www.ijecs.in
International Journal Of Engineering And Computer Science
Volume 13 Issue 10 October 2024, Page No. 26529-26533
ISSN: 2319-7242 DOI: 10.18535/ijecs/v13i10.4918

Behavior of Slab-on-Grade Resting on Expansive Soil

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Abstract

This paper discusses a case study of a residential building in Benghazi that features slab-on-grade foundations supported by expansive soils. Although such structures are uncommon in the area, they can suffer serious damage due to volumetric changes in the soil caused by wetting and drying. The building has a total plan area of 200 m², with tie beams located 1.2 m above the formation level, and expansive soil used as backfill. After being moistened and lightly compacted, 100 mm thick concrete slabs were poured between the tie beams, resulting in varying slab sizes. Following a month of heavy rainfall, significant cracking—longitudinal, diagonal, and warping-occurred in the slabs due to uneven deformation from the expansive soil. The paper includes photographs of these deformations and cracks, along with an analysis of the geotechnical properties of the expansive soil, including its swelling and shrinking characteristics. It also employs an approach to predict the pressure exerted on the slabs due to differential heave.

Key Words: Expansive soil, Swell potential, differential heave

1. Introduction

Although not common in Benghazi, there have been a few instances of slab-on-grade structures supported by expansive soils. These slabs experience significant deformations due to the volumetric changes that occur in these soils when they undergo wetting and drying, leading to severe damage to the structures. This paper presents a case study involving the foundations of a residential building with a total plan area of 200 m², featuring tie beams positioned 1.2 m above the formation level. Expansive soil was used as backfill to the ground floor level. After being moistened and lightly compacted, plain concrete slabs with a thickness of 100 mm were poured between the tie beams, resulting in various slab sizes.

Following a month of heavy rainfall, a pattern of extensive cracks, including longitudinal, diagonal, and warping cracks, appeared on the slabs due to the significant uneven deformation of the expansive soil. This paper includes photographs illustrating the pronounced deformations and the different types of cracks that developed. Additionally, it details the geotechnical properties of the expansive soil, including its swelling and shrinking potential, and applies two distinct methods to predict the pressure exerted on the slabs as a result of differential heave.

2. Overview of the Case

In winter 2016, a local contractor began constructing a one-story residential building with a total plan area of 200 m², utilizing conventional reinforced concrete (RC). The underlying soil layer is recognized for its high bearing capacity, consisting of a mix of limestone rock and hard, non-expansive clay. The footings were designed at 1.5 x 1.5 m with a thickness of 0.4 m, while the columns measured 0.2 x 0.4 m.

The contractor first installed the footings and then built three layers of cement blocks measuring 20 x 20 x 40 cm, followed by the construction of 20 x 40 cm RC tie beams and column necks, as illustrated in Figures 1 and 2. This phase was completed in winter 2017. The contractor then imported fill material composed of expansive clay, unaware of its potential adverse effects on the foundation system. This fill was lightly compacted within the boundaries defined by the cement blocks and tie beams. Subsequently, 120 plain concrete slabs on grade were constructed, which were designed to be structurally independent from the tie beams.

In February 2017, after a month of heavy rainfall, the expansive clay began to swell, causing differential upward movement of the slabs, with the maximum displacement reaching 120 mm at the center and nearly zero at the corners. The authors conducted regular site visits to assess the damage to the structure and gather information about both the supporting soil and the fill material used. This included inspecting nearby buildings and the area's soil profile. No damage from settlement or heave was observed in the surrounding buildings. Based on their experience, the authors confirmed the high bearing capacity of the underlying layer. These observations indicated that the primary cause of the cracks in the building was the heaving of the imported fill material. To investigate the characteristics and swelling potential of this soil, the authors collected three representative samples from various locations, as shown in Figure 1. The samples were promptly transported to the civil engineering department's laboratories for testing. Once there, the soil samples were air-dried, crushed, and sieved through a 2 µm sieve, then stored in a sealed container for several days to equalize their moisture content prior to the testing program.

