity formation from ancient times and escape from such disasters due to the sudden collapse of such cavities. Naturally formed cavities are generally treated while excavation and no scientific approach is followed in typical construction and survive with subsequent consequences.Several incidents of urban roads collapsing in major metropolitan cities like Kolkata, Delhi, Chennai, Bangalore, Hyderabad, and othershave recently been reported. This article presents some of the classical urban cavity collapses from a known source, a scientific understanding of soil engineering in forming cavities,and

Unedited version published online on 18/10/2023

advanced methods to map such cavities in an urban environment. Cavities in Urban areas formed due to loss of fines (soil particles movable in water) for several reasons, which is impossible to stop completely. However, it is possible to identify them using advanced geophysical methods so thatsuch cavitiescan be treated before they collapse and cause undesirable consequences.

NATURALLY FORMED CAVITIES

Natural processes form subsurface cavities, particularly in the Karst region, where erosion removes karst materials with rainwater termed as piping during monsoon season. Piping is a significant concern in highland districts of Kerala and parts of Karnataka, with occurrences of large pipes beneath homes and infrastructure threatening their stability. Hard lateritic soil over Saprolitic clayey layers is common in these regions. Researchers have studied this phenomenon, but comprehensive geological and geotechnical investigations are needed to understand the region's vulnerability[2]. Piping is characterized by pipeable layers within the soil profile that experience hydraulic instability during monsoons. These layers, subjected to particle flow and high hydraulic gradients in hilly terrain like the Western Ghats, enlarge into drains through subsurface erosion, eventually forming large tunnels.

Most piping incidents occur in remote areas with minimal infrastructure and less impact than urban collapses. However, incidents like the 2014 case in Nelliyadukkam, Kasaragod district, involved a significant cavity beneath an under-construction house's foundation[3].Such areas require appropriate treatment to prevent structural failures. Notably, natural cavity collapses progress gradually, providing time to minimize disasters.

URBAN CAVITIES & ACCIDENTS

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In India, land use in urban environments has changed significantly as urbanization rapidly increases due to swift growth in industrial and commercial activities. The locations which were earlier part of natural drainage or lake/pond are now being used for infrastructure and related facilities leading to visible problems like flood inundation during the rainy season due to inadequate drainage. Heterogeneity in subsurface soil layers results in non-uniform settlement due to vibration loads and water migration, leading to Urban cavities. Cavity formation in soil medium (natural or landfilled) leads to a failure of facilities (structural or transportation) on the surface or underground.

Accidents that have been caused due to cavity formation in urban areas available from online news sources[4] are presented in this section. 124 events have been collected, and a summary is presented in Table 1. These events are from major Indian cities like Ahmedabad, Bengaluru, Delhi, Hyderabad, Kolkata, etc. Based on these reports, most incidents of cavity formation in urban environments are related to road cave-ins triggered by different causes (Figure1).

Reported cave-in incidence falls under subsidence sinkholes,and the primary cause for the observed events is– fluctuations in the water table, vibration due to blasting or tunnelling, broken pipelines, unlined old drainage ditches, uncontrolled run-off drainage, etc.Most of the cave-in incidents reported have characteristics of dropout sinkholes. In the present study, the observations which were different from the ones noted in the literature are summarized next:

1. In some events, it has been reported that trenchless technology, used to underlay cables and other utility lines, has indirectly triggered cavity formation by disturbing existing sewer lines. Due to punctures caused to the sewer line during the laying of cables, the sewer lines usually burst over a period causing cavity formation.
2. Some incidents have occurred because of a lack of coordination between government and private agencies. For example, suppose a new communication line has to be laid

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underground. In that case, the communication company will hire an excavator and labourers with no expertise in the compaction requirement for the subgrade. After laying the communication line close to the water supply or sewerage lines, loose soil is used as a backfill without proper compaction. The following relevant agency will overlay the excavated site with pavement material without regard to the subgrade compaction requirement, leading to poor pavement performance and sometimes to catastrophic failure, as in the case of road cave-ins and sinkhole formations.

3. Some cavity or sinkhole formation cases have happened after the performance testing of underground water or sewerage lines. Due to high-pressure conditions generated during the testing phase, leaks will occur, leading to water or sewerage flow at very high pressure in the surrounding soil medium. This flow will erode the soil surrounding it and lead to cavity formation.
4. In a few locations where wells were dug in historical times for drinking, household usage, and irrigation, and at present, filled up or plugged with poor materials have also caused cave-in incidents. Locations of such wells are usually poorly documented due to frequent changes in land ownership and usage. The cave-in may be triggered due to the gradual transfer of filled material from the well locations due to seepage or groundwater table fluctuations.

