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GRAVITY TO CAVITY: GRAVITY MEASUREMENT FOR UNDERGROUND CAVITY DETECTION

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Abstracts: Underground cavities present substantial risks to civil engineering and infrastructure, potentially resulting in subsidence and surface collapses. Traditional wave-based detection methods, such as Ground Penetrating Radar (GPR) and Electrical Resistance Tomography (ERT), are limited by wave propagation issues, interference, and depth constraints, impacting the effectiveness in accurately visualizing subsurface features. In contrast, gravity measurement offers a precise, non-invasive alternative by detecting gravitational anomalies caused by variations in subsurface mass distribution. This paper reviews the principle, technological evolution, and applications of gravity measurement for underground cavity detection, highlighting the development gravimeter from conventional spring-type to advanced quantum type. These advancements have enhanced the precision, portability, and applicability of gravimeter in various fields. In the future, the integration of gravity measurement with conventional geophysical technologies could mitigate the limitations of single-method approaches and increase detection accuracy. Further technological improvements, particularly in quantum gravimeter, is expected to enhance portability, environmental resilience, and cost efficiency, facilitating large-scale deployment and expanding its application in geological exploration, civil engineering, and environmental monitoring.

Keywords: Underground cavity detection, Gravity measurement, Gravimeter principle, Development, Field application, Quantum gravimeter.

1. Introduction

Underground visualisation offers insights about subsurface features that are not possible to obtain through surface observations. The existence of underground abnormalities like cavities and karst caves may cause cave-ins and collapses at surface level, constituting significant risks to both above- and under-ground engineering and construction. The localisation, characterisation and visualisation of such features plays a vital role ensuring safe development and operation of various infrastructures. In the quest to unlock the myths of these hidden features, traditional underground visualisation techniques, such as ground penetration radar (GPR), Electrical Resistance Tomography (ERT), have been valuable in advancing the understanding of the underground. However, these wave-based techniques have long been constrained by limitations in wave propagation, underground medium interference, resolution, depth and environmental conditions, hindering an improved evaluation and assessment of subsurface features.

To address these limitations, gravity measurement technology has emerged as a powerful alternative and complementary approach for underground cavity detection. Unlike wave-based methods, gravity measurement leverages gravitational anomalies that arise from variations in subsurface mass distribution, providing a non-invasive means to identify and characterize underground cavity(Butler, 2008). By utilizing highly sensitive instruments such as gravimeters, it becomes possible to detect even subtle changes in the local gravitational field, offering insights into the presence, size, and depth of cavities. This paper reviews the evolution of gravimeter technology, the principles behind gravity-based cavity detection, and its application in various fields, highlighting the advancements and future potential of this method in underground engineering.

2. Principle of gravity measurement

The application of gravity measurement for underground cavity detection relies on the principle that different subsurface features produce distinct gravity anomalies due to variations in mass distribution. Gravimeters measure these anomalies, allowing for the identification and characterization of underground cavities. Based on the fundamental design, gravimeters can be categorized into two main types: spring-type and free-fall gravimeters, each employing a unique approach to gravity measurement.

2.1.*Gravity field*

Gravitational acceleration is generally consistent across a given region; however, significant variations in subsurface features, such as underground cavities, can create detectable gravity anomalies. The principle of detecting these anomalies involves using a gravimeter to measure small changes in the Earth's gravity field, which indicate differences in mass distribution due to underground cavities. This phenomenon is governed by Newton's law of gravitation $F=GMm/r^{2}$ and Newton's third law of mechanics $F=mg$. Then the relationship between volume of Earth M and gravitational acceleration g can be obtained:$g=GM/r^{2}=GÁV/r^{2}$, Where F is the gravitational force between two masses, G is the gravitational constant that equals to $6.673\times10^{-11}\mathrm{Nm^{2}kg^{-2}}(\mathrm{kg^{-1}m^{3}s^{-2}})$, g is the gravitational acceleration, r is the distance between Earth M and measurement instrument, M is the mass of Earth M, $Á$ and V are the density and volume of Earth M.

