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REDUCTION OF UNDER-ROAD PAVEMENT SINKHOLE HAZARDS BY SOIL IMPROVEMENT

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ABSTRACT: This study describes a lab simulation that simulates the sinkhole that occurs in the sand bed beneath a road model due to pipeline rupture for any pipeline material beneath the road bed. The objective of this study is to stabilize the underlying sand soil with regular Portland cement in order to increase the time it takes for sinkholes to occur and discover preventive measures. A series of model tests is conducted as part of the investigation on a road model built on a sand substrate, both with and without stabilization. A rectangular box container of dimensions 500 x 350 x 150 mm was constructed. Cement concentrations of 4%, 5%, 6%, 7%, and 8% by weight of dry sand were mixed with the sand to create the stabilized sand beds; their percentages of cement content are used by previous studies on stabilizing cement content in soil. According to the findings, cement significantly reduces the likelihood of sinkholes developing. In order to protect the sand from erosion caused by water flowing through pipelines that are beneath roads and to delay the time it takes for sinkholes to form in the soil, cement can be applied. According to the findings, cement percentages of 4% and 5% had little to no impact on when sinkholes arise. The time reported for the 4% or 5% stabilized sand is roughly 30 to 60 seconds, which is also the time at which the sinkhole occurrence of the unstabilized sand substrate occurs. However, sand stabilized with 6% and 7% cement had a significant impact on the sinkhole occurrence time, increasing it by up to 330 seconds. As a result, it is crucial in this field to stabilize the sand bed using such Portland cement ingredients.

Keywords: Sinkhole hazards, Occurrence time, Road pavements, Sand bed, Pipelines.

1. INTRODUCTION

In terms of both cost and function, pavements are an essential part of roads [1–9]. The stability of the underlying layers is the primary determinant of pavement stability [10–16]. A sinkhole due to pipe breakage can cause severe damage to pavement systems. Therefore, understanding its occurrence is an essential objective. In recent years, the term sinkhole has become more usable [17]. It refers to the sudden large collapses in the land surface [18]. Sinkholes have appeared in New York, Florida, and Mississippi in the USA [17], Naples in Italy, Albans in the UK, Australia, and Iraq, among many others. Costly damage has resulted from sinkholes beneath civil engineering structures such as railroads, highways, pipelines, buildings, dams, and reservoirs [19]. Sinkholes can result in or are potential sources of pollution of water supplies [20]. Sinkholes usually result from changes in the surface or subsurface water flow [21]. Artificial activity may also result in sinkhole development and collapse [18]. Channelized draining or any changes made to local surface drainage, excessive groundwater pumping, and leaking lines of water can all cause sinkholes [22]. A sinkhole is a hole or “cavity” in the land that results from water dissolving rock or the surface of the earth and collapsing the soil away over time, as shown in Fig.1. Sinkholes can be deep or shallow, and may form either gradually or suddenly [21, 23]. It may exhibit a visible hole into a cave under the ground, often circular, with a size up to tens of meters in diameter [24, 25].

A concentrated flow of groundwater, wherever the rock has become more permeable or more soluble, causes big spaces in the limestone. Increased surface loading, increased filtration following rainfall, chemical changes in the water, or an increase in the effective weight of the soil overburden as a result of the water table dropping to the point where the cavity bridge is unable to handle the overburden weight can all result in increased solution [17]. Sinkholes typically originate in one of two ways: either a cavity in limestone collapses due to rock collapse, or an unconsolidated overburden cavity develops and causes raveling collapse. When a bedrock cavern's roof collapses, a steep-sided pit with rock walls is created, which may eventually enlarge into interconnecting cave passageways. A cenote is created when the underground cave system is filled with water [21]. In general, when the stimulating action that caused the development of the stream (such as the flow of water) is removed, the direct risk to the surrounding area is greatly reduced. It is usual to fill in small holes with weak concrete pumped into the hole from a safe distance.

Fig. 1 Occurrence of sinkhole in pavement.

