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Review

Detection and Monitoring Technique in Urban Underground Space Engineering – A Review

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Abstract: With the growth of cities, there is a proportional increase in the scarcity of available land. As cities expand land becomes more and more important. Underground space engineering provides a solution to the aforementioned challenge however construction and maintenance of underground spaces have their challenges. Therefore, there is a need for efficient detection and monitoring techniques. Detection techniques are employed for the identification of potential hazards such as structural weaknesses, gas leaks, and water infiltration. Techniques used range from as simple as a visual inspection to more sophisticated tools such as ground penetrating radar. Monitoring systems are frequently employed in underground areas to look for movement and structural changes. These devices can measure stresses, vibrations, and deformations, which can provide important information about the structural health of sub-surface areas. In urban underground space engineering, geophysical techniques like ground-penetrating radar are also utilized to spot possible dangers including voids, fractures, and water infiltration. Urban underground space engineering additionally makes use of data analysis and modeling technologies in addition to these methods. The monitoring data can be processed by these tools to produce predictive insights, enabling engineers to see possible issues before they arise. To maintain the security and durability of these buildings, detection and monitoring techniques must be used in urban underground space engineering. These methods are crucial for guaranteeing the operation and safety of underground places, and their ongoing growth and improvement are crucial for building more effective and sustainable cities for future generations. The effectiveness of urban underground space engineering depends on detection and monitoring methods. These methods enable engineers to spot possible risks and address them before they become serious problems. Engineers may design underground areas that are more effective and sustainable by combining cutting-edge technologies and data analytic tools, ensuring the security and functionality of these buildings for years to come.

Keywords: Urban underground space, Detection, Monitoring, Detection, Ground-penetrating radar

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Introduction

For thousands of years, the underground has provided safety, useful resources, structural support for buildings on the surface, and a place for people to express their creativity or spirituality. In recent years, many urban utilities have been buried. An underground water system built during the Middle Bronze Age (2000–1500 B.C.) for both domestic and agricultural uses was the first water delivery technology in Jerusalem [1]. The majority of people have rarely considered how underground space may improve or be planned to maximize society's sustainability over time. When human activities start to impact the earth and the population struggles to maintain livable standards, undergrounding new infrastructure and associated facilities may be the most effective way to encourage or support the redirection of urban growth into sustainable patterns. There are situations when a building's design precludes interactions with existing or future structures, much alone long-term maintenance. For instance, many of the utility layout techniques used today and, in the past, do not support sustainability goals and do not consider long-term implications on the environment, the economy, society, or natural resources. Technology advancement can improve engineering techniques and raise interest in underground space. Engineering and technological advancements have always been essential to effective and affordable underground development. Cut-and-cover building techniques have been used to build tunnels since the time of the pharaohs. With the advent of the internet, the world has become a much smaller place. As well as ground improvement and waterproofing technology that has been launched and made widely known, the highly automated modern tunnel boring machine is an example of an industry-led advancement[2]. The industry has created numerous analytical and design tools in close collaboration with academia (e.g., finite element analysis methods).

1. Research methodology

A comprehensive literature review of existing research on detection and monitoring techniques in urban underground space engineering provides a foundation for the study. This review includes a broad range of sources, including academic journals, industry publications, and government reports. The collected information is used to identify trends and patterns in the use of detection and monitoring techniques in urban underground space engineering. This analysis can also identify gaps in existing research and inform the development of new detection and monitoring techniques. There is also the use of case study examples of the use of detection and monitoring techniques in urban underground space engineering. These case studies can highlight the effectiveness of specific techniques and technologies and provide insights into best practices.

2. Development of urban underground space engineering

Facilities for supporting underground public services include:

1. Underground traffic, comprising vehicular and pedestrian traffic, as well as underground rail travel.
2. Subsurface municipal engineering, including pipe trenches, energy, gas, and waste sites in addition to underground drainage and water supply systems.
3. Subterranean logistics systems such as pipelines and tunnels are a part of underground logistics.
4. Facilities for underground disaster prevention and mitigation, such as civil air defense systems and other urban amenities.
5. There is also a range of subterranean space amenities that are either presently present or could become so shortly but are not currently utilized by the general public.