Therefore, the existence of an underground cavity indicates a significant mass difference, denoted as • M, between the cavity and surrounding material. This mass difference results in a change in gravitational acceleration, • g, which can be detected by gravimeter, by inverting the obtained gravity anomaly data. Assuming a density of 1.5×10^{3} kg/m^{3} for surrounding material, typical gravity gradient anomaly signals from a 1L cubical void at 1m depth to a cavern at 50m depth can be calculated, as illustrated in Table 1.

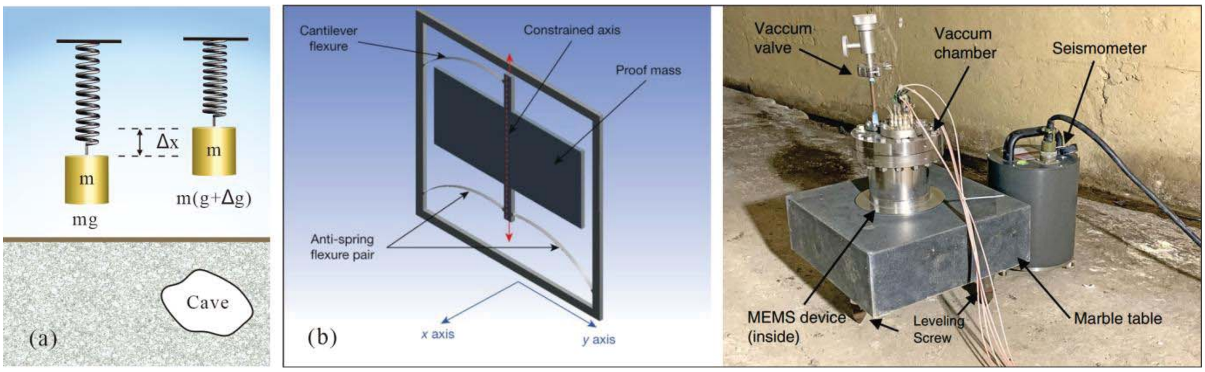
Table 1.Gravity gradient changes from different gravity sources (1E=10^{-9}s^{-2})

Type	G (N·m^{2}·kg^{-2})	¡ (kg/m^{3})	V (m)	R (m)	• g (E)
1L Cubical void	6.673×10^{-11}	1.5×10^{3}	1 Liter	1	0.1 E
Pipe			0.4(radius)×1(L)	3	5.58 E
Tunnel			10(W)×5(L)×5(H)	20	62.6 E
Cavern			50(W)×10(L)×10(H)	50	200 E

2.2.*Spring-type gravimeter*

The spring-type gravimeter detects variations in gravitational acceleration by suspending a test mass m on a spring, using Hooke's Law ($F=kx$) as the fundamental principle, where $k$is the spring constant and $x$is the displacement. The force of the spring balances the gravitational force on the test mass, so the spring's resistance offsets the pull of gravity. This balance allows the gravitational acceleration g to be calculated as$g=kx/m$. When the gravimeter is positioned over an underground cavity, any change in the local gravitational field results in a corresponding change in the displacement x, enabling the gravimeter to detect even small fluctuations in g.

This configuration allows detection of minute changes in gravity. Recent developments have led to the miniaturization of this principle using Micro-Electro-Mechanical Systems (MEMS). MEMS gravimeter integrate the spring-mass system into a compact silicon-based sensor, offering reduced size, weight, and power consumption. Although their sensitivity (typically at the μGal level) remains lower than that of superconducting or quantum devices, MEMS gravimetersare highly promising for portable and cost-efficient gravity sensing in field conditions, including continuous monitoring and urban infrastructure applications. The working principles of spring-type gravimeter and MEMS gravimeter are illustrated in Figure 1.



