Underground Urban Cavities: Consequences and Identification Through an Integrated Approach

K. Panjami and P. Anbazhagan

Abstract Cities have lots of opportunities due to infrastructure development and modern life. But this modern life comes with other inconvenient packages; the most concerning one is high and frequent traffic jams. This traffic congestion can affect the vehicle speed and can increase the pollutant emissions and fuel consumption. Even though traffic jams result from several factors, the most important one is the road condition. Road conditions are highly dependent on the intactness of the subsurface layers of the pavement. Recently, many cities have encountered a sudden failure of roads because of the formation of cavities and weak subsurface layers in the process of natural and human construction activities. Several such incidents are being reported in India; major events are a metro bus and car plunged into a crater in Chennai city, the collapse of an entire street in Hyderabad, and the natural sinking of wells and houses in the Western Ghats in Kerala and North Karnataka. Such cavities and weak zones are unavoidable in cities; at the same time, proper, timely investigation and treatments can minimize such cavities, cavity-related disasters, and traffic-related discomfort to the public by making resilient infrastructure. This paper summarizes several urban incidents and their consequences, followed by a discussion on various reasons how the weak zones form due to improper subsurface layer handling in cities and how it deteriorates road conditions, along with the mapping of a typical cavity in the city using integrated investigation approach for underground metro tunneling.

Keywords Urban cavities · Metropolitan cities · Traffic operation · Resilient Structures · Geophysical methods

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1 Introduction

In India, the transformation of land utilization has undergone substantial alterations, primarily driven by the swift expansion of industrial and commercial sectors. Areas that were once integral components of natural drainage or pond ecosystems are now being repurposed for various infrastructure and related developments. This shift has resulted in evident issues, including flooding during the rainy season due to insufficient drainage capacity. Furthermore, it has caused soil subsidence or cavities to develop underneath, posing a risk to surface and subterranean infrastructure and transportation systems. The creation of voids beneath the surface can result from either natural causes or inadequate engineering practices. Large underground tunnels discovered in lateritic deposits particularly in the northern regions of Kerala and certain parts of Karnataka are examples of natural cavities. The factors contributing to the development of such natural voids include sloping terrain, rainfall intensity, the presence of dispersive clays, and other climatic elements [1]. These types of cavities may not pose a significant threat to communities, as they are primarily observed in rural areas with minimal construction activities. But many urban roads have recently been caved and collapsed suddenly, and many vehicles and people have sunken. Several incidents of urban roads collapsing in major metropolitan cities like Mumbai, Delhi, Chennai, Bangalore, Hyderabad, and others have recently been reported. This article focuses on such incidents that are happening in the major metropolitan cities in India. The cases reported in online news from various parts of the country, and the reasons for their formation are discussed in detail, along with advanced methods to map such cavities in an urban environment. Delle Rose and Leucci [2] have highlighted that knowledge of cavity formation mechanisms and their identification at a local scale is essential for decision-makers. Cavities in urban areas form mainly due to the loss of fines (soil particles movable in water) for several reasons, which are impossible to stop completely. However, it is possible to identify them using advanced geophysical methods so that such cavities can be treated before they collapse and cause undesirable consequences.

2 Cave-In Incidents Reported from Major Metropolitan Cities

Accidents that have been caused due to cavity formation in urban areas of different metropolitan cities in the country, available from online news sources, are presented in this section. A total of 101 events have been collected, and a summary is presented in Table 1. Based on these reports, most incidents of cavity formation in urban environments are related to road cave-ins triggered by different causes.

Reported occurrences of cave-ins fall within the category of subsidence sinkholes, and these events are primarily attributed to factors such as vibrations resulting from activities like blasting or tunneling, damaged pipelines, neglected old drainage

Table 1 A summary of cave-in incidents reported from online news outlets between 2008 and2023

