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Damage Assessment and Strengthening of R/C Building Constructed on Expansive Soils

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ABSTRACT: This paper presents an experience in assessment and strengthening of a R/C building carried out in Sudan during the last year. A four-story R/C framed hospital building was constructed five years ago in the middle of Sudan, by the White Nile River. Due to differential upheaval movement of the underneath expansive clay soils (15-25cm), the building had experienced serious instability problems and severe structural cracks. A comprehensive assessment of the building skeleton including geotechnical investigation, DT and NDT methods revealed the need of five different strengthening and retrofitting techniques; there are, transformation of foundation system from isolated footings to strap foundation to increase the stiffness and rigidity of footings, concrete jacketing of basement floor columns, metal jacketing of the second floor columns, construction of shear walls to enhance the stability of the building and finally CFRP laminates for strengthening of basement floor cover slab. The building had been monitored during and after completion of strengthening and retrofitting works to measure any movements during the last year rainy season. Measurements revealed the efficiency of implemented strengthening and retrofitting techniques.

Keywords: Damage Assessment, Expansive soil, Strengthening, Carbon Fiber Polymers

1. INTRODUCTION

Kosti Military Hospital is a four-story R/C framed building constructed five years ago in Kosti city in the middle of Sudan, by the White Nile River (Fig. 1). The building was designed and constructed over an area of 1350 sq. m to provide advanced medical services for the citizens of the White Nile state. Because of inadequate geotechnical investigation prior to construction, the building was constructed in an area of highly potential expansive soils, without any special considerations for this type of soil.

The building is a R/C frame type building, the frame is a column-flat slab type, supported on isolated footings. All parts of the building are used as rooms for doctors and hospital wards for patients.

As reported by the local governmental authorities, a few years after completion of construction of the hospital, the building started to suffer from cracks and visible movements of the expansion joints. Lack of routine inspection and maintenance and poor previous rehabilitation works had led to continuous and fast development of cracks and movements.

Figure 1. Location of Kosti Military Hospital (Google Earth).

2. LITERATURE REVIEW

Expansive soils are soils that have potential for swelling and shrinkage under changing moisture conditions. The volume change resulting from swelling and shrinking causes damages to structures founded on them. The expansive soil area includes nearly all the agricultural schemes and most of the development projects in Sudan and covers about 40% of the total area of Sudan (Osman and Charlie 1983).

Damages of structures caused by expansive soils have been reported from different locations in the clay plain (Lates et al 1983). The damages include buildings, roads, factories, hydraulic structures etc., and were attributed to lack of proper identification and classification of expansive soils and improper design of the foundations of the damaged structures (Elsharief, 2009).

3. ASSESSMENT PROGRAM AND RESULTS

A comprehensive structural-geotechnical assessment program was designed and implemented. The following sections discuss the steps and findings of this program.

3.1 Visual inspection & excavations

A careful visual inspection was performed for the structural members of the building, it was clear from the inspection that the building was unstable since expansion joints were undergone excessive rotations (Fig. 2) and severe structural cracks were seen in some columns. The maximum opening of the expansion joints at the top of the building was about 13cm which indicates that the building had undergone a total rotation of 0.67 degrees. Fortunately, foundations were not affected by these movements. A number of internal and external footings were excavated for visual inspection and measurements. Excavation has been done on some of the foundations with great difficulty because of the saturation of the clay soil, and in some cases, water gushed profusely about the footings (Fig.3). Because of the upheaval movement of the soils, and probably due to the weakness of concretes some of the basement columns were buckled and crushed (Fig. 4). All sanitation systems of the building were damaged. Leakage and accumulation of waste water and chemicals (waste of hospital's laboratories) around the columns and in contact with the basement cover slab had caused deterioration and corrosion of reinforcement of columns and slabs (Fig. 5).

Figure 2. Opening at expansion joint.

Figure 3. Dewatering during excavation.

