Unknown urban cavities – formation, problem and possible mapping

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Urban living captivates 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 study discusses the most pressing issue of the collapse of urban roads due to the formation of cavities/sinkholes on the subsurface, with scientific reasons and advanced approaches to mapping such cavities in order to reduce urban risk. Sinkhole formations are common in many cities in India, and several such incidents are being reported. Naturally formed sinkholes in lateritic deposits and urban cavities are due to improper handling of the subsurface soil. Typical reasons for the formation of urban cavities are summarized here with scientific explanations based on the density of filling and subsurface water flow. Further, scientific techniques available for identifying such cavities in advanced geophysical methods and the usual procedure for closing these cavities are presented. Regular inspection to focus on the triggering cause and comprehension of the underlying causes and technically designed treatments based on site soils can help prevent cavities from collapsing and subsequent disasters.

Keywords: Cavities/sinkholes, mapping, soil density, subsurface flow, urban living.

URBAN roads are known for smooth and quality rides, undesirable potholes and other problems on the surface/subsurface that cause disasters. Even though heavy road taxes are collected, there is no correlation between road quality, riding quality and road conditions with taxes. Apart from surface road condition defects, many urban roads have recently caved-in and collapsed suddenly, causing distress to vehicles and people. Likely, these are not due to the separation of tectonic plates in Africa[1] but due to poor engineering practices with respect to the soil. Increased urban infrastructure development on the surface and subsurface induces sufficient soil pressure to alter the natural characteristics of Earth, leading to challenges for the inhabitants. Improper soil excavation and refilling lead to instability, and rearranging the soil will lead to further displacement and less soil strength, exceeding the allowable limit. This causes collapse of the surface/subsurface layer, thus forming cavities.

The formation of cavities/sinkholes is a well-known problem in some geological formations, such as lateritic deposits in the Western Ghats (Kerala and some parts of Karnataka, India). These cavities must be mapped and treated before commencing infrastructure works[2]. However, the precise causes and processes responsible for cavity formation are not clear. People in regions susceptible to natural cavity formation have been aware of this risk for generations and do not have access to systematic approaches to prevent disasters arising from the sudden collapse of such voids. Several incidents of urban roads collapsing in major metropolitan cities like Kolkata, Delhi, Chennai, Bengaluru and Hyderabad have been recently 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 advanced methods to map such cavities in an urban environment. Cavities in urban areas are formed due to the loss of soil fines (soil particles movable in water). It is possible to identify cavities using advanced geophysical methods so that they can 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 other infrastructure threatening their stability. Hard lateritic soil over saprolitic clayey layers is common in these regions. Researchers have studied this

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phenomenon, but comprehensive geological and geotechnical investigations are needed to understand the vulnerability of the region[2]. Piping is characterized by pipeable layers within the soil profile that experience hydraulic instability during monsoon. These layers, subjected to particle flow and high hydraulic gradients in hilly terrains like the Western Ghats, form 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, Kerala, involved a significant cavity beneath the foundation of an under-construction house[3]. Such areas require appropriate treatment to prevent structural failures. Notably, natural cavity collapses progress gradually, providing time to minimize disasters.

Urban cavities and accidents

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 that were 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.

Table 1 summarises accidents caused by cavity formation in urban areas (124 events) available from online news sources[4]. These events are from major Indian cities like Ahmedabad, Bengaluru, Delhi, Hyderabad and Kolkata. Based on these reports, most incidents of cavity formation in urban environments are related to road cave-ins triggered by different causes (Figure 1).

The reported cave-in incidents fall under subsidence sinkholes, and the main causes for these are 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, observations which were different from the ones noted in the literature are summarized.

(1) In some events, it has been reported that trenchless technology, used for laying cables and other utility lines, has indirectly triggered cavity formation by disturbing the existing sewer lines. Due to punctures caused to these sewer lines during the laying of cables, they 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 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 pavements and sometimes to catastrophic failure, as in the case of road cave-ins and sinkhole formations.