Depending on the conditions, the duct is usually installed with concrete or other engineering filler. Small settlements occur for several months afterward as the weight of the concrete stabilizes. New sewers are usually formed by water flow as mentioned above, and thus are largely avoided by concern for good civil engineering practices, especially adequate surface drainage and avoiding scale changes in the water table [26].

A number of reviews were prepared in the domain of sinkhole monitoring and remediation [17, 26-33]. These reviews concluded that there is a vital research gap in this domain. In addition, a number of studies were implemented in the domain of sinkholes under roads [18-20, 22, 34-52]. Moreover, a few studies were implemented in the domain of sinkholes related to pipelines [20, 21, 23, 47-49]. To the best knowledge of the authors, no such research developed a downscaled model to simulate the sinkhole occurrence in the sand bed beneath road pavements that occurred due to breakage of a pipeline. Therefore, this study is a novel study as it adopts this approach. In addition, this study utilizes the developed model to investigate the effect of soil improvement of pavements' underlying layers on the time of sinkhole occurrence. The improvement of the tunnel in soft soil by using different depths of geogrid was carried out by Awlet et al. [50]. The conclusion was that using a geogrid at a depth of 0.5 foundation width represents a good reinforcement of soft soil.

2. RESEARCH SIGNIFICANCE

This study aims to enhance the understanding of sinkhole stabilization without complete plugging, a critical challenge in geotechnical engineering. It presents an experimental program to evaluate the effectiveness of Portland cement as a soil stabilizing agent to delay or prevent sinkhole formation. Additionally, the research introduces a laboratory-based simulation of sinkhole development caused by pipeline breakage beneath a sandy soil layer under a road model. The outcomes are expected to contribute valuable insights into preventive measures, enabling more resilient infrastructure design and risk mitigation strategies in sinkhole-prone areas. This work addresses both practical application and theoretical advancement.

3. MATERIALS USED

3.1 Sand

In this research, sand used as a foundation bed was obtained from a construction site. Prior to testing, the sand was dried in the laboratory by oven at 105°C for 24 hours. Afterward, it was sieved on sieve No. 4 to remove the undesirable materials. The laboratory tests were implemented to determine the physical properties of soil. The results of these tests are presented in Table 1. The Particle-size distribution curve of the sand used is shown in Figure 2.

Table 1. Physical properties of the sand used.

Test name	Property	Value
Specific gravity	Gs	2.67
	D_{10}	0.25 mm
	D_{30}	0.4 mm
Grain size analysis	D_{60}	0.7 mm
	Cu	2.8
	Cc	0.914
	USCS	SP
Maximum dry unit weight	γ_d(max)	18.5 kN/m^3
Minimum dry unit weight	γ_d (min)	14.0 kN/m^3
Specific gravity	Gs	2.66
Natural water content	Wc %	5.0 %

USCS = Unified Soil Classification System.

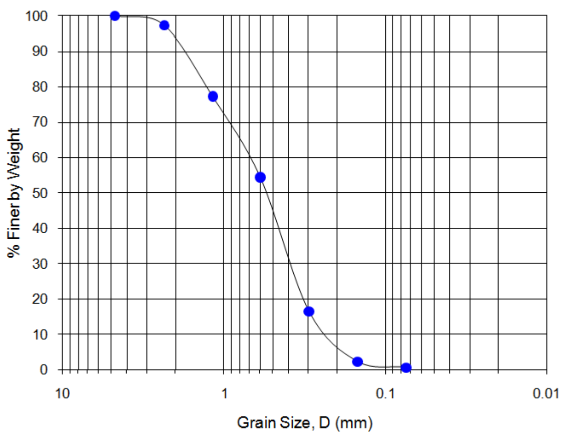

Fig.2 Particle-size distribution curve of the sand used.

3.2 Cement

Ordinary Portland cement was used as a stabilizer material. The cement was mixed with sand at different percentages depending on the dry weight of sand.