Despite being more resistant to earthquakes than surface structures, underground spaces are much more susceptible to other natural disasters like fires and explosions[3, 4]. The ability to effectively utilize urban underground spaces' anti-disaster capabilities is expected to play a significant role in protecting urban populations from both natural and military disasters. Investigation exploring potential methods to prevent or mitigate losses from disasters like fires and explosions underground should also be given careful study[5, 6]. The development of the transportation infrastructure leads to the construction of underground roadways to improve traffic flow in big cities. New subway sections are being constructed as a substitute for surface-based public transportation. Modern commercial, residential, and office buildings now require new subsurface utility projects.

Urban underground space engineering detection and monitoring methods take several precautions to guarantee the security and functionality of these buildings. These actions consist of:

(i) Testing techniques: To find possible risks such as ground instability, water penetration, and poor air quality, a range of testing techniques are performed. These approaches include visual inspection and sensor-based monitoring, as well as geophysical technologies like seismic tomography and ground-penetrating radar.

(ii) Classification of tactics and equipment: Based on the technology and approaches used, strategies and tools are categorized. By considering elements like the size and complexity of the structure, its intended purpose, and any potential hazards it may encounter, this classification aids engineers in choosing the best tools and techniques for each case.

Improvement of safety and performance: Installation of fire suppression, smoke control, and emergency ventilation systems are just a few of the steps being taken to increase the safety and functionality of underground spaces. To guarantee that these systems are operating properly, routine maintenance and inspection are also crucial.

(iii) Leak detection methods: These methods are used to find potential leaks in subsurface areas, especially leaks of refrigerant. These methods include gas detection devices, ultrasonic testing, and visual inspection.

2.1 Disasters typically associated with urban underground spaces

However, these spaces can also be subject to various disasters that can have severe consequences. In this article, we will discuss some of the disasters typically associated with urban underground spaces.

2.1.1 Fire

Fire can have a disastrous effect on underground urban areas. Fires in these areas have the potential to result in major harm, property loss, and even fatalities. Firefighters and emergency personnel have particular difficulties in underground spaces because of their small size, poor ventilation, and complicated geometry[7]. Many things, such as electrical problems, heating systems, and combustible items, can start fires in underground urban areas. Due to the oxygen shortage and combustible ingredients found in underground locations, these fires can develop swiftly. Long-term effects of fire on subsurface urban areas are also possible[8]. Underground areas are susceptible to structural damage from fires, which compromises their usability and safety. Other safety risks might result from important infrastructure being damaged by flames, such as electrical equipment, water, and gas lines. On February 18, 2003, an arsonist lit a train on fire in the Daegu metro fire, which resulted in 192 fatalities and 151 injuries at the Jungangno station of the Daegu Metropolitan Subway in Daegu, South Korea[9-11]. Within minutes, the fire had spread to two trains. Unfortunately, Daegu subway trains were not equipped with fire extinguishers, and there were no sprinklers or emergency lights at the station. The darkness disoriented many victims and the station became filled with smoke as the ventilation systems proved to be inadequate. Passengers fell victim to asphyxiation as they were looking for exit points. It is crucial to take steps to prevent and mitigate the consequences of fires within subsurface spaces, as fires have a serious impact. Underground urban spaces must be safe and functional, which requires the use of cutting-edge technologies, regular maintenance, inspection, and emergency response planning. By doing this, we can fully take advantage of the underground urban spaces building structures that are more resilient and sustainable for future generations.