The source of collected information on cavitycollapse events is grouped based on the region and season of the incident. Entire India was taken as four zones with respective climate seasons. Figure 2shows the number of cavities formed in the four-zone and seasons. From Figure 2, one can also observe that reported incidents are very few for central and eastern regions due to the lack of availability of online reports for these regions. Also, we would like to highlight that the collected data is just a sample of a population of numerous events that might have occurred but went unreported.

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From the reported incidents, the different cave-in stagesand influencing factors have been identified and highlighted(Figure 3). Time scales for different stages may vary from a few hours to months. It depends upon the exposure and intensity of the influencing factors. Based on the reported incidents in urban environments, the leading causes of cavity formation are groundwater flow, groundwater table fluctuations, leakage in water or sewerage lines, and poor soil compaction as a subgrade for pavements. A few cases have been where excessive rains, along with poor drainage channels, have accelerated the movement of fines through the subgrade, leading to the collapse of the pavement.

FORMATION OF URBAN CAVITIES

Several road openings and collapses due to the formation of cavities in the subsurface are being reported in cities where too much excavation and refilling of soil are frequent, and construction of subsurface structures is predominant. These collapses can be grouped into Excavation & Dewatering, Underground Structure & Tunneling, and Unknown Leakage of Water & Air. A typical case of each with respective ground caves and the scientific reason behind such cavitiesformation are explained below:

Excavation & Dewatering

Open excavation, bracing, and dewatering are commonly practised in urban areas to construct 5 to 30 meters deep basements. When the water table exceeds the excavation depth, and the soil contains high fines content, dewatering attempts to extract water with fines and drain it away from non-excavated areas. However, heavy dewatering during the rainy season can lead to afaster drawdown of fines from the surrounding region, resulting in minor surface cracks, cave-ins, and floor collapse. The authors observed multiple instances of such occurrences, highlighting the impact of excavation and dewatering on ground subsidence in soil deposits rich in fine particles.

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The typical case study of the effect of excavation and dewatering in the central part of Bangalore is presented here. Two side roads surrounded the site, and the northeast corner of existing structures and vacant (garden) at other locations, as shown in Figure 4. The deep excavation was started with the construction of the diaphragm wallin the site before the rainy season and continued with the help of dewatering during heavy rainy months. Initial cracks were formed on 5th September, followed by a larger cavity on 10th October; the IISc team visited on 12th October and was advised to stop the dewatering and excavation immediately at 7.5 m below the road. Details of observation with respective field visit photos are presented in Figure 4. A study of geotechnical reports found that the region has soil with more than 60 % fines (<0.425 mm) from 3 to 8 m depth from road level & below 8 m soil has more than 40 % fines.

During the field visit, we noticed that the excavation depth is about 7.5 m from the road level. The East and south sides of the excavated site have ample open space and an elevated gardenthan the west and east sides. Surface and subsurface levels are dipping towards the northwest side. A powerful dewatering method of a well-point system was installed on the site, as shown in Figure 4a, and water was pumped continuously. Close observation at the site found lots of soil fines in the outlet of pumped water and foot valvelocation, which means that soil fines are mixable and transportable by water pumping pressure being removed during excavation and dewatering. Continuous raindrops percolate and move towards low-pressure locations (pumping sump point in excavated site) with transportable soil fines. The continuous removable soil fines can cause coarse particle skeleton and reduce soil density, reducingsoil strength and increasingdeformation.Loss of support, i.e., reduced strength of soil and increased deformation below flexible (Bitumen road) surface, forms crack, and below rigid surface forms space in the initial stage, increasing of removal of more and more fines due to continuous water flow (rainy season), lead empty

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spaces and collapse. In the site, acavity formed on the East side of the excavation site below the concrete surface (Figure 4b), and cracks formed on the south side of the site (Figure 4c). This cavity formation can be explained by the fact thata larger open soil surface (garden) area allows for the percolation of more rainwater and the removalof more fines,thereby forming a cavity faster on the eastern side of the excavation site. At the same time, less open soil surface (south side only tar road and less garden area) allows less surface water flow. It removes the lesser amount of soil fines and forms cracks in the flexible surface even though the amount of rain, duration of rain,and dewatering arethe same for both sides. This case shows that excavation and dewatering in the region with larger soil fines deposit can create artificial cavities and associated consequences. So, there is a need to adopt proper excavation and dewatering methods based on subsurface soil and surrounding area, which minimizethe removal of soil fines and formation cavities.

