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(Research Article)

Case study of bearing capacity failure in a 4-story reinforced concrete building

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Abstract

This case history analyzes the bearing capacity failure of a 4-story reinforced concrete building in Benghazi, Libya, constructed in Fall 2000. The building has a plan area of 65 m^2 and is supported by an 80 cm thick raft foundation resting on collapsible sandy loess, which can lose shear strength when wet.

Several months before the building's failure, nearby construction work caused a broken pipeline, leading to significant water leakage. This moisture infiltrated the soil under the foundation, reducing its bearing capacity, particularly on the northern side. In winter 2002, the building began to tilt northward due to this reduced capacity, although inspections revealed no structural cracks, attributed to the rigidity of the raft foundation and reinforced concrete shear walls.

The paper discusses the geotechnical properties of the supporting soil and uses finite element analysis to show that the bearing pressures exceeded allowable limits under wet conditions, emphasizing the importance of moisture content in assessing soil stability. This case highlights the complexities of foundation design and the critical impact of environmental factors on soil behavior, advocating for thorough geotechnical assessments and ongoing monitoring of conditions around structural foundations.

Keywords: Collapsible soil; Loess; Bearing capacity; Case history

1. Introduction

This case history examines the bearing capacity failure of a 4-story reinforced concrete building located in Benghazi, Libya. Constructed in Fall 2000, the building features a total plan area of 65 m^2 and is supported by an 80 cm thick raft foundation. The building rests on a profile of sandy loess, a soil type that has been categorized in the literature as collapsible due to its significant decrease in shear strength when subjected to moisture.

The sandy loess layer beneath the building extends more than 6 meters below the foundation level, a characteristic typical of the lithological profile in this region of Benghazi [1, 2]. Given the nature of this soil, its engineering properties can be drastically altered by changes in moisture content. This fact is critical to understanding the events leading to the building's failure.

Several months prior to the sudden failure of the building, a local construction company began work on infrastructure in the vicinity. During this process, a broken pipeline resulted in substantial water leakage. Soil samples collected from nearby excavated test pits revealed that this water infiltrated the soil beneath the building's foundation. This infiltration led to a marked decrease in the soil's bearing capacity, particularly on the northern side of the building.

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In winter 2002. as a result of the reduced bearing capacity, the structure experienced tilting predominantly towards the north. Despite this significant movement, inspections of the structural elements revealed no cracks or signs of distress. This observation can be attributed to the rigidity of the raft foundation and the reinforced concrete shear walls on the ground floor, which effectively maintained the integrity of the structure even as it settled unevenly.

The paper discusses the geotechnical characteristics of the supporting soil, alongside a description of the building's construction. It further analyzes the induced bearing pressures on the supporting soil using finite element analysis. This analysis indicated that the bearing pressures exceeded the allowable limits established by Terzaghi's bearing capacity equation, particularly under wet conditions[6,7,10]. This discrepancy underscores the importance of considering changes in moisture content when assessing soil stability and structural integrity.

This case history serves as a crucial reminder of the complexities involved in foundation design and the significant impact of environmental factors on soil behavior. The interaction between construction activities, soil characteristics, and moisture conditions can lead to catastrophic failures if not adequately addressed in the planning and engineering processes. The findings emphasize the need for thorough geotechnical assessments and continuous monitoring of environmental conditions in the vicinity of structural foundations.

2. Impact of Tilt on Structural Stability

Despite a significant tilt towards the north, a detailed inspection of the structure revealed no visible cracks or deformation. This resilience is attributed to the building's rigid foundation and well-designed reinforced concrete facade walls, which allowed for rotation without excessive stress on the superstructure.

Moreover, the slenderness shape of the building and the asymmetry of the raft foundation increases the overturning moment, reducing stability and making it more vulnerable to potential overturning events. This precarious situation required immediate action to ensure safety, especially while awaiting further evaluation or demolition.

To address the instability, 100 kN of sandbags were evenly placed on all floors, particularly on the south side, to help mitigate the tilt and improve stability. The building was also continuously monitored using surveying equipment to detect any additional movement, ensuring the safety of nearby personnel until a decision about demolition could be reached. This proactive strategy underscores the significance of thoughtful weight distribution and ongoing monitoring in managing compromised structures.

3. Soil Horizons and Their Attributes

The geological map of Libya's Benghazi sheet shows that the coastal area features a distinct layer of beach sand extending inland, influenced by sea-origin winds that have formed sand dunes. This sandy terrain primarily consists of fine-grained, poorly graded calcareous material, affecting its stability. Alongside the beach sand, red eolian silt from southern regions mixes with the sand, creating a unique soil texture. Beneath this sandy layer lies a substantial limestone rock layer, crucial for geological stability.