(3) Some cavity or sinkhole formations have occurred 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, have been filled up or plugged with poor materials, cave-in incidents have been reported. 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 materials from the well locations due to seepage or groundwater table fluctuations.

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

From the reported incidents, the different cave-in stages and influencing factors have been identified (Figure 3). Timescales for different stages may vary from a few hours to months. It depends upon the exposure and intensity of

Table 1. Summary of causes for urban sinkholes and related incidents for the reported events

Causes	No. of incidents
Leakage in water pipelines	23
Leakage in sewerage lines	61
Metro tunnelling work	16
Poor backfill	10
Rainwater seepage	3
Waterlogging	2
Unknown	8

Figure 1. Cavity formation incidents due to (***a***) water pipe burst (26 June 2018, Mumbai); (***b***) metro tunnelling (2 August 2016, Bengaluru); (***c***) metro tunnelling (1 October 2021, Bengaluru), (***d***) improper compaction of subgrade (5 November 2016, Hyderabad).

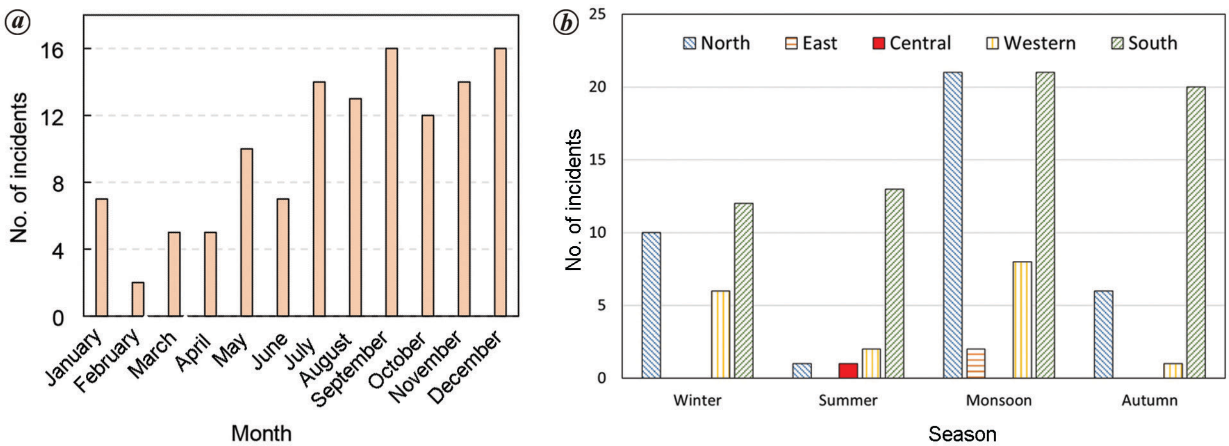

Figure 2. ***a***, Monthly variation in the reported number of incidents. ***b***, Seasonal variation of events for different regions of India.

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. In a few cases, excessive rainfall 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 on the subsurface are being reported in cities where excavation and refilling of the soil are frequent, and construction of subsurface structures is predominant. These collapses can be grouped based on the possible cause of formation such as excavation and dewatering, underground structures and tunnelling, and unknown leakage of water and air. A typical case of each with the respective ground caves and the scientific reasons for the formation of such cavities are explained below.

Excavation and dewatering

Open excavation, bracing and dewatering are commonly practised in urban areas to construct 5–30 m deep basements. When the water table exceeds the excavation depth and the soil contains high fine content, dewatering attempts

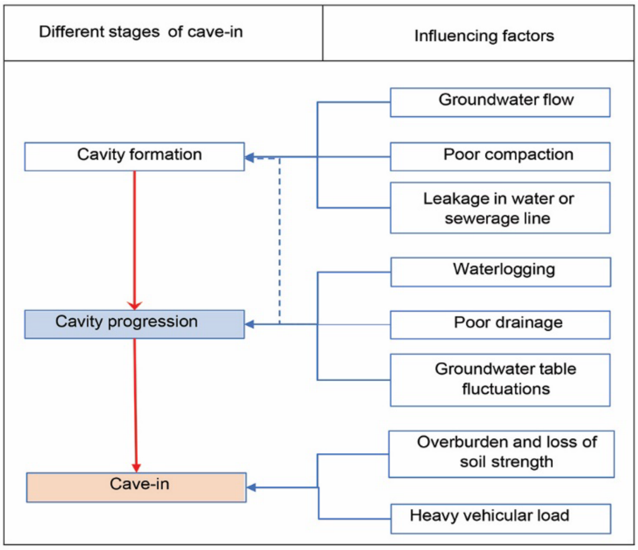

Figure 3. Factors affecting different stages of cavity/sinkhole formation.

