

Prototype of Sinkhole Detection Model with Sensor Alarm

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Abstract

Sinkholes are a serious geological hazard that can disrupt public services, damage infrastructure, and even lead to fatalities. These events can occur suddenly and without visible warning, making early detection critical for risk mitigation and public safety. This study introduces a prototype sinkhole detection model designed to address this need through the integration of sensor technology and a real-time warning system. This model uses sensors to continuously monitor key geotechnical parameters such as soil moisture, ground vibration, and pressure changes. These parameters are known indicators of ground instability that could signal potential sinkhole formation. Sensor data are processed in real time using threshold-based analysis and statistical evaluation to detect significant changes in soil conditions. To evaluate the effectiveness of the prototype, the model is rigorously tested under controlled conditions. Simulated sinkhole scenarios are created to mimic real-world situations, allowing researchers to assess the system's responsiveness and accuracy. However, as the tests were conducted solely in a controlled environment, the system's performance in actual field conditions remains unverified, which may affect the generalizability of the results. The results of these tests indicate that the model can reliably identify early signs of sinkhole development and trigger timely alerts. Based on its performance during testing, this prototype appears to be a practical, scalable, and cost-effective solution for sinkhole detection. This research contributes to improving geotechnical safety by enabling proactive measures and reducing the potential impact of sinkholes.

1. Introduction

In many regions of the world, sinkholes pose a serious geohazard, particularly in urban and suburban areas with significant populations and infrastructure. A sinkhole forms when the ground surface collapses due to the dissolution of soluble bedrock such as salt, gypsum, or limestone by groundwater [1]. This process, known as karstification, gradually creates underground voids that can no longer support the weight of the overlying material, leading to sudden and sometimes catastrophic ground collapse [2]. In addition to causing physical harm to infrastructure and property, sinkholes can seriously threaten public safety, as demonstrated by the many tragedies that have occurred around the world [3].

Concern over sinkholes has grown in Malaysia, especially in urban areas where drainage systems, subterranean water pipelines, and heavy building all contribute to soil instability [4]. A woman fell into a sinkhole that was eight meters deep in Kuala Lumpur, according to a recent occurrence that was covered by BBC News in

2024 [5]. Public and governmental attention has been brought to the critical need for early detection and warning systems that can identify sinkhole formation before major damage occurs as a result of such disasters.

Even while there are advanced technologies like GPS monitoring systems, Ground Penetrating Radar (GPR) [6], and other geophysical techniques, these solutions are frequently expensive, require complicated installations, and need skilled operators to operate and interpret data. These limitations reduce the likelihood of widespread adoption, particularly in environments with little funding, small scales, or temporary [7][8]. Therefore, a more easily deployable, cost-effective, and accessible early warning system is desperately needed in places that are at risk [8].

The creation of a small-scale sinkhole detection prototype with a sensor-based alert system is presented in this research [9]. In order to identify early indications of erosion or ground movement, the model combines motion sensors that have been inserted in the soil [10]. When substantial soil displacement is recorded, these sensors are linked to a processor that activates an audible alert system, providing an instant warning [11]. Three main objectives serve as the foundation for the research:

- i. To design a small-scale sinkhole detection model using AutoCAD
- ii. To construct a model with a motion sensor that detect soil erosion and evaluate an alarm
- iii. To evaluate the effectiveness and sensitivity of the sensor in detecting soil

According to a thorough literature study, there are two types of sinkhole detection techniques: direct and indirect. High-resolution subsurface images produced by technologies like Ground Penetrating Radar (GPR) are perfect for locating voids and cracks [12], but their effectiveness varies depending on the soil and requires skilled operation. Although GPS tracking provides precise, extensive coverage, the costs of setting up and maintaining it are significant. Even though visual inspection is cheap, it can only detect surface changes and is very dependent on the observer skill. Sensor based systems, on the other hand, offer constant, real-time monitoring and are able to identify ground movement before obvious indications of subsidence appear. In geotechnical monitoring, tools like motion detectors, displacement sensors, and inclinometers are frequently used to evaluate slope and structural integrity. Such sensors are used in this study to replicate real world sinkhole conditions and early warning capabilities. Through the incorporation of this technology into a small, expandable prototype, the project fulfils practical and instructional objectives such as demonstrating system functionality in real-world scenarios, enabling hands-on testing, and providing a foundation for future development or scaling. It advances knowledge of sinkhole formation and encourages the creation of inexpensive, flexible detection devices. In the end, this study offers a workable way to enhance civil infrastructure safety and early warning systems in sinkhole prone areas.