Name of city	Reason for cavity formation	No. of incidents
Ahmadabad	Underground metro construction	2
	Leakage in water pipelines	3
Bangalore	Poor backfill compaction	4
	Leakage in water pipelines	6
	Underground metro construction	4
Bhopal	Leakage in water pipelines	1
Chennai	Poor backfill compaction	1
	Leakage in water pipelines	7
	Underground metro construction	10
	Leakage in sewer pipelines	7
Coimbatore	Leakage in water pipelines	2
	Leakage in sewer pipelines	2
Delhi	Leakage in water pipelines	5
	Leakage in sewer pipelines	7
	Poor backfill compaction	2
	Rainwater seepage	4
Gurugram	Leakage in sewer pipelines	2
	Rainwater seepage	1
Hyderabad	Leakage in sewer pipelines	3
	Leakage in water pipelines	5
	Poor backfill compaction	1
Ludhiana	Leakage in sewer pipelines	7
	Leakage in water pipelines	2
Madurai	Leakage in sewer pipelines	3
	Leakage in water pipelines	1
Mumbai	Leakage in sewer pipelines	3
	Leakage in water pipelines	6
	Underground metro tunneling	1

ditches, uncontrolled runoff drainage, poor excavation and refilling techniques, and improper compaction. Many of these incidents reported exhibit characteristics of sinkholes formation. In certain instances, it has been documented that the utilization of trenchless technology for laying cables and utility lines indirectly contributed to the formation of voids by disturbing pre-existing sewer lines. The act of puncturing sewer lines during cable installation often leads to eventual ruptures in the sewer lines, causing voids to form over time. Some incidents can be attributed to a lack of coordination between government and private agencies. For example, when a new communication line needs to be buried underground, communication companies may employ excavators and laborers who lack expertise in properly compacting the subgrade. After laying communication lines near water supply or sewerage lines, loose soil is often used as a backfill without adequate compaction. Subsequent agencies responsible for overlaying the site with pavement material may neglect the necessary subgrade compaction, resulting in poor pavement performance and, in some cases, catastrophic failure, such as road cave-ins and sinkhole formation [3]. In a few cases, cavity or sinkhole formation has been linked to the post-testing phase of underground water or sewerage lines. The high-pressure conditions generated during testing can lead to leaks, causing the rapid flow of water or sewage at high pressure within the surrounding soil. This flow erodes the neighboring soil, ultimately resulting in the formation of voids. Instances have arisen in areas where historical wells, once used for drinking, household needs, and irrigation, have been subsequently filled or plugged with inadequate materials. Locations of such wells are often poorly documented due to frequent changes in land ownership and usage. Road collapses may be triggered by the gradual transfer of the filled well material due to seepage or fluctuations in the groundwater table. Figure 1 depicts a case of a hole formed in Kalbadevi, Mumbai, Maharashtra due to a water pipe burst.

Underground conditions beneath road surfaces can impact the operational efficiency of road networks. Small air pockets formed below the surface due to loss of soil fines will eventually convert to a huge hole and ultimately entire surface collapses. Weaker zones in the subsurface get reflected on the surface by means of some cracks and settlements, which influence the smooth traffic operation. Figure 2 shows cracks and subsidence formed at the surface as an indication of the subsurface cavity. These surface indications are mainly observed in the case of asphalt pavements and should be monitored properly to avoid sudden collapses in the form of

Fig. 1 Road caved in due to water pipe burst at Kalbadevi, Mumbai, Maharashtra (26 June 2018)

cave-ins and sinkholes. Instances have been reported from urban areas in which a huge cave was formed all of a sudden. In 2022, there was a massive sinkhole observed in Kolar Road, Bhopal, due to a pipeline burst as shown in Fig. 3. Also, the entire street of Goshmahal in Hyderabad caved in due to an Open drain/nullah covered by concrete slab below the road as shown in Fig. 4. There is a high chance of vehicles to fall into these holes, especially in crowded municipal cities.

Fig. 2 **a** Kannapiran Mill Road, Coimbatore (10 May 2016) **b** MG Road, Kumaran Nagar, Padi, Chennai (03 November 2020)

Fig. 3 A 10 feet sinkhole formed in Kolar area; Bhopal due to pipeline burst (01 May 2022)

Fig. 4 Road stretch in Goshmahal, Hyderabad caved in due to Open drain/nullah covered by concrete slab below the road

3 Formation of Urban Cavities

In cities where extensive soil excavation and refilling, as well as the construction of subsurface structures, are common, numerous instances of road fissures and subsurface voids have been documented [3]. These incidents can be categorized into four main groups: unknown Leakage in pipelines, Improper dewatering techniques, Poor excavation & refilling, and Underground Structures & Tunneling. A typical case of each with respective ground caves and the scientific reason behind such cavity formation are explained below.