Figure 4. Typical surface cracks and cavity formation due to excavation and dewatering.

to extract water with fines and drain it away from non-excavated areas. However, heavy dewatering during the rainy season can lead to a faster drawdown of fines from the surrounding region, resulting in minor surface cracks, cave-ins and floor collapse. We observed multiple instances of such occurrences, highlighting the impact of excavation and dewatering on ground subsidence in soil deposits rich in fine particles.

A typical case study of the effect of excavation and dewatering in the central part of Bengaluru, Karnataka, is presented here. As shown in Figure 4, two side roads surround the site, with an existing structure in the north east side and a garden area on other side. A deep excavation started with the construction of the diaphragm wall in the site before the rainy season and continued with the help of dewatering during heavy rainfall. Initial cracks were formed on 5 September 2021, followed by a larger cavity on 10 October. Our team visited the site on 12 October and advised immediately stopping the dewatering and excavation at 7.5 m below the road. Figure 4 presents details of observations with the respective field-visit photographs. A study of geotechnical reports revealed that the region has soil with more than 60% fines (<0.425 mm) at 3–8 m depth from the road level, while below 8 m, the 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 eastern and southern sides of the excavated site have ample open space and an elevated garden compared to the western and eastern sides. Surface and subsurface levels are dipping towards the northwest. A powerful dewatering method of a well-point system has been installed at the site, and water was being pumped continuously (Figure 4 *a*). A closer examination at the outlet showed that there were plenty of fine soil particles in both the pumped water outlet and at the foot valve location. This suggests that the soil fines were getting mixed with water and be carried away by the water pressure when it is pumped out during excavation and dewatering. Continuous raindrops percolate towards low-pressure locations (pumping sump point in the excavated site) with transportable soil fines. The continuous removable soil fines can give rise to coarse particle skeleton and reduce soil density and soil strength while increasing deformation. This leads to weakening of the subsurface layers and increased deformation beneath the flexible (bitumen road) surface resulting in the formation of cracks at the surface and cavity below the surface in the initial stage, increasing removal of more fines due to continuous water flow (rainy season), leading to empty spaces and collapse of entire surface. In the site, a cavity was formed on the eastern side of the excavation site below the concrete surface (Figure 4 *b*), and cracks formed on the southern side of the site (Figure 4 *c*). This cavity formation can be explained by the fact that a larger open soil surface (garden) area allows for the percolation of more rainwater and the removal of more fines, thereby forming a cavity faster on the eastern side of the excavation site. At the same time, less open soil surface (southern 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 and duration of rainfall and dewatering are the same for both sides. This case shows that excavation and dewatering in the region with larger soil fine deposits can give rise to artificial cavities and associated consequences. So, there is a need to adopt proper excavation and dewatering methods based on the subsurface soil and surrounding areas, which minimize the removal of soil fines and the formation of cavities.

Unknown leakage of water and sewage

Excavation for water, sewage, gas pipelines and underground utilities is common 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 from the figure 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 similar compaction with the same effort. Thus, loose refilling with lower water content leads to loose soil 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 causing subsurface flow. Such water leakage can compact the soil and create empty spaces beneath the pavement or hard surfaces. To prevent the formation of cavities, it is important to ensure proper compaction, regardless of the excavation size.