2.1.2 Subsidence

Underground urban places can sustain severe harm from subsidence, which is the sinking or settling of the ground surface. Many variables, such as anthropogenic activity, environmental conditions, and natural geological processes, can cause this. The subsidence is from the shifting or the disturbance of the strata above the excavated subsurface space. When the soil or rock is disturbed, there will be a redistribution of ground stresses leading to the sinking or settling of the ground as a new state of stress equilibrium is achieved. When Sofia Metropolitan was being built between the years of 2006 and 2008, a tunnel 20 meters deep was dug beneath the diagonal intersection of two streets. A multilayer ground was needed for a swift drop of groundwater; however, this was accompanied by irregular subsidence[12]. The building's front face on "Tsar Liberator" Blvd. experienced negative foundation settlement as a result of this quick decline and the groundwater level's sizeable amplitude. Building external arches began to crack, more fissures appeared and disappeared, and a serious threat to the stability of the structure appeared. The most likely source of the active earth pressure wedge that led to the land and structure sinking was the ground imbalance brought on by the excavator digging roughly 20 m deep for groove walls. After the subway was finished, a vent was built where the soil subsidence near the structure was roughly 5 mm. Although the sinking was only slight, the building's issues quickly got worse. The northeast and southwest towers, which had the heaviest fasteners and were the closest to the shaft and tunnel, experienced the biggest fractures[13]. The fissures had a width that ranged from hardly perceptible to 20 to 21 mm. The use of ground sensors to detect ground movement, regular inspection, reinforcement support, and effective emergency response planning can be employed to reduce the impact of subsidence.

2.1.3 Flooding

In underground spaces, flooding is quite likely to occur. Flooding can have devastating consequences for underground spaces. The water can damage the electrical systems, causing power outages and disrupting transportation networks. Floods can also damage the structural integrity of the structures, leading to collapse and endangering public safety. There are three reasons behind that. First of all, the situation of rainfall and floods above the earth has a high likelihood. In addition, the excess water quickly seeps into the ground, impeding people's ability to walk. Finally, there aren't many escape routes, and people congregate near them. Furthermore, connecting underground corridors and building floors is a regular occurrence in Japan. Under these conditions, water can easily reach underground spaces, including tunnels connected to buildings. As a result, in certain areas, people must descend steps from neighboring buildings in the case of a flood to reach the lower ground. While underground buildings, such as underground shopping malls, served as shelters for commuters stranded at work after the Great East Japan Earthquake in 2011, these regions could also become dangerously prone to flood disasters. As previously noted, Japan's underground spaces require disaster-prevention measures against earthquake, fire, and flood calamities. Preventing flooding in urban underground spaces requires proper planning, design, and construction. Engineers must consider the location of underground spaces and the drainage systems required to prevent flooding. Proper waterproofing, sealing, and drainage systems are essential to ensure the safety and longevity of these structures.

3 Monitoring

Geotechnical and construction monitoring programs provide the basis for understanding the response of the earth to excavation and the consequences of building on already-existing structures and the environment[14, 15]. Because it frequently lasts less time than monitoring for infrastructure operations, construction monitoring may be more demanding (often less than five years). Monitoring tools must be more durable because they may be put through difficult conditions during construction. Monitoring the behavior of the underground facility and its surroundings during construction aids in ensuring safety, evaluating performance, validating plans, and recommending any necessary design modifications. Figure 3.1 below shows a typical monitoring system.