3.1 Unknown Leakage in Pipelines

Undetected leaks of water, sewage, and air or gas can potentially initiate the development of surface imperfections in the pavement. Furthermore, they can give rise to voids or lead to a reduction in soil strength due to complete saturation. Subsurface layers with a higher content of fine soil particles (particles smaller than 75 μm) are prone to retaining water/gas or traveling along with the flow of water/gas [3]. This movement of fine soil particles alongside the flow of water/gas can result in the erosion of the subsurface soil layer beneath the road surface, creating a vacuum space or causing settling in the surface pavement layer. A model study was conducted to understand the cavity propagation in flexible and rigid pavements with underground leak in the pipe and it was found that cavity propagation underneath in flexible pavements gives surface indications in the form of cracks and settlement while there will not be any surface indication in rigid pavements unless it collapsed suddenly. Table 1 shows that out of 101 cases collected 78% of issues are reported due to unknown leakages in pipelines. 10-foot sinkhole formation incident in Kolar area, Bhopal, due to leakage in an underground drinking water pipeline is a typical example. A huge sinkhole was formed by the gradual erosion of the subsurface and the same is shown in Fig. 3.

3.2 Improper Dewatering Techniques

The construction of subterranean structures necessitates dewatering, especially substantial dewatering during the rainy season. The gradual shifting of soil fines causes alterations in texture and compromises the integrity of subsurface layers beneath the pavement, giving rise to weak and compressible strata. This phenomenon can play a role in the development of surface cracks and voids in roads, leading to the deterioration of the surface and boundaries of neighboring sites or areas. It is evident that water can transport soil particles in its flow, contributing to the natural formation of alluvial deposits. The capacity of soil particles to be carried depends on the pressure exerted by the soil and water on the floor. Conversely, in urban settings, it leads to the formation of vacuum spaces and the loosening of subsurface layers. Fine-grained soil, particularly with a significant portion being silt and low cohesion, can lose up to 50% of its content when subjected to water flow [3]. Therefore, any conditions promoting such phenomena can result in the removal of these fine particles. The cavity formed in Bengaluru, Bosch site on 10 October 2021 was an example of this category.

3.3 Poor Excavation and Refilling

In the time of repair works and laying of utility lines, the excavation and subsequent refilling processes are often conducted without adequate compaction, either due to size limitations or a lack of awareness. This practice initiates the creation of voids within the ground and the settling of subsurface layers due to self-compaction. This disturbance to the natural soil structure and composition carries the risk of triggering ground settlements in the adjacent soil, which may lead to the development of loose textures or voids. A case of such an incident was reported in Safilguda, Malkajgiri, Hyderabad, and Telangana in November 2016. A more detailed explanation can be found in Anbazhagan et al. [3].

3.4 Underground Structures & Tunneling

In addition to the issues of undetected pipe leakage and inadequate soil compaction in utility lines, another main concern is the tunneling and underground structures. Tunneling below ground is an efficient technique for creating transit lines while minimizing disruptions to the surface environment. Tunneling in hard rock is generally trouble-free, but dealing with soft rock and soil layers can be quite challenging. To address this, the Slurry-shield Tunnel Boring Machine (TBM) is frequently deployed in mixed subsurface conditions, which encompass weathered rock and soil layers with varying degrees of compactness. This TBM employs pressurized bentonite slurry to counteract the pressures from groundwater and the surrounding earth [4]. Proper TBM pressure management is critical to control surface settling and the formation of voids [5]. Out of 101 cases considered for the study, 14 cases were of metro tunnel work as depicted in Table 1. One such incident was reported from Poonamallee High Road, Chennai, in 2015 due to metro tunneling work.