Unknown Leakage of Water &Sewage

Excavation for water, sewage, gas pipelines, and underground utilities is a common process on urban roads. After completing the work, the excavated areas are filled with soil, raising the surface level. However, the compaction process for refilling these excavations is often not followed systematically, resulting in lower density than the maximum possible or dry density. Loose filling without proper compaction leads to lower filling density, particularly for cohesive soils with fines exceeding 15%, which form lumps and increase air voids.Figure 5 shows typical compaction and density as a function of water content and soil type. It can be seen in Figure 5 that in non-cohesive soil, more compaction can be achieved at lower water content, but cohesive soil with more fines needs higher water content. Fine-grained soil needs more water than coarse-grained soil to achieve a similar degree of compaction in the same compaction effort. Upon understanding refilling and compaction, one can say that loose refilling with lower water content leed to loose soil

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packing in utility excavation and refill.Loose filling and allowing for auto compaction/consolidation are commonly practised, although the degree of compaction achieved through auto compaction depends on the season. Dry seasons may result in less compaction, while rainy seasons can lead to more compaction. Achieving maximum density during refilling depends on soil type and water content. Loose refilling with lower water content in utility excavation leads to loose soil packing, allowing water to percolate from the surface and create subsurface flow. This water leakage can compact the soil and create empty spaces beneath the pavement or hard surfaces. So proper compaction, irrespective of the size of the excavation,should be closed by adopting proper compaction to avoid such cavity formation.

Underground Structure &Tunneling

Agglomerated urban populations necessitate a comprehensive transportation system, including underground structures for transit lines. Underground tunnelling is an effective method for constructing transit lines without disturbing the surface environment. While tunnelling in hard rock presents no issues, weak rock and soil layers pose several challenges. The Slurry-shield Tunnel Boring Machine (TBM) is commonly used in mixed subsurface layers, i.e., weathered rock and soil layers ranging from loose to dense. It employs pressurized bentonite slurry to counteract groundwater and earth pressures[5]. TBM pressure is crucial in surface settlement and cavity formation, but these issues are often not reported in urban projects.

Urban areas are formed by filling natural drains, water bodies, and quarries as the City grows[6]. Geological and artificial heterogeneity in the subsurface creates critical problems. Recently, a TBM in Bangalore encountered a massive pile of garbage[7]. Such problems arise due to inadequate subsurface knowledge and poor management of TBM operating pressure.Estimating and controlling face pressure during tunnelling is essential to prevent

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settlement and sinkhole formation[8]. Insufficient face pressures can lead to over-excavation and large voids, while excessive face pressures can breach blow-out limits and cause slurry leakage. These problems are prevalent in Indian cities' underground metro TBM operations.Subsurface profiles along tunnel alignmentswith lost soil fines and loose filling contribute to excavation settlements and blow-out incidents.

A quarry-filled site along the tunnelling alignment exemplifies blow-out sinkhole formation.A typical section quarry-filled site along tunnelling and blow-out sinkhole formation is shown in Figure 6. The surprising subsurface profile (Figure 6) is usually expected in many cities. Higher face pressure in hard rock (left side of Figure 6) continues in the absence of subsurfacedata in TBM; when the subsurface profile changes from hard rock to loose soil (Figure 6). Face pressure applied in TBM becomes higher than confining pressure due to soil, then higher face pressure breaches blow-out limits and causes slurry leakage to the surface and collapses (Figure 6a).Proper subsurface profiling using integrated subsurface investigation[9] can help to know soil and rock profiles along Tunnel alignment in Urban areas, which can help control TBM's face pressure and thereby minimise sinkhole formation and slurry blow-outs in Urban underground Tunnel construction.

Deformation of Underground Pipe

Apart from the above well-established observations, we can also speculate void space creation due to lengthwise deformation of the rigid pipe due to deformable layers of loosely filled surrounding materials. Figure 7 shows a typical scenario of pipe deformation due to vehicle movement above loosely filled soil in the surroundings. In the case of newly laid underground utility lines, improper compaction (during its placement) and higher stiffness of the pipeline compared to the surrounding soil medium will lead to uneven stress distribution along theutility line and surrounding media. As the newly filled soil settles due to heavy vehicular load, utility pipes will carry a large proportion of the load due to their high stiffness

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(compared to the surrounding soil medium). This loading may result in stress concentration at the joints of the utility line, triggering a leakage or burst at the nearby joints. This fluid leakage will accelerate soil erosion around pipelines. This deformation can be reduced by making the surrounding soil denser and stiffer through proper compaction.