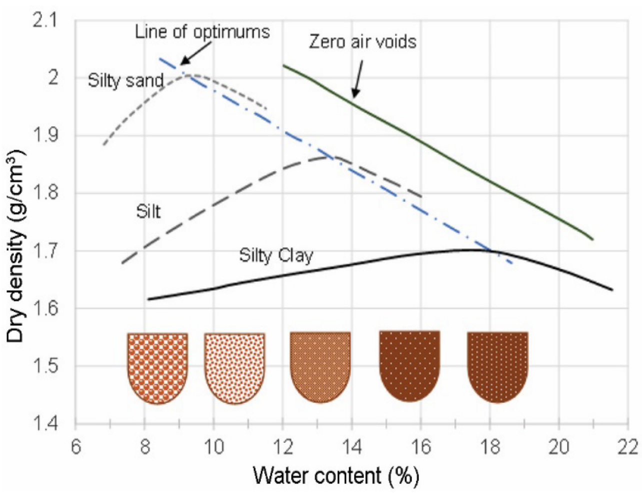

Figure 5. Typical compaction plot of different soil types and the effect of water content.

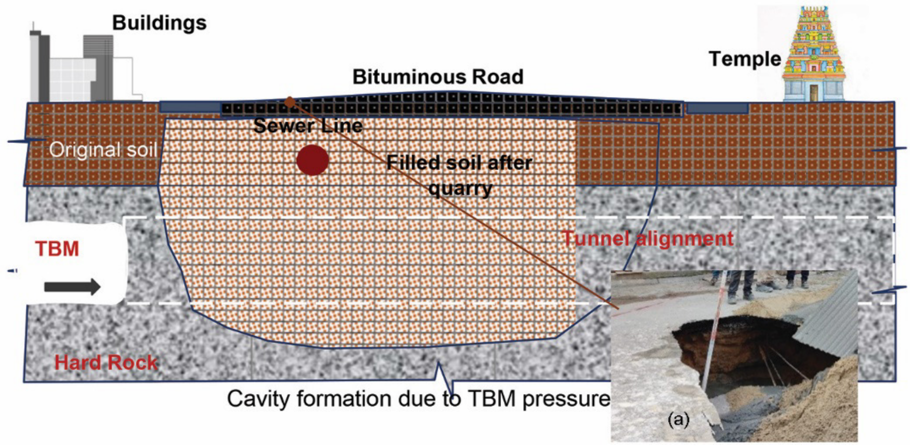

Figure 6. Blow-out cavity formation due to underground tunnelling work in a city.

Underground structure and tunnelling

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 rocks and soil layers pose several challenges. The slurry-shield tunnel boring machine (TBM) is commonly used in mixed subsurface layers, i.e. weathered rocks and soil layers ranging from loose to dense. It employs pressurized bentonite slurry to counteract groundwater and earth pressure[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 a city grows[6]. Geological and artificial heterogeneity in the subsurface causes critical problems. Recently, a TBM in Bengaluru 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 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 underground metro TBM operations in Indian cities. Subsurface profiles along tunnel alignments with 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. Figure 6 shows a typical section of a quarry-filled site along tunnelling and blow-out sinkhole formation. The surprising subsurface profile is usually expected in many cities. Higher face pressure in hard rocks (left side, Figure 6) continues in the absence of subsurface data 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 the soil. The higher face pressure breaches blow-out limits, causes slurry leakage to the surface and collapses (Figure 6 *a*). Proper subsurface profiling using integrated subsurface investigation can help determine soil and rock profiles along the tunnel alignment in urban areas[9]. This can help control the face pressure of TBM and thereby minimize 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 a 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 the utility 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 (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. Such fluid leakage will accelerate soil erosion around pipelines. Such 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 due to 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. Whereas, cavities formed in urban areas