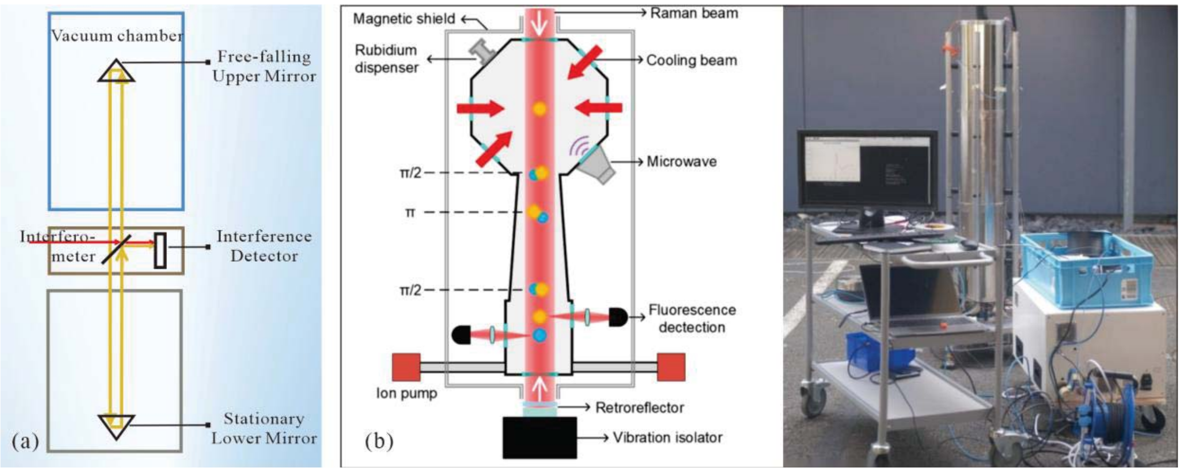
(a) Principle of Spring-type Gravimeter (b) MEMS Gravimeter

Fig.1. The working principles of spring-type gravimeter and MEMS gravimeter

2.3.*Free-fall type gravimeter*

The free-fall gravimeter determines local gravitational acceleration by placing a test mass within a vacuum, allowing it to fall freely without the influence of external forces, such as air resistance, which ensures an exceptionally precise measurement. The device uses the principles of kinematics ($y= gt^{2}/2$), where y is distance and $t$is the time of falling. By precisely measuring the time of fall using advanced timing technologies like laser interferometry, the gravimeter can calculate the local gravity acceleration $g=2y/t^2$, small variations in local gravity are detected as slight changes in the measured fall time.

A breakthrough in this category is the development of quantum gravimeters, which replace macroscopic test masses with clouds of ultra-cold atoms. These atoms are manipulated using stimulated Raman transitions to form an atom interferometer, wherein the phase shift between matter waves encodes the local gravitational field. This technique, rooted in atomic physics, enables absolute gravity measurements with exceptional precision (down to sub-μ Gal). Quantum gravimeters are immune to mechanical drift and have demonstrated success in detecting shallow tunnels and voids in real field environments. Their robustness and long-term stability offer significant potential for high-resolution gravity surveys, particularly in civil engineering, resource exploration, and environmental monitoring.The principles of free-fall gravimeters and quantum gravimeters are shown in Figure 2.



(a) Principle of Free-fall type Gravimeter (b) Quantum Gravimeter

Fig.2. The principles of free-fall gravimeter and quantum gravimeter

3. Application in cavity detection

The advancement of gravity detection technology is evident not only in ongoing technological innovations but also in its effective application in the field. In karst regions, gravity measurement has proven instrumental in monitoring groundwater pathway changes and identifying subsurface voids to prevent surface collapses. For example, a study in Italy utilized the LaCoste-Romberg D64 spring gravimeter and airborne gravimetry to successfully detect and map karst caves(Braitenberg et al., 2016). Ground-based gravimeters showed particular effectiveness in detecting smaller, shallower voids with diameters as small as 5 meters. In urban applications, a sudden street collapse in France prompted gravimetric surveys that identified gravitational anomalies, which were subsequently confirmed as voids through drilling(Jacob et al., 2020). In archaeological settings, the CG-5 gravimeter was used to map a subsurface cavity beneath a church in Slovakia(Pánisová and Pašteka, 2009), employing Euler deconvolution and 3D modeling techniques to determine the cavity's depth and shape accurately.