EXPERIMENTS ON CAVITY FORMATION

The natural formation of Karstic features is because of the influence of a combination of physical, chemical,hydrological, and tectonic factors[2]. These formations are a slow process and generally give enough warning time,and do not cause any big disasters. Similarly, cavities formed in urban are predominantly due to human activities and are catastrophic, including loss of lives. These risks can be minimized if we understand the formation and detect them promptly.

Soil Fines

A simple test was performed to understand the removal of soil fines during dewatering and the possible amount of soil removed in the total quantity of soil. A typical excavation and dewatering site in Bangalore is selected for the investigation;Bangalore has soil witha rich amount of soil fines and reported many subsurface problems due to excavation and underground metro construction. Our team collected bulk soil samples and water from the outlet of the dewatering pump. These samples are oven-dried to remove in-situ water and follow the standard grain size distribution analysis carried out as per ASTM D6913 and IS 2720-4 (1985) reaffirmed in 2020. Site soil has 50% coarse-grained soil, of which gravel (>4.75 mm) is 0.42%, coarse sand is 1.58%, medium sand is 16.17%, and fine sand is 31.58%. The remaining 50% are fine-grainedand have 42% of silt and 8% clay through Hydrometer analysis as per ASTM D7928& IS code. The water collected at the outlet of the dewatering pump wasabout 22 g of soil fines in 1 litreof water. After sieve analysis, it was noticedthat around 50 % of soil particles are moved along with water for the site soil; this 50

Unedited version published online on 18/10/2023

% also concurs with the amount of silt and clay particles found in the soil sample. So it is necessary to designthe dewatering by taking into account soil layers in the site such that no soil fines are removed during dewatering.

Compaction and Loss of Fines

It is clear from previous sections that fine-rich soil can lose some fines along with passing water. So any condition favouring the same can remove those fines. However,it is unclearin which condition the significant fines will be lost, as water flow can happen due to subsurface flow (rains), groundwater drawdown (excavation dewatering), and leakage in underlain pipes. To understand the same, simple experiments setup were designed, filled with different possibilities of the degree of compaction up to in-situ density and allowed for subsurface flow. Water flow simulates maximum rain on the surface and leakage within the soil layer.For this purpose, a rectangular box with a controlled outlet valve is used. An acrylic mould of dimension 20x15x15cm is considered, and a drainage valve is provided on one side of the mould. Soil borrowed from the excavation site is filled into the mould for different dry densities, i.e., 0.86 g/cc, 0.91 g/cc, 1.03 g/cc, and 1.59 g/cc. First, mould was filled with soil as per-field filling density, and water was sprayed to simulate the rainand allowed to saturate and flood.Next, the drainage valve was opened, and discharge water was collected. The percentage of soil fine washed out in that discharge water was calculated.Also,the reduction in soil volume and settlement value was noted due to the water passage. It was noticedthat the washing out of fines decreases with increasing density,which isnegligible forsoilcompactedtoits maximum dry density.

Similarly, pipe leakage was simulated instead of surface water flow from rain for in-situ density filling in pipeline laying, similar to filling explained previously, as shown in Figure 8. These experiments indicate that loose soilfromnatural or man-made filling with more silt fraction can lose soil fines and settle due to water flow conditions. This loss of

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finescan happenbelow surfaces such as the bitumen/white topping road and any hard floor, leading to cavity formation. These quick and straightforward experiments can be extended for larger-scale studies to solve these issues in Cities.

EARLY DEDUCTION OF CAVITIES

Early detection of cavities is crucial to stabilize the ground and prevent damage. Traditional detection methods, such as aerial photographs and field inspections, have limitations and often result in false predictions. Geophysical methods offer effective solutions for detecting underground voids. Ground Penetrating Radar (GPR) uses high-frequency electromagnetic waves to obtain subsurface detailsand can identify subsurface cavities based on waveform analysis. Multi-channel Analysis of Surface Waves (MASW) studies how surface waves change as they propagate, providing dispersion patterns and shear wave velocity profiles that can reveal anomalies like cavities. Electrical Resistivity Tomography (ERT) method delineates high resistivity regions suggesting air voids, while low resistivity regions water-filled voids. Integrating multiple geophysical methods has proven to be more efficient and precise in cavity mapping. Studies have successfully combined GPR, MASW, and ERT to identify subsurface cavities and obtain properties of the materials for remediation. Examples include cavity identification at Kannur International Airport in Kerala, where GPR and MASW techniques were used[2], and a 3D GPR and MASW study in the Salento Peninsula in Italy for identifying Karstic terrains[10]. The integrated approach has also been applied in Chinese cities using a 3D GPR system, identifying numerous cavities through reconstructed depth slices. Overall, geophysical methods offer valuable tools for detecting subsurface cavities and mitigating their risks. In India, a very limited attempt was made to understand cavity formation before or after underground construction activities. It may be necessary to know the subsurface profiles and their intactness before open excavation or utility line

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excavations/drilling or tunnelling operation and also aftercompletion of these work so that the intactness of subsurface is maintained and cavity/sink hole formation due to these activities can be reduced. Rightnow, there is no standard to mandate these kinds of surveys in Urban areas, but they need to be developed by each city government.