4. TESTING EQUIPMENT

4.1 Model Container

The sandy soil was put in a cuboid container with dimensions of (500 × 350 × 150) mm, these dimensions depend on finite element analysis to recognize the suitable size of box dimensions. The box boundaries were selected to be far away from the stressed zone. The box was made of glass with a thickness of 10 mm. The model container contains two holes with 19 mm in diameter made at a distance of 100 mm from the base of the container. The water pipes were attached to the holes to ensure water access to the model container in order to perform the erosion process of soil within the container. Figure 3 shows the model container used.

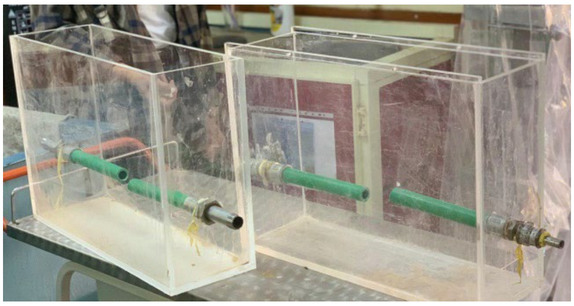

Fig. 3 The model container.

4.2 Model of Water Supply

A cylindrical steel tank, 270 mm in diameter and 550 mm in height, was used as a water supply. The steel tank is equipped with control valves that allow water to flow into the model container, as illustrated in Figure 4. The elevations of the water supply were selected to provide a suitable flow under the road model.

Fig. 4 The model of water supply.

4.3 Road Model

A cork material with a thickness of 10mm and a length of 500 mm was used to represent the model of road pavements. A few toy cars were put on the model of the road pavements to simulate the real case as shown in Figure 5.

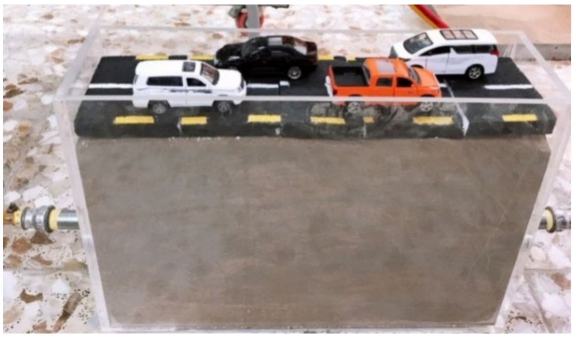

Fig. 5 The model of road pavements on a sand bed.

5. PREPARATION OF SAND BED

Two types of sand beds were prepared: a sand bed without stabilization and a sand bed stabilized with Portland cement. The preparation of the sand bed inside the model container involves placing the sand in three layers, each with a depth of 100 mm, to maintain a total depth of the sand bed of 300 mm. Each layer was compacted to achieve a dry unit weight of 14.9 kN/m³, corresponding to a 25% relative density. To prepare the stabilized sand bed, the sand was adequately mixed with ordinary Portland cement at different percentages by weight of the dry sand (4%, 5%, 6%, 7%, and 8%). Figure 6 illustrates the steps of sand bed preparation.

Fig.6 The steps of sand bed preparation.

6. TESTING PROCEDURE

After setup, the control valves were opened to allow water to flow into the model. Afterwards, the sinkhole occurrence was carefully observed, and the time of sinkhole occurrence in the sand bed in both models (the control and the one with stabilized sand bed) was recorded. The test was stopped when the collapse of the soil and the model road occurred. Figure 7 shows the complete setup.

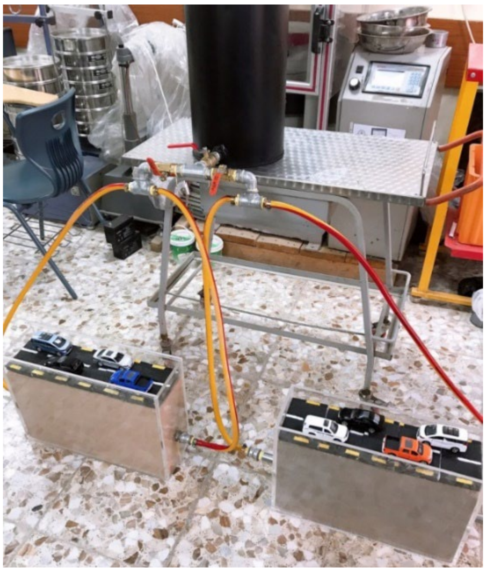

Fig. 7 Complete setup.