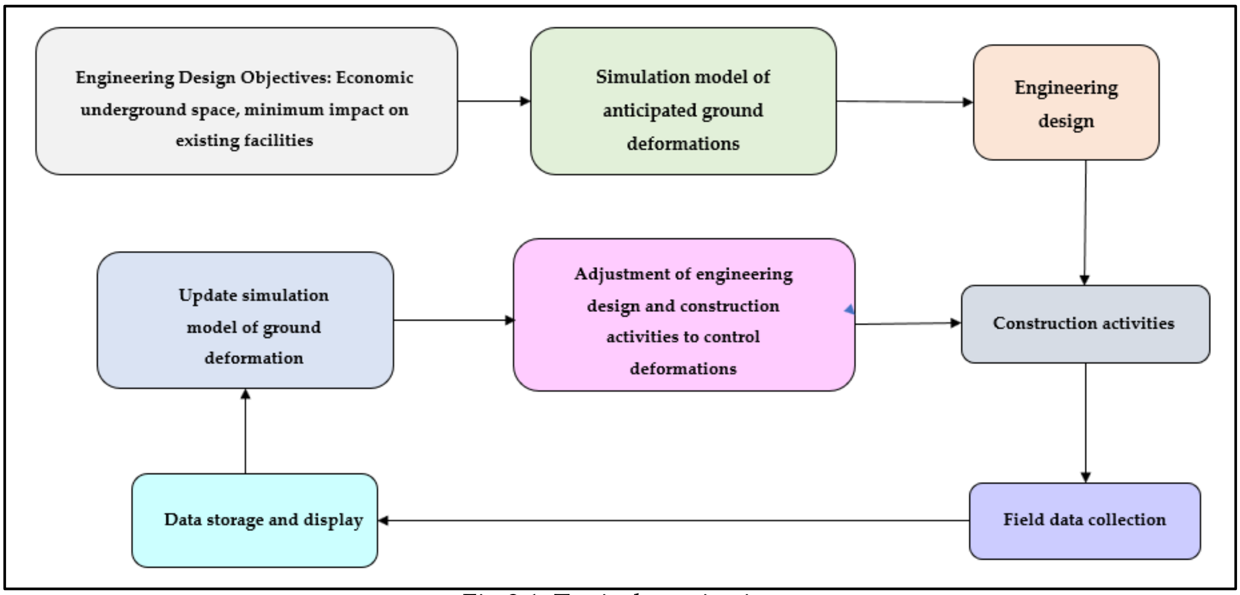

Fig 3.1: Typical monitoring system

The way a picture changes over time can give insight into how a project is coming along, but it can also tell us things like how excavation will affect the nearby infrastructure. The conservation of groundwater resources and the quality of the air above and below the surface is aided by the monitoring of water volumes and pressures as well as water and air quality. To identify opportunities for efficiency improvement, contractors frequently track and evaluate construction processes and operations (such as shift utilization, equipment downtime, maintenance or replacement, ground support installation, muck volumes, and grout takes). Moreover, contractors routinely check for ground gases in excavations, including methane, carbon monoxide, and hydrogen sulfide. Engineers continuously advance their capacity to employ such technologies in ever more creative ways, and the use of sensors to detect the geotechnical and structural displacements of specific structures, projects, or operations is well established in practice. The requirement for a system of systems approach, which denotes a need to develop integrated systems that can monitor urban system conditions, is a major premise of this paper. To monitor the consequences of changes in one system element on other system elements, information about all of a system's components can be collected during all stages of their life cycles.

The characterization tools that are utilized will depend on the depth of interest and the type of ground (such as soil versus rock or saturated versus partially saturated). It is possible to monitor both natural and artificial properties utilizing non-invasive technology as well as traditional in situ techniques (such as direct measurement) (like geophysical). Many construction businesses guide site characterization technology options using extensive lists of tools and methods. The proper use of the instruments and instruction in their use, however, are frequently just as crucial as the technology itself.

3.1 Invasive Technologies

In-situ testing equipment allows for accurate physical measurements of material properties. Traditional penetration tests and cone penetrometer tests (e.g., electric, piezocone, and seismic tools) are used to sample or test soil strata directly by drilling or shoving sampling instruments into the earth. Rock samples and testing can be done via both core drilling and core removal. Borings are used to characterize the local geology as well as factors such as soil strength, stiffness, dynamic shear wave velocity, and groundwater characteristics and quality. A single digging might or might not reflect the subsurface just a short distance away given the likely geological variation.