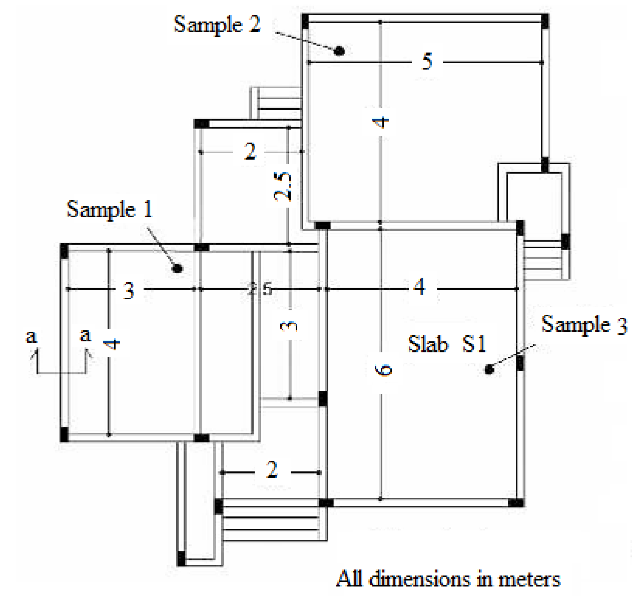

Fig 1. General layout of slabs on ground

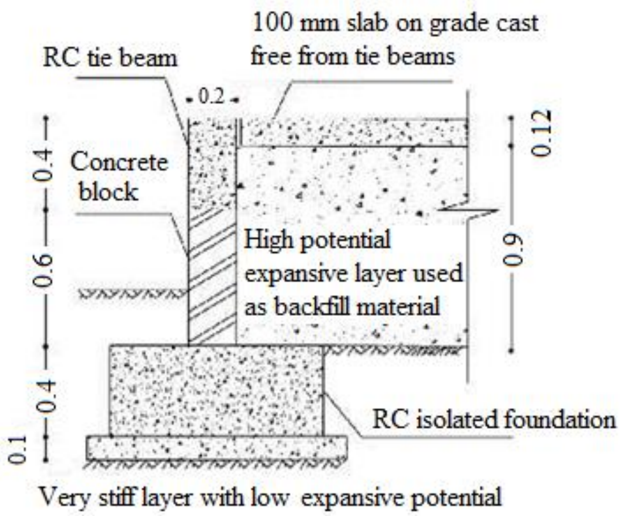

Fig 2. Section a-a

3. Physical Properties of Soil

The laboratory testing program includes visual inspections and classification tests essential for soil identification. Tests on the collected representative samples are conducted in accordance with current ASTM standards (Section 4 Vol. 04.08) [1]. The analysis includes particle size distribution, Atterberg limits, and specific gravity. All test results are compiled in Table 1. Based on the findings, the fill material can be classified according to Casagrande [2] as inorganic clay with high plasticity (CH), and according to Unified Soil Classification System (USCS) as fat clay (CH). Some types of clay may be positioned above or below the A-line, making it impossible to determine their expansive properties solely based on their location on the plasticity chart.

Table 1. Physical properties of soil samples

Sample No	Specific gravity	Moisture content %	Liquid Limit (LL)%	Plastic limit (PL) %	Plasticity index (PI) %	Colloids %
1	2.63	14.2	78	30	48	26
2	2.68	14.8	80	32	48	26
3	2.61	13.0	81	34	47	26
Average	2.64	14.0	79.7	32.0	47.7	26.0

4. Swell Potential

The expansivity of the fill material is evaluated using several parameters, including its liquid limit, plasticity index, activity, free swell, and oedometer tests [1,3,4,7,9]. The plasticity index is calculated as the difference between the liquid limit and the plastic limit. Soil activity is determined by the percentage of soil particles that pass through a 2 µm sieve. The free swell test [4] involves adding 100 ml of oven-dried soil, which has passed through a 425 µm sieve, into a 100 ml measuring cylinder filled with distilled water. The volume of the soil is recorded after it settles at the bottom of the tube (typically between 3 to 24 hours). Free swell is defined as the increase in soil volume upon immersion in water, expressed as a percentage of the initial volume. The oedometer test [4] requires placing the dry specimen in a consolidometer, which is then inundated with distilled water. A vertical confining pressure of 7.0 kPa is applied, and deformation is monitored for 24 hours or until the deformation rate falls below 0.005 mm/h, with a minimum recording time of 3 hours. The percentage of volume expansion is calculated as the change in sample height relative to the initial height.