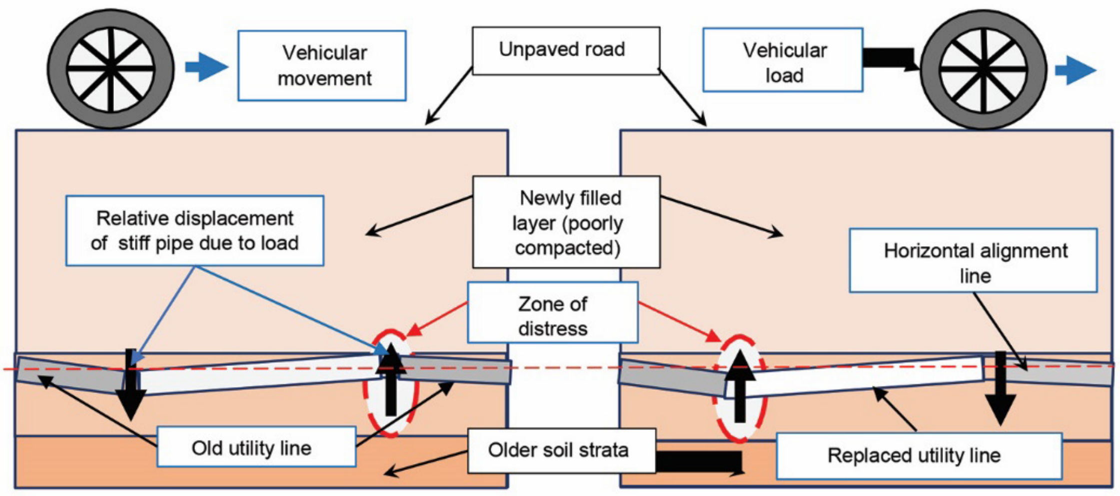

Figure 7. Breakage of utility pipes (laid in poorly compacted backfill) due to uneven settlement of surrounding media caused by uneven compaction from vehicular load.

are predominantly due to human activities and are catastrophic, including loss of lives. These risks can be minimized if we understand the formations and detect them quickly.

Soil fines

A simple test was performed to understand the removal of soil fines during dewatering and the amount of soil removed during the process. A typical excavation and dewatering site in Bengaluru was selected for this. This city has soil with a large amount of fines and has 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 were oven-dried to remove *in situ* water and the standard grain-size distribution analysis carried out according to ASTM D6913 and IS 2720-4 (1985), reaffirmed in 2020. The site had 50% coarse-grained soil, of which gravel (>4.75 mm) was 0.42%, coarse sand 1.58%, medium sand 16.17% and fine sand 31.58%. The remaining 50% was fine-grained soil, having 42% silt and 8% clay, as revealed by hydrometer analysis according to ASTM D7928&IS code. The water collected at the outlet of the dewatering pump was about 22 g of soil fines in 1 litre of water. After sieve analysis, it was observed that around 50% of soil particles had moved along with water to the site soil; this also concurs with the amount of silt and clay particles found in the soil sample. So, it is necessary to take into account soil layers in the site so 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 fines. However, it is unclear under which conditions significant fines will be lost, as water flow can occur due to subsurface flows (rainfall), groundwater drawdown (excavation dewatering) and leakage in the underlain pipes. To understand the same, simple experiments were designed, by preparing samples filled with different compaction degrees up to *in situ* density and subsurface water flow was applied on these samples. Water flow simulates maximum rainfall on the surface and leakage within the soil layer. For this purpose, a rectangular box with a controlled outlet valve was used. An acrylic mould of dimension $20 \times 15 \times 15$ cm was considered, and a drainage valve was provided on one side of the mould. Soil from the excavation site was filled into the mould for different dry densities, i.e. 0.86, 0.91, 1.03 and 1.59 g/cm^3. First, the mould was filled with soil according to field filling density, and water was sprayed to simulate rainfall and allowed to saturate and flood. Next, the drainage valve was opened, and discharge water was collected. The percentage of soil fine washed out in the discharge water was estimated. Also, the reduction in soil volume and settlement value was noted due to the passage of water. It was observed that the washing out of fines decreased with increasing density, which was negligible for soil compacted to its maximum dry density.

Similarly, pipe leakage was simulated instead of surface-water flow from rainfall for *in situ* density filling in pipeline laying, similar to that explained previously (Figure 8). These experiments indicate that loose soil from natural or human-made filling with more silt fraction can lose soil fines and settle due to water-flow conditions. This loss of fines can occur below surfaces such as the bitumen/white-topping road and any hard floor, leading to cavity formation. Such quick and straightforward experiments can be extended for larger-scale studies to solve these issues in Indian cities.