Oriented probing tools, horizontal and angled directional boreholes, and other techniques can be used to evaluate specific properties or the distribution of materials. Horizontal probing allows for subsurface exploration along the alignment of a tunnel or other infrastructure. The building of civil subsurface structures uses oriented exploration devices less frequently than the energy exploration sector. This may be due to the procedure being unfamiliar to site investigation specialists or the cost. It may be claimed that owners and contractors, who stand to save money, gain more from incentives for efficiency than engineers do. Recent developments in boring technology include cryogenic drilling capabilities for boring in difficult materials and measurement while drilling (MWD) devices that provide early information on the materials useful for guiding future borings and organizing an efficient testing schedule. The profession has not yet adopted these techniques in a significant way. Cryogenic drilling, as opposed to traditional drilling methods, can generate more representative samples of subsurface materials and fluids while lowering the risk of cross-contamination, avoiding the use of drilling fluids like mud in the borehole, and producing less waste from the study. Figure 3.2 shows the setup for cryogenic drilling.

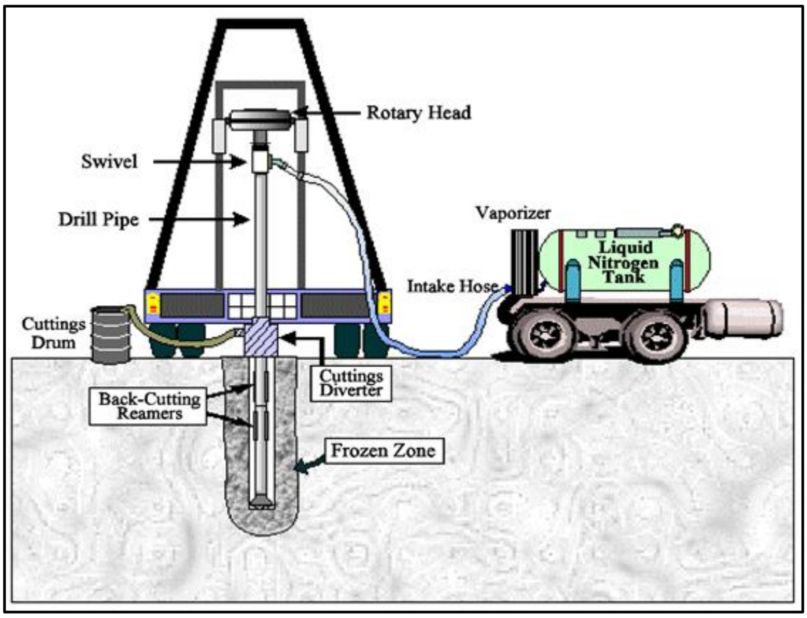

Fig 3.2: Cryogenic drilling[2]

3.2 Non-invasive technologies

Remote sensing tools such as satellite and terrestrial LIDAR, digital photogrammetry, radiometric technologies, and interferometry techniques, as well as ground geophysical techniques such as cross-hole tomography, seismic refraction, and reflection, potential field methods [gravity, magnetic], spectral analysis of surface waves (SASW), geoelectric and electromagnetic which provide data from which subsurface correlations can be inferred, are non-invasive site characterization tools[16-18]. To provide a more thorough understanding of subsurface conditions, non-invasive techniques are best employed in conjunction with intrusive procedures[19].

Non-invasive technologies have the advantages of being quick to employ and being able to define bigger subsurface areas[20, 21]. The fact that data must typically be reduced from their original form—inversion modeling is frequently needed to assess ground zonation and material properties—is a drawback. As these models are non-unique (a single data set can produce an endless number of models, for example), specialized knowledge and skills are needed to reduce and analyze the data. Some of these techniques can be expensive, but as they grow more widespread and technology (like laser scanning) advances, the price of data collection and processing will decrease.

Non-invasive technologies offer a significant improvement in data collection related to ground properties and the presence and location of existing structures, but there are physical restrictions on the size of objects that can be characterized and the material property differences that can be found concerning the depth of investigation that is feasible.