TREATMENT OF SINKHOLES

Closing of cavities is eventually carried out to treat caved holes irrespective of their formations. Naturally formed cavity locations are avoided if space is available to shift residential structures or cavities are treated with suitable filling for normal residential and other infrastructures. In several cases, naturally formed cavities under residential areasare treated byfilling locally available boulders/ stones and soil without taking proper steps to divert subsurface water flow through piping. Sometimes even the piping path will be blocked due to this stone/soil filling, leading to new cavities forming.

Usually, urban cavities are filled with self-compacting concrete soon after cavities are noticed and closed quickly. Urban cavities are usually very shallow (just below the road surface) and extend up to a few meters as per formation time. After noticing the sinkhole, the hole shall be filled with lean concrete strength of less than 5 Mpa. Once the hole is filled with concrete, the entire area's (influenced zone) probing will be conducted using Cone Penetration Test(CPT). Once it reaches natural/hard soil, the cone will be driven until the hard formation or natural soilis reached. If any loose packet/ unfilled cavity is present, it shall be recorded as per the penetration rate of the cone. After getting the investigation report through CPT, further, if necessary, ground improvement schemes are adopted according to the soil properties.

Typical treatment of Urban cavities with field photos is shown in Figure 9. In a Metro project, cavities are confined through circle shape grouted columns, as shown in Figure 9as

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per grain size analysis, and the zone of the weak zone is based on penetration values. Grouting is carried out considering the material's grain size, and pressure is applied perpenetration resistance. Multiple TAM (Tube a Manchette) pipesare installed and grouted using single and double-packer methods. Filling cavities using plain cement concrete is a usual practice in many cities. The authorspoint out that the filling of cavities essentially makes the situation complex in the Urabn area, as free-flow concrete can surround utility lines and make them non-flexible and result in non-service friendly.

Another problem the authorsvisualizes is thatconcrete has a higher density, stiffness, and lower permeability than surrounding soil in cavity-formed locations. So this non-uniform density, stiffness, and permeability may trigger geotechnical issues for uniform and dynamic loading in the longer run. So one has to work out the scientific treatment of cavities in the Urban area, similar to naturally formed cavity filling, so there is no future problem due to this urban cavity treatment.

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SUMMARY AND CONCLUSION

Cavities and Sinkholes always create trouble for the inhabitants. Their impact is based on the population and infrastructure in that area. The reason for the cavity formation may be natural or man-made. Natural Cavities are formed mainly due to subsurface erosion during the monsoon season, which causes the removal of fine karst materials along with the rainwater. The property damage and troubles to the society associated with natural cavities are less since they occur in rural areas with less population. But the losses due to the cavity formations in urban areas need special attention and care considering its associated issues. Causes of Urban cavities are man-made, such as Improper Excavation & Dewatering, Unknown Leakage of Water & Sewage, Underground Structure &Tunneling,and Deformation of Underground Pipes. One of the most pressing issues is the collapse of Urban roads due to the formation of Cavities/sinkholes in the subsurface. The scientific reason and advanced approach to mapping such cavities to reduce urban risk are presented in this paper.Experiments are conducted to check the amount of fines washed out during dewatering, and it is found that the loss of fines is more when the field is in a loosely filled condition. The cavity formation is gradual and starts from the subsurface, and it is essential to deduct the subsurface cavities in its starting stage to avoid catastrophic failure at later stages. Geophysical methods such as Ground Penetrating Radar, Multi-Channel Analysis of Surface waves, and Electrical resistivity survey help identify the cavities in their initial stage. Proper measures can be taken to prevent immediate collapse. Various ways of filling the cavities with locally available soil /boulders, cement grout, and self-compacting concrete exist. In many cases, these mitigations are done without adequately understanding the reason for cavity formation. If one area is filled, there are chances for other sites to get affected; hence mitigations need to be suggested to arrest the reasons for cavity formation completely.

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