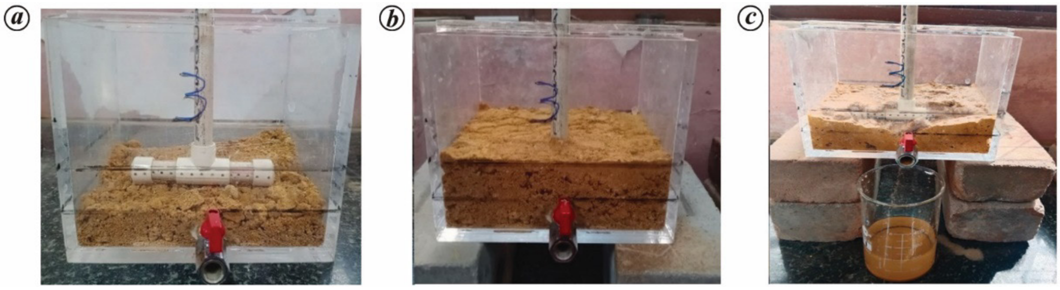

Figure 8. Typical experiment to simulate water leakage from a pipe. ***a***, Mould filled with soil and underwater pipe. ***b***, Soil filled with leakage from pipe. ***c***, Soil layer after pipe leakage and the soil fines are lost.

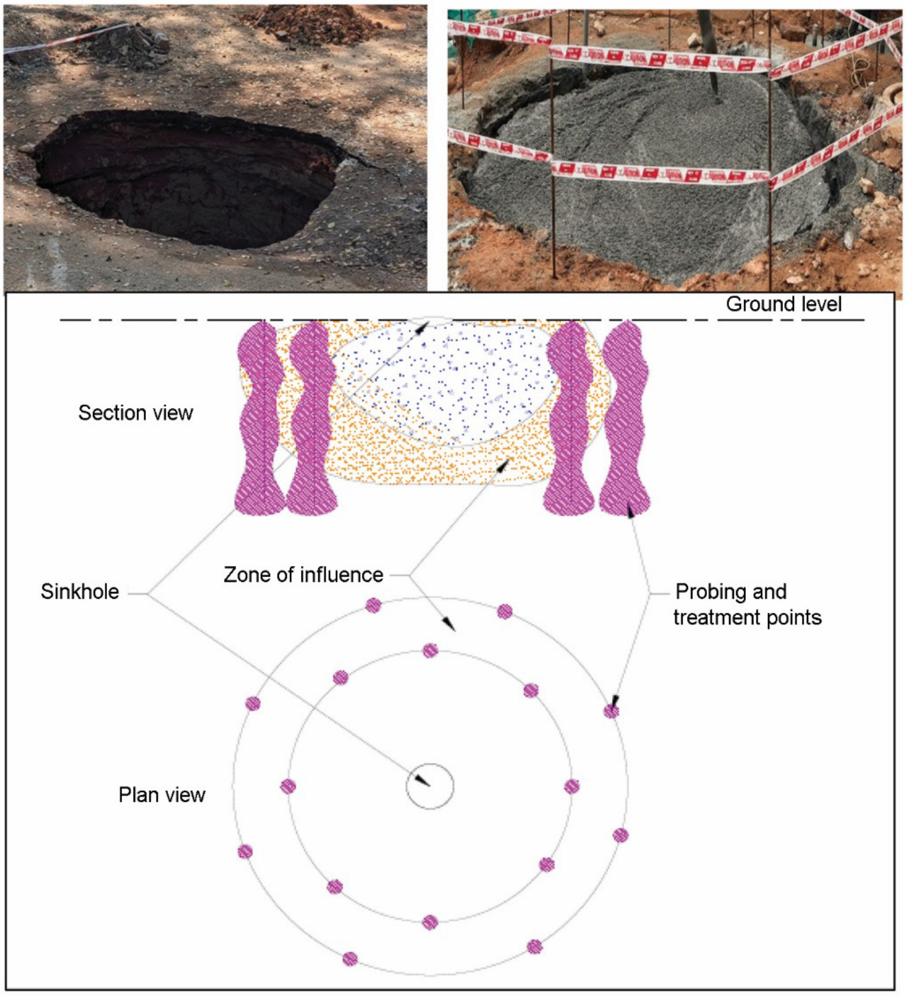

Figure 9. Treatment of urban cavity close to a metro project.