3.2.1 Ground Penetrating Radar (GPR)

GPR is a non-destructive method for finding items and structures underground that employs electromagnetic radiation. This method is frequently employed in urban subterranean space engineering to find utilities like water and gas pipes. Moreover, the presence of voids and cavities in the earth can be determined using GPR[22]. Planning and development of all types of structures now require detailed knowledge of the locations and courses of the underground wires and pipes that make up the utility networks in the region. Digging is required for extending subway lines in large cities, at the very least in areas where subway stations are constructed with surface exits[23]. There must be some utility network deviation route work done as a result, which must be done beneath the streets of big cities. The exploration of these subterranean utility networks is made possible by GPR systems, which are based on modern microwave transmission and receiving technologies, software for automatic data collecting, and specialized software for processing and interpreting this information[24].

Pipelines and subgrades can be located underground using stepped frequency GPR. Its main objective is to enable frequency scanning for the simultaneous detection of many geological entities. The stepped frequency GPR is a multi-resolution radar in the frequency domain, and the authors claim that the multi-resolution detection method in the time domain has not been defined[25-27]. Transient electromagnetic sources in the time domain have broader frequency ranges than radiation sources in the frequency domain, which helps locate intricate subsurface objects. The time "t," or the interval between the time of emission and the time of reception of the signal returned by reflection, is measured by the GPR compact system by sending electromagnetic pulses into the ground[28]. The speed of these pulses will change depending on the physicochemical characteristics of the materials if radar impulses pass through various materials on their way to the "target" we want to record. As a result, the reflection and refraction velocities of the associated waves vary depending on the dielectric properties of the materials. Radar signals can be sent using a variety of antennas. High resolution is made possible by good frequencies at the expense of research depth[29]. Low frequency causes the resolution to decrease while the depth of study increases. Figure 3.3 illustrates the concept of ground-penetrating radar.

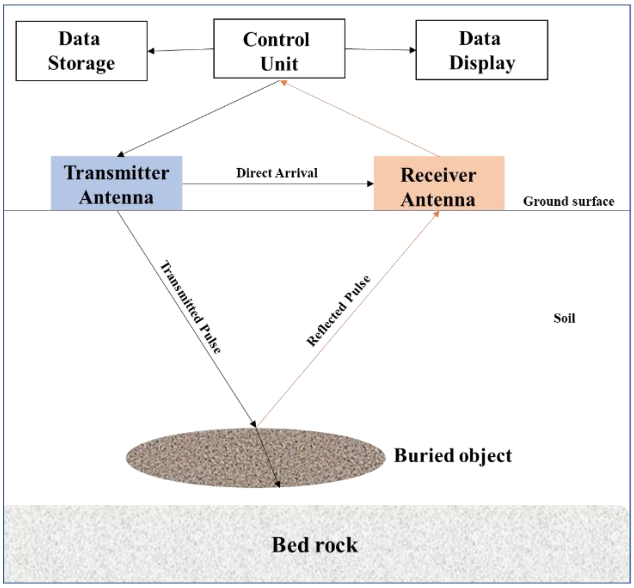

Fig 3.3: Ground Penetrating Radar

When applying electromagnetic techniques for the non-destructive identification of subsurface locations, high production efficiency may be attained. These methods have thus become the most effective tools for urban space detection operations. The standard magnetic source electromagnetic devices, such as the fixed source loop and center loop approaches, have been found to have poor radiation directionality and rapid signal attenuation. Moreover, in a severe interference environment, exploration is significantly impacted. As a result, it is impossible to accomplish the fine detection of urban subsurface targets. These technologies' resolution results are also limited by the simple excitation signal and one data processing method, making it difficult to accurately identify urban subsurface objects at various resolutions and sizes.