7. RESULTS AND DISCUSSION

7.1 Sinkhole Occurrence Time in Control Model

Firstly, the test was implemented on the control model (the pavement road model on the sand bed without stabilization) to observe the sinkhole occurrence in the sand bed beneath the pavement's road model due to the flow of water underneath. It was clearly observed that the sinkhole occurred because of the erosion and collapse of the soil due to water flow from the broken pipeline, which is buried in the soil. The sinkhole tends to develop gradually in the sand bed during approximately 30 seconds. Figure 8 shows the progress of sinkhole occurrences in the sand bed without stabilization.

The study by [53] examined the potential use of chitosan, a soil amendment, to enhance the durability and erodibility of soft soil. Both the untreated and chitosan-treated samples were subjected to a 5-hour soaking cycle and a 43-hour drying cycle until they failed. To determine the durability index, the unconfined compressive strength (UCS) of samples made with varying dosages (0.5, 2, 4%), and cured for 14, 28, 60, and 90 days, was assessed at the beginning and after each drying cycle. After being amended with 2%, the soft soil was allowed to heal for 90 days and withstand five cycles with a UCS of over 1,000 kPa.

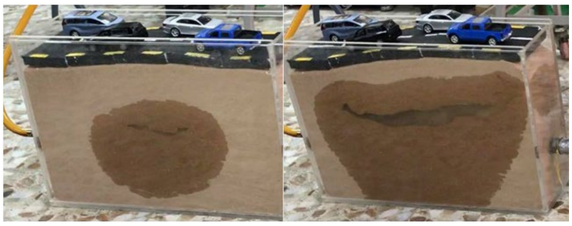

Fig. 8 Progress of sinkhole occurrence in the sand bed without stabilization.

7.2 Sinkhole Occurrence Time in the Improved Model

The second stage of testing involves applying the procedure described in subsection 7.1 to the improved model, which is the model with a sand bed stabilized with different percentages of ordinary Portland cement, as previously mentioned. The results show that stabilizing the sand bed with 4% and 5 % of ordinary Portland cement has a slight or no effect on the time of sinkhole occurrence, as the sand bed behaves similarly to the control one; the recorded time of sinkhole occurrence was (30 to 60) seconds. However, stabilizing the sand bed with 6% and 7% of ordinary Portland cement has a significant effect on the time of sinkhole occurrence, as it increases to reach 330 seconds. This time is about 11 times that of the control model case. This improvement can be attributed to the significant increase in the erosion resistance of the sand bed. The increase in erosion resistance can be due to two reasons. First, the presence of sufficient particles of Portland cement fills the voids in the soil, which obstructs the water flow in the sand bed structure. Second, the Portland cement provides an effective bond among the sand particles, which hold these particles together.

Figure 9 shows the progress of sinkhole occurrence in the stabilized sand bed. Nevertheless, stabilizing the sand bed with 8% Portland cement shows that the sand bed behaves as an impermeable layer, and the flow of water causes swelling in the soil without the occurrence of the sinkhole. This behavior can be attributed to the sufficiency and fineness of the Portland cement particles, which completely fill the voids in the soil, thereby increasing its density and hardness. These promising results reflect the great effect of the suitable percentage of Portland cement on the time of sinkhole occurrence in terms of its effectiveness in preventing the erosion of the sand bed beneath the road pavements. The relationship between the Portland cement content and the time of sinkhole occurrence is shown in Figure 10. From the observation of the sinkhole occurrence in the models, three main types were noted: collapse-sinkholes, subsidence-sinkholes, and solution-sinkholes. As expected, a subsidence-sinkhole occurred in the sand bed without stabilization. However, the solution-sinkhole occurs in a stabilized sand bed with (6% and 7%) of Portland cement. This behavior reflects the effect of Portland cement as a stabilizer on sinkhole type, as it increases the density and hardness of the soil as previously mentioned. Figure 11 shows the sinkhole occurrence in the stabilized sand bed after removal of the model of road pavements.