4 Impact of Sinkholes on Traffic Performance

The consequences of sinkholes are extensive, impacting various facets of traffic management. The sudden emergence of a sinkhole can result in sudden and severe disruptions to road infrastructure, prompting closures that give inconvenience to commuters and necessitate traffic rerouting. Consequently, this often leads to heightened traffic congestion in surrounding areas, causing delays and frustration among commuters. Sinkholes pose significant safety hazards for motorists and pedestrians, with the risk of vehicles or individuals near a sinkhole at the time of its formation being susceptible to falling into the depression, resulting in accidents and potential injuries. Additionally, the damage inflicted by sinkholes on underground utilities, such as water and sewer lines, can complicate repairs and worsen the disruption to traffic flow. The financial burdens on municipal authorities for repairing sinkhole-damaged infrastructure encompass not only the actual repair work but also indirect costs related to traffic management, rerouting, and potential compensation for affected businesses. Local businesses, in particular, bear the brunt of negative impacts from sinkhole-related road closures, experiencing reduced accessibility that may lead to a decline in customer footfall, affecting revenue. Effectively managing sinkhole incidents requires prompt emergency response efforts, including the coordination of emergency services, area securing, and the implementation of safety measures. The occurrence of sinkholes underscores the significance of long-term urban planning and infrastructure maintenance, emphasizing the need for measures that identify and address potential sinkhole-prone areas in advance to alleviate the impact on traffic performance. On analyzing the data of cave-in incidents, the cases were mainly reported from crowded traffic locations. Once there is a weaker zone initiated below the subsurface due to loss of fines, it will create some surface indications in the form of

Fig. 5 Barricades being erected to divert traffic near Rama Talkies Junction in Visakhapatnam in October 2022

alligator cracks and subsidence, and these can intensify with traffic load and can lead to subsidence in a faster rate. In turn, once there is a cave-in formed it further affects the operation of smooth traffic flow. Traffic congestion is very common in most of the cities in associating to these kinds of sinkhole incidents. This traffic congestion can influence the average vehicle speed, pollutant emissions, and fuel consumption. Vehicle speed was found consistently decreased with reduction of road width, due to the sinkhole formations. Also, the pollutant emission increases due to the vehicles in traffic jam, which also causes drastic increase in fuel consumption [6]. Figure 5 shows how the sinkhole formed in the middle of the road diverts the traffic and increases the traffic congestion.

5 Identification of Urban Cavities Using an Integrated Geophysical Approach

Identifying and deducing subsurface issues promptly is essential due to the potential for substantial land subsidence and the associated risks to urban populations. Underground voids or the development of weakened subsurface layers (resulting from saturation) beneath pavements and anomalies are frequently overlooked until surface openings or subsidence occurs, posing threats of property damage and potential personal injuries. Geophysical methods offer viable solutions for detecting underground voids and loose fillings. Techniques like Ground Penetrating Radar (GPR) and Multichannel Analysis of Surface Waves (MASW) have demonstrated potential in identifying subsurface issues [7–9]. Geophysics employs physical measurements to infer underlying parameters. Subsurface heterogeneities, such as loosened soil, soil lacking fines, cavities, or water pockets, deviate from the surrounding homogeneous conditions. The varied range of geophysical methods facilitates the measurement of contrasts between subsurface structures and the surrounding lithology. To investigate the presence of underground anomalies such as weak zones in urban areas, a survey was conducted in Bengaluru MG road and the results are presented in this section. A comprehensive survey utilizing Ground Penetrating Radar (GPR) and Multichannel Analysis of Surface Waves (MASW) was conducted to assess the effectiveness of early detection of subsurface problems in the pavement. The equipment employed in this investigation was the Mala GX GPR, produced by Mala Geoscience. This apparatus consisted of bi-static antennas with shielding, specifically 450 MHz and 750 MHz ground-coupled antennas, a GPR acquisition system, interconnecting cables, and an odometer as shown in Fig. 6. Also MASW survey employed with a 12-channel seismograph fitted with geophones operating at a frequency of 4.5 Hz was used for the survey, which is shown in Fig. 7.

Weak zone was identified from the GPR survey and radargram of the same is given in Fig. 8 with weak zone marked at a depth of 6 m. Shear wave velocity diagram obtained from the MASW survey also reveals the presence of low velocity region at a depth of 6 m as marked in Fig. 9, which confirms the presence of underground anomaly.