3.2.2 Infrared

Infrared imaging technology has drawn attention in industrialized countries due to its many militaries and commercial applications and has become recognized as a significant indication of technological prowess and level of national development[30]. In the absence of light, infrared imaging equipment can take photos of different targets and monitor temperature changes across all targets. In the aftermath of explosions or fires, it is perfectly suited for efficient real-time monitoring and search and rescue activities[31]. To ensure safety, it is essential to increase the usage of infrared imaging technologies in underground settings. Figure 3.4 below shows an image from an infrared imaging system for hot and cold-water pipes.

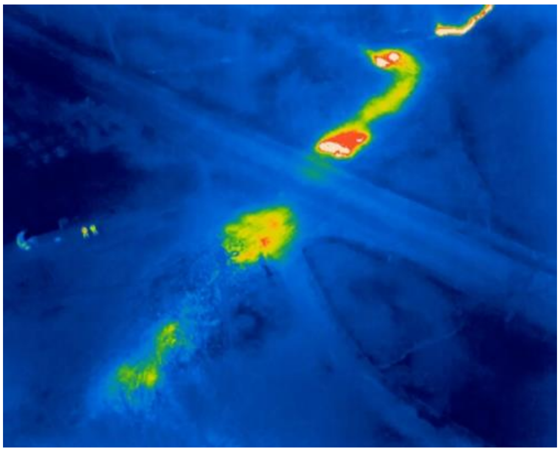

Fig 3.4: Thermal imaging picture showing different temperatures

Compared to visible light imaging, infrared imaging technology has the potential to improve security in urban underground settings[32]. The technology used for infrared imaging does not require visible light. It is capable of gathering precise temperature difference images in total darkness while properly estimating the temperature of people and objects in its field of view. Furthermore, smoke and dust may be used to produce images. While requiring little power and light, it also provides network monitoring and real-time picture sharing. Inherently safe is the usage of infrared imaging technologies[33]. Infrared imaging technology is used in the following ways in urban underground areas: surveillance of urban metro/railway transportation safety; safety monitoring of targets at air raid shelters, parking lots, transportation junctions, and other enormous underground spaces with low illumination levels; damage detection in oil, natural gas, water, and heating pipelines; detection of short/open electrical circuits; and emergency rescue apparatus for explosions and fires. real-time monitoring[34].

3.2.3 Transient electromagnetic (TEM)

While searching for complex-sized and-structured urban underground locations, pulse scanning is a better option than frequency scanning approaches. To increase radiation intensity, enhance radiation direction, and achieve high-power and directed radiation, a new type of high-performance transient electromagnetic source was developed[35, 36]. The new source was a reflector antenna with two trapezoidal plates. The design of the reflector antenna increases radiant power. The antenna was shaped like a horn, which directed the radiation's energy distribution[37].

Transmitting complex waveforms, or a mix of waveforms with different frequency components, to achieve its purpose of boosting the frequency components of excitation signals. To enable multi-resolution detection of subsurface targets and to provide more specific information on the underground target body, a combined correlated superposition method is applied to the findings of multiple waveforms[38]. Next, synthetic aperture technology was created and synthesized utilizing several apertures of different sizes to enhance the horizontal and vertical resolutions and enable multi-scale information extraction in urban underground environments[39]. Figure 3.5 illustrates the principle transient electromagnetic method.