The application of Calcium lignosulphonate (CLS) and granite sand (GS) as sustainable stabilizers that may be mixed with clayey soils was examined in the study of [48]. The CLS dosages that were taken into consideration were 0.25%, 0.5%, 1%, and 1.5%, while the GS dosages were 30%, 40%, and 50%. The GS–CLS blended soil samples that were cured for 7 and 14 days were subjected to direct shear and consolidation testing. At an optimal dosage of 30% GS and 0.5% CLS, the modified stabilizers enhanced the consolidation properties and shear parameters. The cohesion and internal friction angles showed the greatest gains, at 84% and 163%, respectively.

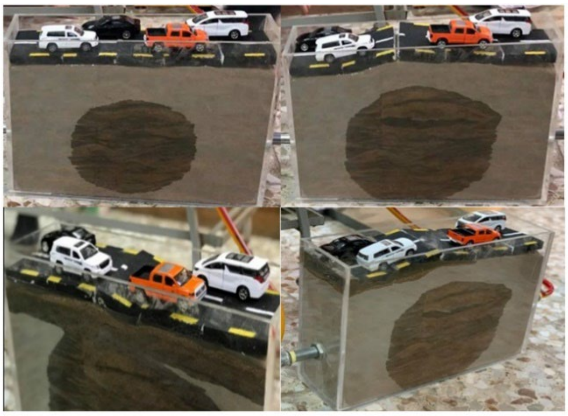

Fig.9 Progress of sinkhole occurrence in the stabilized sand bed.

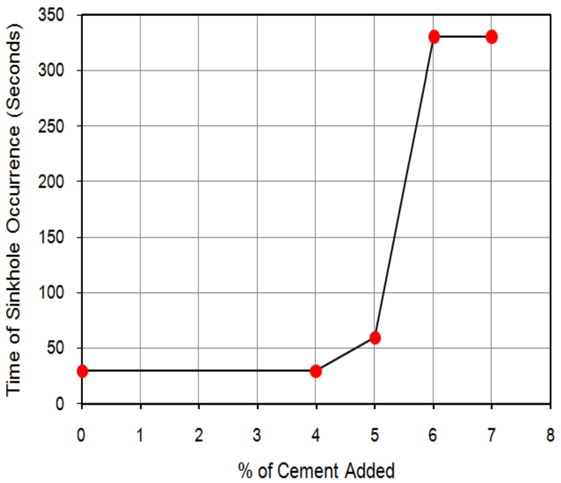

Fig.10 Relationship between cement content and time of sinkhole occurrence.

Fig.11 Sinkhole occurred in the stabilized sand bed.

8. CONCLUSIONS

The following conclusions are obtained from experimental work:

1. The sinkhole occurred in the sand bed of road pavements due to erosion and collapse of soil caused by water flowing through it.
2. Stabilization of the sand bed with Portland cement vitally minimizes the sinkhole hazard and increases the time of sinkhole occurrence in sandy soil through increasing the soil density and hardness, which increases its resistance to erosion.
3. The time of the sinkhole occurrence is approximately 30 seconds in the sand bed without stabilization based on the model. However, the time increases to about 330 seconds when the sand bed is stabilized with (6% and 7%) of Portland cement.
4. Stabilizing the sand bed with 8% Portland cement prevents the sinkhole occurrence, and the sand bed behaves as impermeable soil as the Portland cement particles entirely fill the voids in sand.
5. Stabilizing the sand bed with Portland cement affects the sinkhole type. A subsidence-sinkhole was observed in an unstabilized sand bed. However, a solution-sinkhole was observed in the sand bed stabilized with (6% and 7%) of Portland cement.
6. Portland cement is considered a good stabilizer for sandy soil; this material is cheap, available, and considered an economical method for field applications for practicing engineers for treating this case.

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