Early detection 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 details and can identify subsurface cavities based on waveform analysis. Multi-channel analysis of surface waves (MASW) examines 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) delineates high-resistivity regions, indicating air voids from low-resistivity regions, revealing 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 limited attempt has been made to understand cavity formation before or after underground construction. It may be necessary to know the subsurface profiles and their intactness before open excavation or utility line excavations/drilling or tunnelling operation, and also after completion of these work so that intactness of the subsurface is maintained and cavity/sinkhole formation due to these activities can be reduced. At present, there is no standard to mandate these kinds of surveys in urban areas, which is the need of the hour in all Indian cities.

Treatment of sinkholes

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

Usually, urban cavities are filled with self-compacting concrete soon after they are noticed and closed quickly. Urban cavities are usually shallow (just below the road surface) and extend to a few metres according to formation time. After noticing a sinkhole, it is generally filled with lean concrete of strength less than 5 MPa. Once the hole is filled with concrete, probing is done in the entire area (influenced zone) using a cone penetration test (CPT). When it encounters natural or compacted soil, the cone will be advanced until it reaches the firm substrate or the natural ground. If any loose packet/unfilled cavity is present, it is recorded according to the penetration rate of the cone. After getting the investigation report through CPT, if necessary, further ground improvement schemes are adopted according to the soil properties.

Figure 9 shows the typical treatment of urban cavities with field photographs. In a metro project, cavities are confined through circular-shaped grouted columns, as shown in Figure 9, according to grain size analysis, and the weak zone is based on penetration values. Grouting is carried out considering the grain size of the material, and pressure is applied in accordance with penetration resistance. Multiple TAM (Tube a Manchette) pipes are installed and grouted using single and double-packer methods. Filling cavities using plain cement concrete is a usual practice in many cities. The filling of cavities makes the situation complex in urban areas, as free-flow concrete can surround utility lines and make them non-flexible and result into a lack of service-friendliness.

Another problem is that concrete has a higher density, stiffness, and lower permeability than the surrounding soil in cavity-formed locations. This may cause geotechnical problems for uniform and dynamic loading in the long run. So, one has to develop a scientific treatment of cavities in urban areas, similar to naturally formed cavity filling, so there is no future problem due to urban cavity treatment.

Summary and conclusion

Cavities and sinkholes always cause problems for inhabitants of the region. Their impact is based on the population and infrastructure in that area. The reason for cavity formation may be natural or human-made. Natural cavities are formed mainly due to subsurface erosion during the monsoon season, which causes the removal of fine karst materials along with rainwater. Property damage and hazards to society associated with natural cavities are less since they occur in rural areas with low populations. However, the losses due to cavity formation in urban areas need special attention, considering the associated issues. The causes of urban cavities are human-made, such as improper excavation and dewatering, unknown leakage of water and sewage, underground structure and tunnelling, 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 reasons and advanced approach to mapping such cavities to reduce urban risks are presented in this study. Experiments were conducted to check the amount of fines washed out during dewatering. It was found that the loss of fines was greater when the field was in a loosely filled condition. Cavity formation is gradual and starts from the subsurface. It is essential to deduct subsurface cavities in their starting stage to avoid catastrophic failure at later stages. Geophysical methods such as GPR, MASW and ERT help identify the cavities in their initial stage. Proper measures can be taken to prevent immediate collapse. There are various ways of filling the cavities with locally available soil/boulders, cement grout and self-compacting concrete. In many cases, mitigations are done without adequately understanding the reasons for cavity formation. If one area is filled, there are chances that other sites will be affected. Hence, mitigations need to be suggested to completely eliminate the reasons for cavity formation.

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