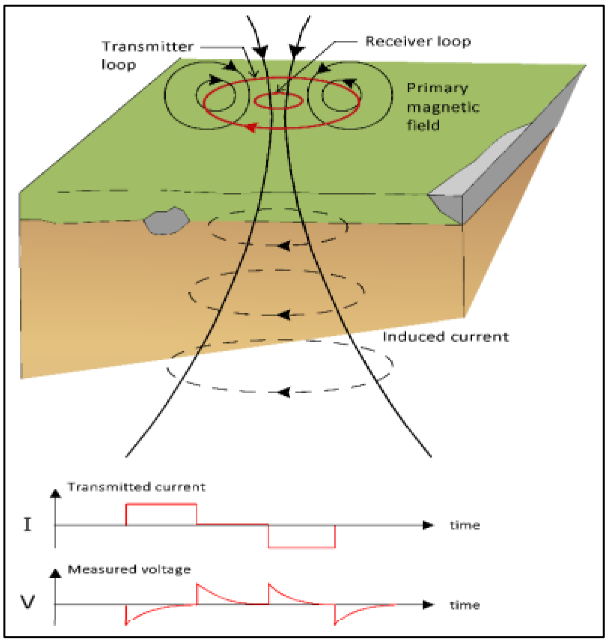

Fig 3.5: Principle of Transient electromagnetic method[40]

The interpretation of high-performance transient electromagnetic excitation sources remains to be done. Due to its extremely high level of computing complexity, implementing 3D inversion in the processing of transient electromagnetic data is difficult. It is impossible for the observed electromagnetic fields in the field to directly reflect the distribution of subterranean geo-electricity, but the apparent resistivity might. The apparent resistivity notion will also be easier to generalize because it requires less computing power than 3D inversion.

3.2.4 Underground space image transmission

There is a need to promote research into a dispersed locatable infrared imaging terminal and use this for image transmission produced by a real-time monitoring system. Concentrate on infrared imaging technology research and development[41]. Combine multi-spectrum imaging with ground wave communication technology[42]. Meanwhile, we must build a real-time catastrophe monitoring system using cutting-edge Internet of Things technologies. Many disasters could happen in an underground area. To achieve real-time detection and ranging, we must therefore use several sensors in addition to image sensors (biology, smell, vibration, smoke, etc.). These sensors could be combined to enable thorough monitoring of the conditions underground.

Finally, there are numerous applications for infrared imaging technology in the security and defense of urban underground environments. Being a critical technology for a growing national strategic industry, infrared imaging technology is getting a lot of attention[43]. After tens of years of study, the fundamental detecting elements of uncooled infrared imaging techniques have become more domesticated. Infrared imaging technology can be mass-produced, has a wide range of applications, consistently provides high-quality images, and might be used for emergency rescue operations and imaging safety monitoring[44].

4 Conclusion

By intelligently developing and utilizing urban underground space, land resources may be prudently conserved, land utilization efficiency can be successfully raised, and transportation congestion can be successfully decreased. The ecological environment of the city may be improved, urban pollution may be significantly reduced, the city's historical and cultural landscape may be preserved, the city's green space may be significantly increased, and infrastructure capacity may be somewhat increased with effective development and use of urban underground space. The advantages of the city's underground regions may be improved by thoughtful planning, which could potentially speed up the city's development. Urban subsurface space needs to be properly developed and used for the city to expand more quickly and effectively. Significant geotechnical engineering issues arise during the tunneling process. To successfully handle such issues, people in charge of implementation should optimize the rules governing tunnel construction and ensure that all tasks are completed routinely, scientifically, and in an ordered manner. All organizations involved in the development of underground spaces should join forces to ensure the proper technical condition of underground construction, establish assessment criteria for negative factors, determine methods and put those measures into practice, as well as establish coordination procedures in case of accidents and unfavorable situations caused by humans. One of the top concerns is to respond promptly to keep a facility in the good working condition given the complex interactions that occur between people, infrastructure, and the environment at all stages of activity.

The future of detection and monitoring will most likely involve the advancement of existing technologies as well as the implementation of some new ones. The discovery and observation of underground places are anticipated to become more and more dependent on the development of modern sensors, such as fiber optic sensors and wireless sensors. These sensors can provide real-time information on the health of the structure, the environment, and potential threats, enabling engineers to make necessary repairs before more significant problems occur. To analyze and interpret data from underground places, it is anticipated to become increasingly vital to integrate data analytics methods, such as machine learning and artificial intelligence.

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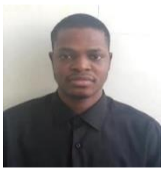

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