2. Methodology

The methodology implemented to develop a small-scale sinkhole detection model integrated with a sensor-based alarm system. The process was created to ensure that the prototype is functional and reliable by integrating design planning, material selection, model manufacturing, and performance testing. The goal was to create a model capable of identifying soil erosion and ground movement that might contribute to sinkhole formation while employing low-cost and easily available technology suited for academic and practical civil engineering applications. The methodology's initial phase entailed conducting preliminary research and reviewing the literature. Several academic sources and case studies were examined to gain an extensive understanding of sinkhole formation mechanisms, existing detection methods, and the significance of sensor systems in early warning applications [13]. The focus was on geotechnical risk variables such as subsurface water flow, soil displacement, and infrastructure leaks. This research validated the use of motion sensors as a viable component for real-time soil movement detection, while also highlighting the viability of small-scale acrylic enclosures [14].

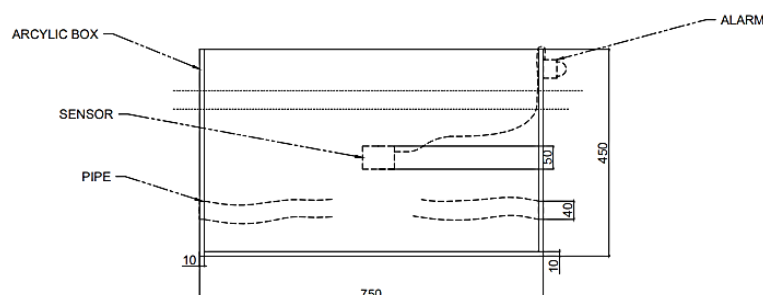


Fig. 1 Front view of Model

After the evaluation stage, the design phase was conducted using AutoCAD software to create technical drawings for the prototype. The model was designed as a rectangular acrylic box measuring 750 mm in length, 450 mm in width, and 300 mm in height as a Fig. 1. This prototype represents a cross-section of soil and includes a horizontal PVC pipe to simulate subsurface infrastructure. A motion sensor is positioned near the embedded pipe, representing a potential leak source, while an external alarm system is mounted to provide audible alerts. The sensor is programmed to activate a mechanical buzzer when it detects displacement beyond a certain threshold, functioning as an early warning system. AutoCAD was chosen because of its accuracy and scalability, which enable correct component placement and easy layout modification for future revisions or modifications. The third step of the process focuses on obtaining materials and model building. Materials were sourced from both the online supplier and local vendors. Acrylic sheets, PVC pipes, and adhesives were among the primary building components. The model's electronic components comprised a motion sensor, a 12V mechanical buzzer, switches, wiring, and a microcontroller interface. To imitate real-world geological conditions, the acrylic box's soil material consisted of layers of sand, gravel, and clay. The model was put together by fusing the acrylic panels, embedding the PVC tubing, and connecting the sensor and alarm system. The electrical components were wired such that the system could detect motion and trigger the buzzer in response to soil movements [15].

The prototype was thoroughly tested and evaluated throughout the final stage. The testing approach centred on the sensor's responsiveness, the alarm system's dependability, and the model's general functionality under varying settings. Simulated erosion was created by gradually removing soil surrounding the pipe region to see if the sensor could reliably detect displacement. Different soil types, which are gravel, sand, and laterite, were tested to assess sensitivity under different compaction and moisture conditions. Each trial was administered several times to ensure uniformity and dependability. The data gathered during testing was utilised to assess detection accuracy, reaction time, and probable false positives or negatives. In conclusion, the technique used in this research provided a disciplined way to develop, create, and test an effective sinkhole detection model. The combination of theoretical study, CAD design, hands-on building, and practical testing guaranteed that the final prototype achieved its goal of becoming a cost-effective early warning tool. This technique also allows for further improvement and scalability, making it appropriate for both instructional and professional civil engineering applications. The model highlights the feasibility of using low-cost sensors into geotechnical monitoring systems, which contributes to continuing efforts to improve infrastructure safety and hazard reduction.

3. Results and Discussion

The data analysis of the small-scale sinkhole detection model, which was built using an integrated motion sensor system and created using AutoCAD, is presented in this chapter. The accuracy of the design, sensor performance, and soil behaviour in sinkhole simulation scenarios are the main areas of evaluation. The physical prototype's fabrication was successfully guided by the AutoCAD design. Accurate component alignment was guaranteed by the software's measurements and arrangement, which included the motion sensor positioned vertically, the horizontal pipe, and the transparent acrylic enclosure. Throughout the studies, the use of transparent material made it possible to continuously observe soil displacement and collapse events. It was helpful to validate sensor activation at different stages of soil movement with this visual access. The actual prototype was built with gravel, sand, and laterite layers. The sensor was positioned between the soil layers with the goal of detecting soil movement (Fig. 2). In order to replicate leaking situations, water infiltration was introduced close to the pipe during testing [16].