The American Society for Testing and Materials (ASTM) [1] outlines a procedure similar to that of Holtz & Gibbs [4], with the sample mixed to approximately 50% saturation and compacted in two layers within the ring. The expansion index is calculated as 1000 times the change in height divided by the initial height. Table 3 presents the swell potential of the soil in relation to its various properties, as determined from the aforementioned tests. Table 4 details the swell potential of the tested fill material based on the criteria established in Table 3.

Table 2. Sweel potential for different soil characteristics after Holtz and Gibbs [4]

Colloidal %	LL %	PI%	Free swll index %	% expansion in oedometer [4]	Expansion index	Degree of expansion
-	-	-	-		0.21	Very low
< 15	< 39	< 18	< 50	< 10	21-50	Low
13-23	39-50	15-28	50-100	10-20	51-90	Medium
20-28	50-63	25-41	100-200	20-30	91-130	High
> 28	> 63	> 35	> 200	> 30	> 130	Very high

Table 3. Expansion potential of the soil samples

Sample No	LL %	PI%	Colloidal %	Free swll index %	% expansion in oedometer [4]	Expansion index
1	78 (VH)	48 (VH)	26 (H)	160 (H)	22 (H)	125 (H)
2	80(VH)	48(VH)	26 (H)	163 (H)	23 (H)	123 (H)
3	81(VH)	47(VH)	26 (H)	170 (H)	24 (H)	120 (H)

VH = (Very high) , H = (High)

5. Distress to Slabs on Grade

The slabs on grade were built in January 2017 without accounting for the uplift forces caused by soil heaving. Following a month of heavy rainfall, uneven movement of the expansive fill material occurred, with the most significant uplift at the center of the slabs and minimal movement at the corners. This differential heaving of up to 120 mm created substantial stresses that exceeded allowable limits, resulting in typical patterns of wide cracks in both one-way and two-way slabs. At the corners of the two-way slabs, torsional cracks were observed due to warping effects, as illustrated in Figures 3, 4, and 5. To estimate the pressure exerted by the expansive clay on the slabs, an approach described in [5] is applied, using the two-way slab S3 as a representative case. Nayak and Christensen state that the pressure caused by the expansive clay can be calculated using the following equation:

$$P_p = [(0.03583)PI^{1.1}(C/\omega)^2 + 3.791]6.895\ kpa \qquad (1)$$

$$PI = plasticity\ index, C = colloidal\ \%, \omega = moisture\ conten\ \%$$

Substituting for PI=37, C=26, ω = 14 in equation (1)

$$P_p = [(0.03583)37^{1.1}(26/14)^2 + 3.791]6.895 = 71.38\ kpa$$

Fig 3. Typical crack pattern of one- and two-way slabs

Fig 4. Cracks at the corners of slab S1 due to warping

Fig 5. Differential heaving of slab S1

6. Conclusions

This case study illustrates the harmful effects that expansive soils can have on supported structures. Significant differential heaving of up to 120 mm was observed in the slabs on grade. This differential heaving may be linked to the friction resistance resulting from adhesion between the soil and the perimeter walls, which might not have been accurately represented in laboratory tests. The authors believe that the findings from this case study better reflect the soil behavior in real-world conditions, serving as a form of large-scale testing for this type of expansive soil. The results are highly valuable for engineering applications when dealing with such soils.

The authors note that while typical indicators like liquid limit, plasticity index, and activity often overestimate soil expansivity compared to oedometer test results, in this case, these values provide a more realistic potential for expansivity when compared to the oedometer findings. Additionally, the swell pressure predictions by Nayak and Christensen [5] were used to estimate the pressure from soil swelling, which was significant enough to cause cracks in the slab on grade.

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