These cases emphasize the extensive application and effectiveness of conventional gravimeters in various domains of underground cavity detection, more cases are shown in Table3. However, recent advancements in quantum gravimetry remain predominantly in the experimental and theoretical stages. In 2022(Stray et al., 2022), a breakthrough at the University of Birmingham marked a significant milestone when a 2×2 meter tunnel at a depth of 0.5 meters was successfully detected outside the laboratory, representing a major step forward for quantum technology in civil engineering. This achievement demonstrated the high precision and sensitivity of quantum gravimeters, indicating their potential for cavity detection. Quantum gravimeters, which utilize cold atom interferometry, have reached exceptional accuracy, capable of detecting minimal gravity variations. The commercial DQG model currently achieves precision levels of 10^{-9}m/s^2, meeting or exceeding the highest standards of conventional gravimeters. Despite this progress, quantum gravimetry is still in its infancy, with numerous technical challenges yet to be resolved. Addressing these challenges is expected to yield even greater precision and stability, opening new research directions and practical applications in underground cavity detection.

Table 3. Representative studies on underground cavity detection using conventional gravimeter

Gravimeter	Scenario	Anomalies	Depth (m)	Reference	Purpose of study
CG-5	Field site	Karst cavity	6 to 10.5	(Arisona et al., 2023)	Microgravity surveys employing geophysical tools successfully detected extensive hidden cavity systems and modeled gravity anomaly data to determine the densities of geological units.
CG-6	City area	Karst cavity	50 to 750	(Saibi et al., 2019)	Gravity measurement identified subsurface anomalies consistent with deep cave systems, revealing the distribution of underground karst
Lacoste Romberg D	Village area	Cavity	2	(Leucci and De Giorgi, 2010)	A comprehensive geophysical survey utilizing microgravity and ground-penetrating radar (GPR) mapped subsurface karst features, revealing cavities and voids that pose geological risks
Quantum gravimeter	University campus	tunnel	0.5	(Stray et al., 2022)	The detection capability of the quantum gravimeter was tested outside lab and a tunnel with a burial depth of 0.5m and a diameter of 2*2m was measured

4. Conclusion and outlook

Gravity measurement has become a vital and non-invasive tool for underground cavity detection, offering high sensitivity to mass anomalies that indicate the presence of voids. This review summarized the physical principles, technological developments, and field applications of gravimeters, ranging from classical spring-based devices to emerging quantum systems. The inclusion of Micro-Electro-Mechanical Systems (MEMS) has enabled more portable and low-cost deployment, while quantum gravimeters, based on cold atom interferometry, have achieved sub-μGal precision, marking a new frontier in gravity sensing.

In the future, the application of gravimetric techniques will extend far beyond cavity detection. Promising fields include groundwater monitoring, volcano activity analysis, coal seam exploration, and long-term tidal observation. These domains demand high temporal stability and spatial resolution, both of which can be delivered by next-generation gravimeters. Quantum gravimeters, with their drift-free absolute measurements, are particularly suited to these applications and are expected to benefit from further improvements in miniaturization, robustness, and cost-effectiveness.

On the hardware side, continued development of MEMS-based and quantum-based sensors will support the transition from laboratory research to real-world deployment, especially in environments with complex terrain or access limitations. Simultaneously, innovations in software will play an increasingly critical role. Artificial intelligence (AI) techniques, such as machine learning, deep neural networks, and wavelet-based signal processing, are expected to enhance noise suppression, increase the resolution of inversion models, and enable real-time data interpretation.

Ultimately, the integration of advanced sensing hardware and intelligent software frameworks will significantly expand the capability and reliability of gravity-based subsurface exploration. This fusion of technology will not only improve detection accuracy for hidden cavities but also serve broader goals in geotechnical safety, environmental monitoring, and sustainable infrastructure development.

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