To evaluate the soil properties for the tilted building, traditional borehole methods were deemed risky, prompting the excavation of two test pits as shown in Fig 1 (test pit 1 at 2.0 meters and test pit 2 at 3.2 meters). Undisturbed soil samples were collected using Shelby tubes for analysis. Tests conducted as per ASTM standards, included soil classification via the Unified Soil Classification System (USCS), moisture content, specific gravity, liquid limit, plastic limit, plasticity index, cohesion, angle of internal friction, and unit weight [3,4,8,9]. Test results are summarized in Table 1. The findings indicated that the upper soil layer comprises reddish-brown, loose to medium-dense sandy loess.

Collapsible soils, like the aeolian loess in this region, are particularly susceptible to instability when saturated or disturbed, characterized by low plasticity and low dry densities. In dry conditions, they exhibit reasonable strength. A graph illustrating the relationship between limiting dry unit weights and liquid limits aids in identifying collapsible soils. If a soil sample's natural dry unit weight is below the limiting line, it is likely collapsible. This understanding is crucial for predicting construction issues and ensuring structural stability.

Overall, the soil in this area is classified as collapsible, highlighting the necessity for thorough geotechnical investigations and engineering measures in foundation design to mitigate risks associated with soil collapse and ensure long-term stability.

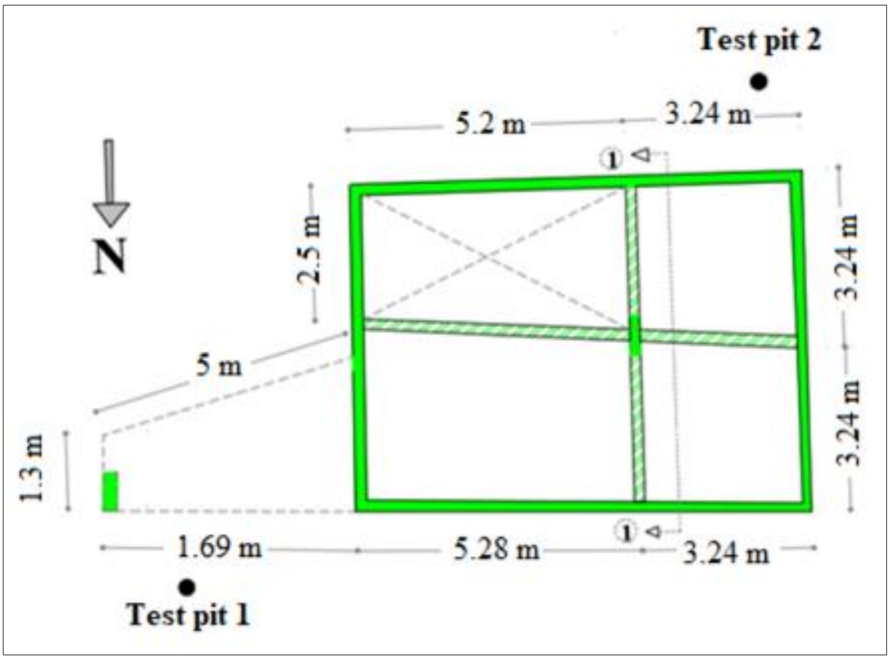

Figure 1 Plan of ground floor

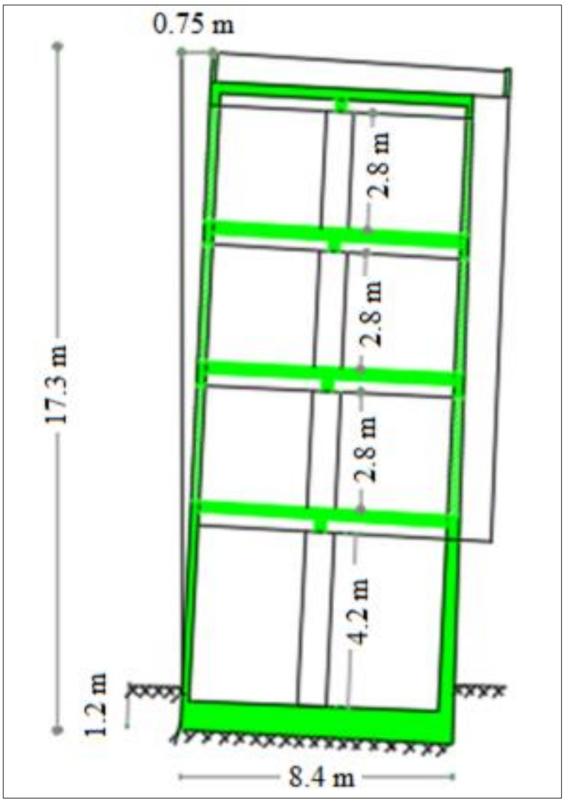

Figure 2 Cross section 1-1 after building tilt

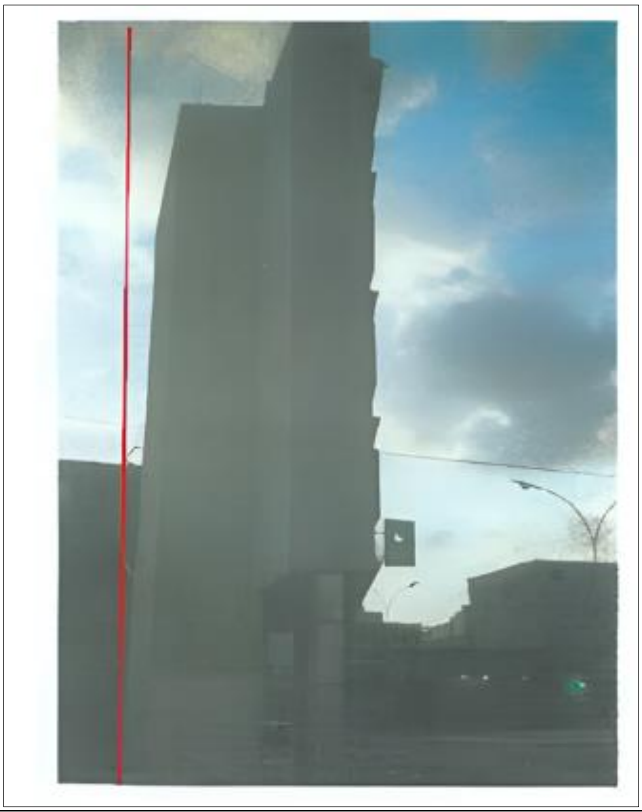

Figure 3 General view of the building after tilt

Table 1 Soil properties and classification

TB No	Sample No	Depth m	MC %	LL %	PL %	PI %	ϕ	C	γ	USCS
1	1	0.5	16.1	19.2	16.5	2.7	13.3	8.1	17.6	Poorly graded sand with silt (SP-SM)
	2	1.2	16.8	20.3	17.5	2.8				
	3	2.0	16.6	18.8	16.3	2.5				
2	1	0.5	8.8	20.2	18.8	1.4	26.8	15.8	17.3	
	2	1.5	10.1	19.6	17.4	2.2				
	3	2.5	11.3	20.5	18.5	2.0				

G = specific gravity=2.7, γ= bulck unt weight, ϕ in degrees

Typical collapsible soils are usually lightly colored, low in plasticity, with liquid limits under 45 and plasticity indices below 25. They also tend to have relatively low dry densities. This type of aeolian loess often demonstrates collapsing behavior. Generally, these soils exhibit low shear strength, but they possess significant strength and stiffness when dry.

Fig 5 displays a graph of limiting dry unit weights plotted against their corresponding liquid limits. For any given soil, if the natural dry unit weight is below the limiting line, it is likely to be collapsible, as noted by Holtz and Hilf [5]. The chart clearly indicates that the supporting soil can be classified as collapsible based on its characteristics.