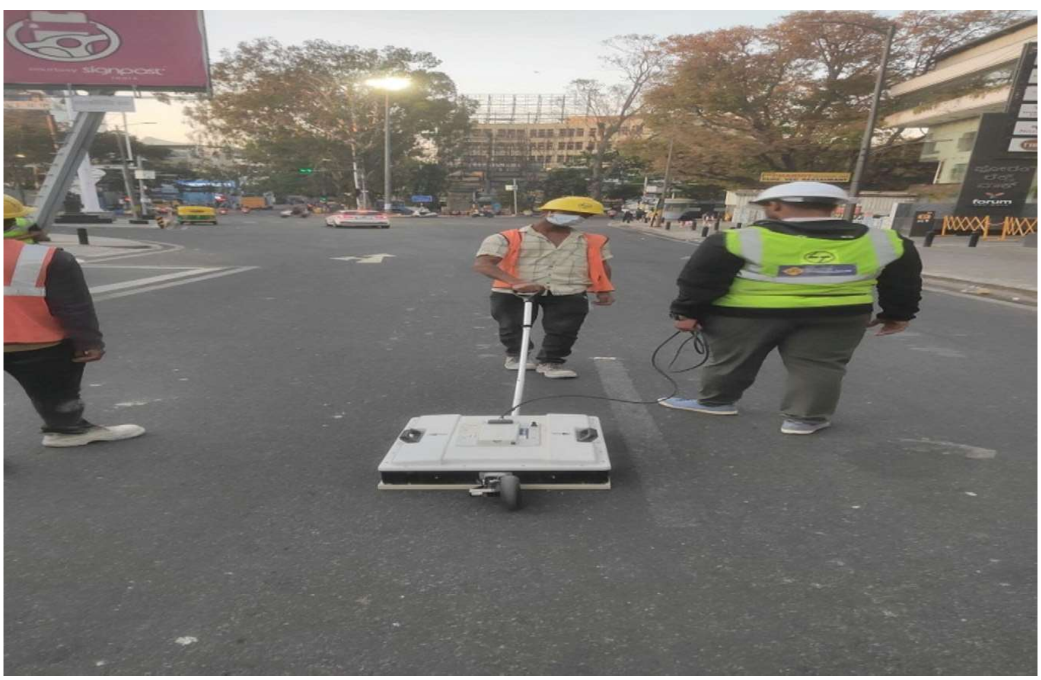

Fig. 6 GPR survey conducted in MG road

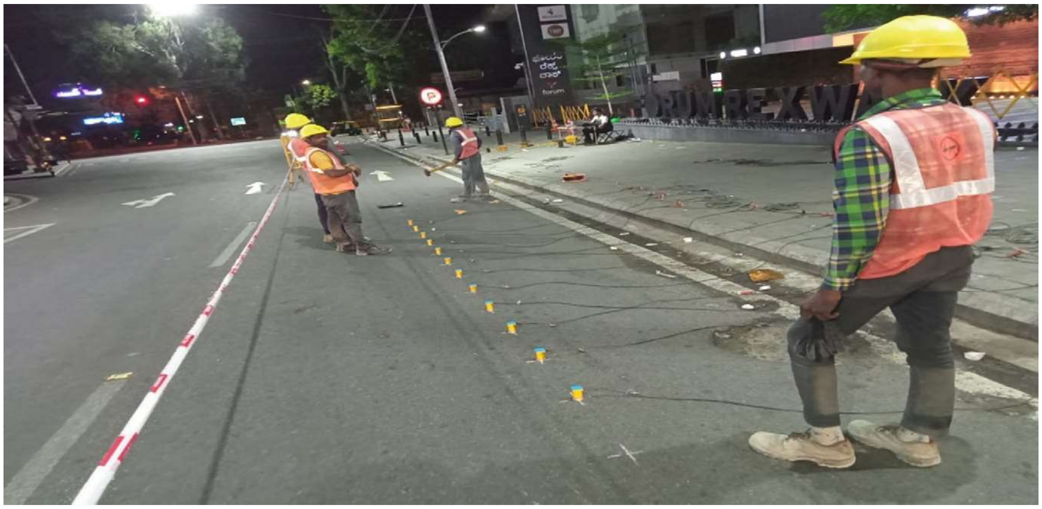

Fig. 7 MASW survey conducted in MG Road

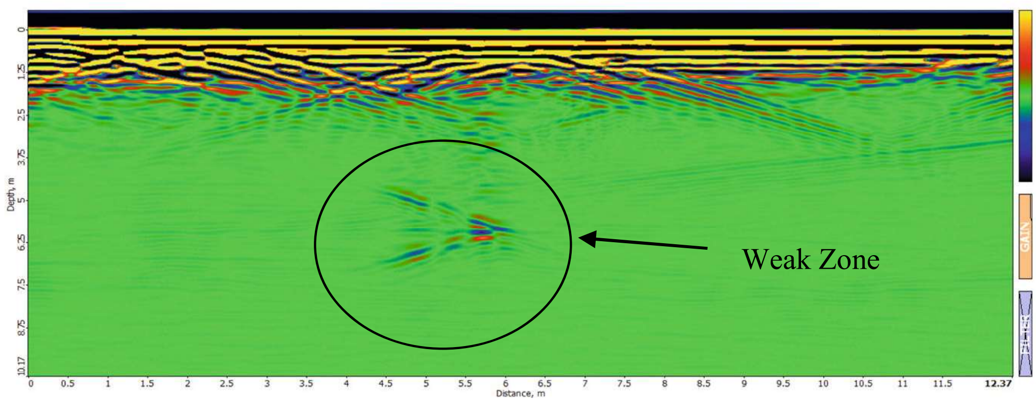

Fig. 8 Typical radargram from the Bengaluru MG road with weak zone marked

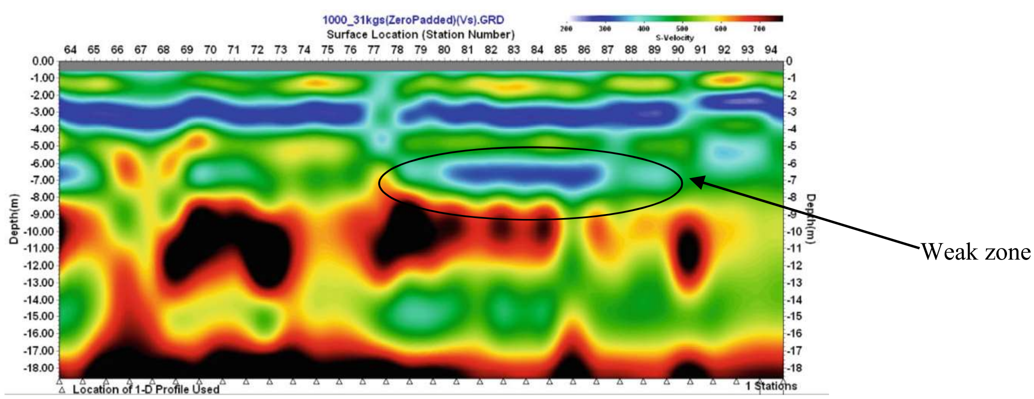

Fig. 9 2D shear wave velocity of the area from MASW

6 Conclusion

Cavities and sinkholes consistently pose challenges for residents, and their effects depend on the population and infrastructure in the affected area. The formation of cavities can be attributed to either natural or human-induced causes. This paper gives focus to the cavities formed in urban areas due to various reasons. In recent times, numerous urban roads have experienced sudden collapses, resulting in the sinking of both vehicles and pedestrians. Incidents of road collapses have been reported in major metropolitan cities such as Mumbai, Delhi, Chennai, Bangalore, Hyderabad, and others. Details of various cave-in incidents that happened in major cities collected from online news sources are presented as a table. A total of 101 incidents were documented and their reasons of formation are analyzed. It is found that the main causes of cavity formation belong to 4 categories namely leakage in sewage and water pipelines, Improper dewatering techniques, Poor excavation and refilling, and underground Structures & Tunneling. A typical case of each category with respective ground caves and the scientific reason behind such cavity formation are explained in detail. It is seen that subsurface conditions and cave-in incidents affect the operation of smooth traffic flow and lead to traffic congestion and leads to increase in pollutant emission and fuel consumption. This paper highlights the necessity of timely identification of underground cavities using geophysical methods. Survey results of underground weak zone from Bengaluru MG Road with GPR and MASW survey are presented to show the effectiveness of these methods in detecting cavities before complete collapse.

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