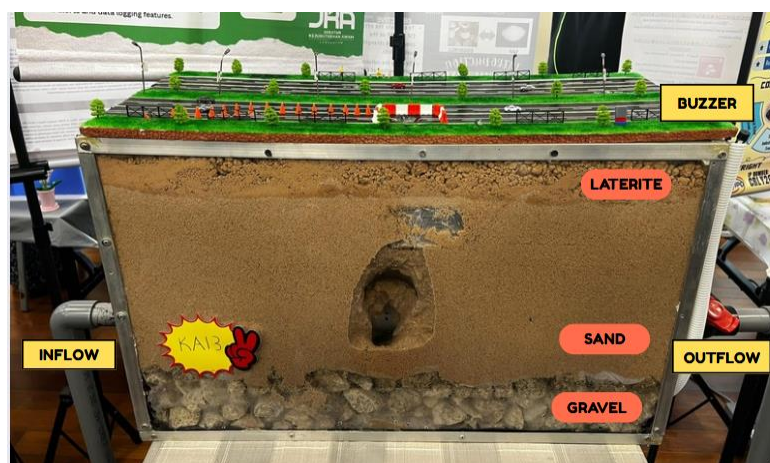


Fig. 2 Model sinkhole with sensor alarm

The outcome showed that when saturation levels increased over time, soil displacement increased as well (Table 1 and Fig.3), ultimately setting off the motion sensor. This reaction validated the sensor's ability to identify early erosion indicators. Additional information about the laterite soil's geotechnical behaviour was obtained through laboratory testing which is moisture content, plastic limit and liquid limit [17]. These results showed that saturated laterite soil had decreased shear strength and was more prone to collapsing. This is consistent with field observations, which show that weaker, more moist soils are more likely to develop sinkholes [16][17]. The model was tested under controlled erosion settings in three different experiments. Once noticeable soil moving was identified, sensor activation happened consistently in every session. The alarm system sent out a loud warning signal in a timely manner. Soil displacement increased steadily until the critical threshold was achieved, according to graphs that plotted time against erosion level. The model validated its function as an early-warning system by successfully detecting underground instability before visible collapse occurred.

Table 1 Soil Displacement Over Time

Time (Sec)	Displacement (cm)
2	0.2
4	0.3
6	0.6
8	1.0
10 (Average)	1.2 (Sensor Activated)

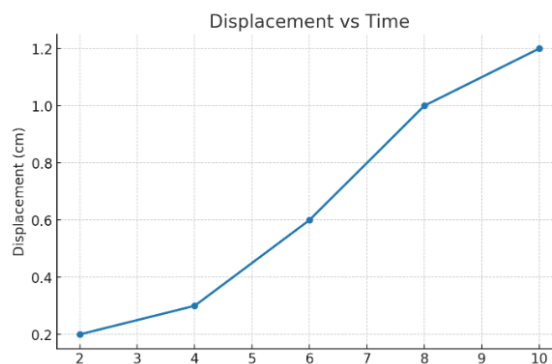


Fig. 3 Displacement vs Time Curve for Combined Soil Layer

A standardised soil type was also used for the duration of the trial to test the sensor system in a controlled setting. The trials were sufficient to assess the system's sensitivity and functionality, however, excluding soil variables such as moisture content and different soil types may limit the reliability of the results in real-world applications, as the sensor's performance under varying conditions remains untested. When erosion hit a crucial threshold, the sensor activated the alarm in response to the simulated soil movement. This demonstrates the system's potential as an affordable and useful tool for small-scale sinkhole detection by showing that it can deliver timely notifications under specific conditions. All things considered, the model showed that combining a motion sensor with a small-scale acrylic replica is a workable way to simulate and identify the early stages of sinkhole formation [15]. The information gathered gives validity to the idea that sensor-based models can offer early warnings in soil settings that are susceptible to instability and erosion. This model could be used as a basis for future research and development of scalable detection systems that improve infrastructure resilience and public safety.

4. Conclusion

This study successfully fulfilled its aim of developing a small-scale sinkhole detection model that integrates sensor-based early warning systems. Using AutoCAD, a detailed and accurate design was created to represent underground conditions, which was then constructed as a physical prototype using acrylic and layered soil materials. The prototype effectively demonstrated how motion sensors can detect early soil movement due to simulated underground water leakage. When soil displacement was detected, the system successfully activated an alarm, providing real-time alerts of potential sinkhole formation. Testing under different soil types, including dry sand and laterite, confirmed that the sensor system was both responsive and reliable, although some delay in detection was observed in cohesive soils like laterite due to their water retention properties. While the model

functioned well in a controlled environment, some limitations were noted, including the need for more advanced features to handle field conditions and multiple sensor placements for wider coverage. Nonetheless, the research showed the feasibility of using a low-cost, small-scale model for educational and early-warning purposes. For future improvements, the incorporation of multiple sensors, data logging systems, and real-environment testing is recommended to enhance performance and practical application. Overall, this project contributes meaningfully to civil engineering by offering a simple yet effective solution for monitoring and preventing sinkhole-related hazards in urban and rural areas.

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Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

Author Contribution

The authors confirm contribution to the paper as follows: **study conception and design:** *Mohamad Azim Mohammad Azmi*; **data collection, analysis, and interpretation of results and draft manuscript preparation:** *Norikman Norhadi, Nazri Haminozain, Maisarah Husna Isa*. All authors reviewed the results and approved the final version of the manuscript.

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