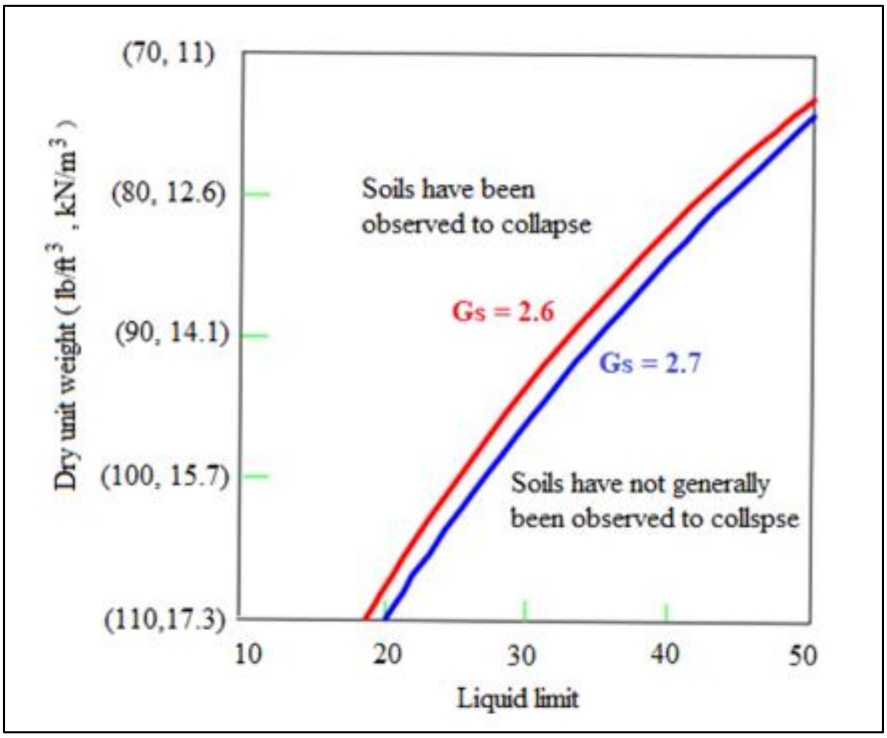

Figure 4 Collapsible and non collapsible loess

4. Disturbance to Supporting Soil

In Spring 2002, a local construction company began infrastructure work on Al-Mehdawi Street, including sewage and water pipeline installation and manhole construction up to 2 meters deep, located near an existing building's foundation. This was done without necessary precautions, posing significant risks to the building's structural integrity.

During construction, which ended in Fall 2002, witnesses reported severe water leakage and flooding, leading to destabilized soil conditions. Test results from test pit 1 indicated about 80% moisture saturation, while test pit 2 showed only damp conditions. This difference in moisture content critically affected soil behavior, with test pit 1 exhibiting reduced shear strength due to saturation, increasing the risk of failure.

The disturbances from the construction activities adversely affected the supporting loess, causing localized shear failure beneath the building's north side. These events highlight the need for careful planning and protective measures in construction near existing structures. The resulting soil saturation not only jeopardized the stability of the supporting soil but also raised concerns about the building's long-term viability. Proper geotechnical assessments and construction practices are essential to prevent such issues and ensure structural safety.

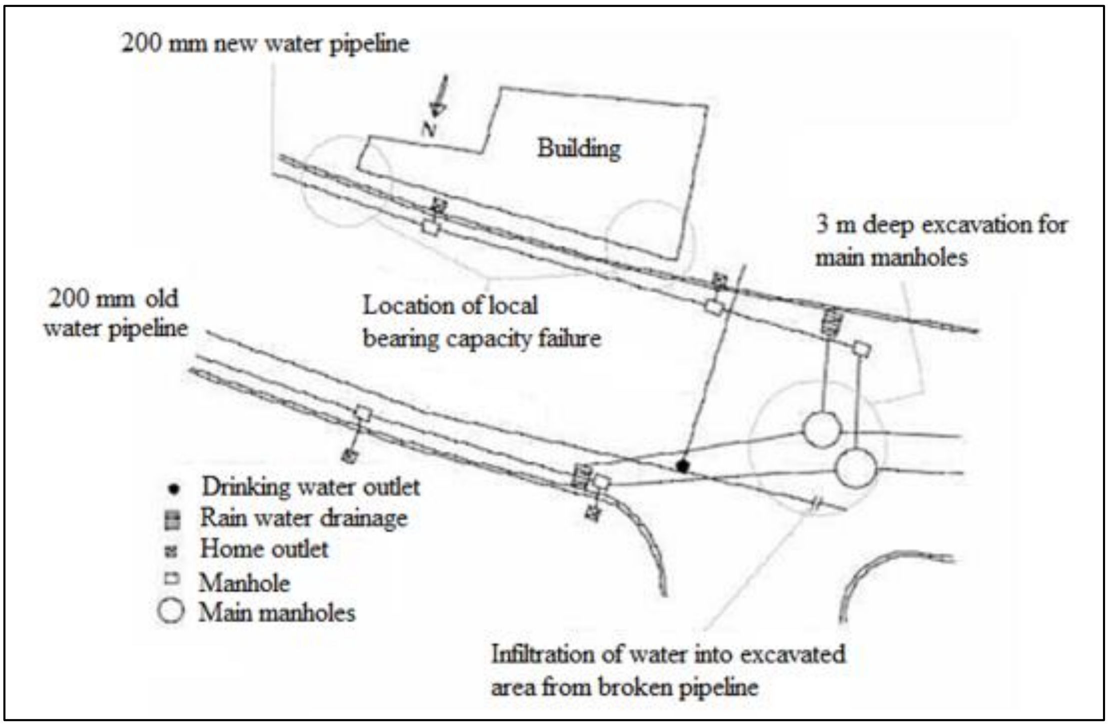

Figure 5 Location of building, the excavation for infrastructure and broken old pipeline

5. Load-Carrying Capacity of supporting soil layers

The bearing capacity of soil is crucial for the stability and safety of structures. Terzaghi's equation, a standard method for assessing shallow foundation capacity, was used in this evaluation, relying on key soil parameters such as moisture content, specific gravity, and shear strength.

The analysis found a net ultimate bearing capacity of 147 kN/m^2 at test pit 1, compared to 300 kN/m^2 at test pit 2, highlighting a nearly 50% decrease at test pit 1 due to higher moisture content. This saturation can significantly impair load-bearing ability, emphasizing the need to consider environmental factors in construction.

Correlation data showed that the service pressure at test pit 1 exceeds its bearing capacity, indicating a risk of structural failure, while test pit 2 remains safely within limits. To mitigate risks associated with collapsible soils, effective drainage, controlled construction activities, and careful excavation practices are essential. Implementing these measures can enhance the safety and longevity of structures on challenging soil types.

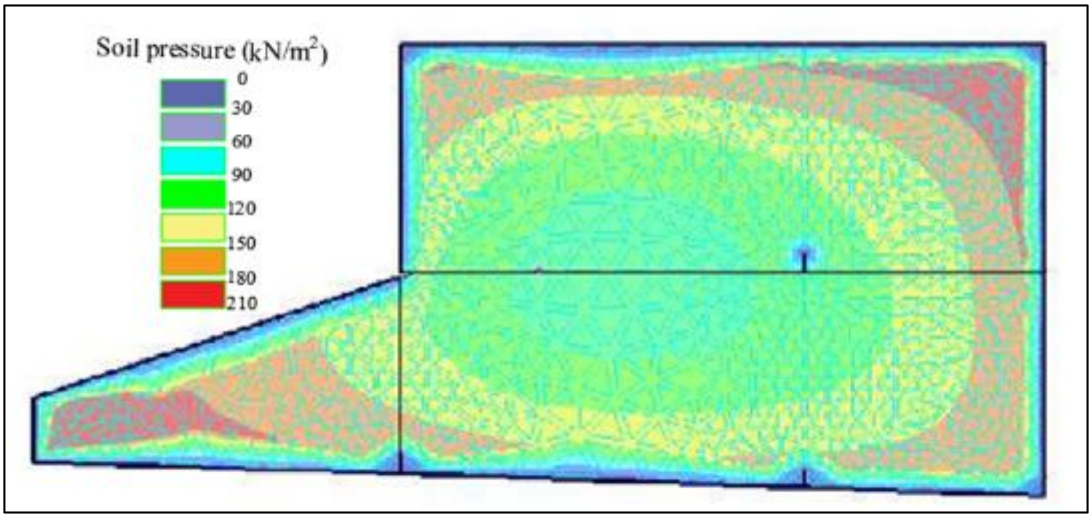

Figure 6 Soil pressure underneath foundation (finite element method solution)

6. Conclusion

The supporting soil of the tilted building consists mainly of sandy loess, which is prone to losing shear strength when saturated. Significant water leakage during nearby infrastructure construction led to wet conditions that compromised the soil's structural integrity, increasing the risk of failure under the foundation's load.

Excavation work near the building foundations, reaching depths of 1 to 3 meters, was performed without necessary precautions, further reducing the soil's shear strength by disrupting its natural structure and allowing more water to infiltrate. This lack of protective measures destabilized the soil and worsened conditions for potential failure. Excavation near buildings on sandy or silty soils should be approached with extreme caution, implementing protective measures like sheet piling to maintain soil stability and prevent disruption. Additionally, effective drainage systems should be established around the foundation to minimize water infiltration, thereby reducing the risk of saturation.

The asymmetrical shape of the building's foundation resulted in concentrated stresses at the edges, which can lead to localized failures in already compromised soils. Proper design considerations are crucial to ensure the foundation can distribute loads without exceeding the soil's bearing capacity.

In summary, understanding the relationship between soil properties, construction practices, and foundation design is vital for preventing similar failures in future projects. By following these recommended precautions, engineers can improve the safety and longevity of foundations built on challenging soil types.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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