Figure 4. One of buckled basement columns

Figure 5. Corrosion of reinforcement of basement slab and columns

3.2 Detailed geotechnical investigation

3.2.1 Drilling of Boreholes

Three boreholes were drilled, two of them to about 10.0m and the third one to 15.0m depth, in different locations around the building. The boreholes were drilled using a rotary soil mechanics drilling rig. Disturbed soil samples were collected at 1-m meter intervals for visual inspection and classification tests. Undisturbed samples were taken at 1.5-m intervals from the cohesive soil. The standard Penetration Test (SPT) was performed in silt or sand layers or whenever there was difficulty in getting undisturbed soil samples. The SPT was performed by driving an open tube sampler (50mm O.D.) by the blows of a standard automatic hammer weighing 64kg and falling freely from a height of 760mm. The number of blows required to give tube penetration of 300mm was taken as SPT-N value.

3.2.2 Excavation of Test Pits

Three test pits were excavated manually to about 4.0m at different locations around the building. The disturbed soil samples were collected at each meter interval for visual inspection and laboratory testing.

3.2.3 Groundwater

No groundwater was observed during the drilling of boreholes in this site. It is expected to be far below the effective zone of the foundations.

3.3.4 Soil Conditions

The soil profile for the two boreholes and test pits is shown in Appendix (A). The three boreholes showed relatively similar soil stratification consisted of dark brown silty clay of high plasticity (CH) and dark brown to yellowish greyish very loose to medium dense clayey sand (SC) at the top 4.0m to 5.5m. Below this alternative layers of very stiff brown low plastic silty clay (CL) and very stiff brown low plastic silt (ML) and very stiff dark to light brown highly plastic silty clay (CH) were encountered down to the bottom of boreholes at 10.0m and 15.0m depths.

Test pits soil profile showed one layer of dark to light brown silty clay of high plasticity (CH) extending down to the bottom of test pits at 4.0m depth.

3.2.5 Laboratory Testing

Laboratory tests were performed on a number of disturbed and undisturbed soil samples. The tests included Atterberg limits, grain size analysis, natural moisture content, UU triaxial test, consolidation test, swelling pressure test and chemical tests. The procedures followed were in general conformance with those recommended in the British Standard BS 1377 (1990). Soils were classified according to the Unified Soil Classification System (USCS).

3.2.5.1 Classification Tests

The objective of these tests was to reveal soil types encountered at different depths of the boreholes. Tests carried out included Atterberg limits, grain size analysis and natural moisture content. These classification tests confirmed the soil profile described in subsection 3.5.

3.2.5.2 Atterberg Limits

The tests were carried out on clayey soil samples taken from different depths. The results gave liquid limit values ranging between 29% to 85% and plasticity index values between11% to 60%. This indicated high swell potential for the clayey soil at the present site.

3.2.5.3 Grain Size Distribution

The grain size distribution of the soil samples was determined in the laboratory. The results of this test with combination of Atterberg limits test results were used to assess the soil types according to the Unified Soil Classification System (USCS).

3.2.5.4 Natural Moisture Content

The natural moisture content was determined from undisturbed samples and by weighting the disturbed samples obtained from SPT sampler in the field and then the test was continued in the laboratory.

3.2.5.5 UU-Triaxial Test

The undrained unconsolidated (UU) triaxial test was conducted to measure the shear strength parameters of the soil. The average measured shear parameters (Ø & C) were 9.33° and 45.93 kPa respectively.

3.2.5.6 Consolidation Tests

Consolidation tests provide information for use in evaluating the compressibility of the soils and estimating the settlement of foundations established on these soils. The consolidation tests were performed on undisturbed clayey samples. First, the swelling pressure test was conducted on the samples. Then the samples were loaded beyond the swelling pressure to allow consolidation to proceed.

3.2.5.7 Swelling Pressure Test

The swelling pressure tests were conducted on undisturbed soil samples. The volume of the soil was kept constant in an oedometer cell, while the soil was saturated with water during the test. The results are shown in Table 1 below. The results reflected low swelling pressures. This is due to high moisture content of these samples, usually high swelling pressures depend on high moisture content deficiency. Also the soil samples may be subjected to some disturbance during mobilization.

Table 1: Swelling Pressure Test Results

B.H. No.	Depth (m)	Swelling Pressure (kN/m^2)	Initial Moisture Content (%)	Final Moisture Content (%)	Soil Type According to USCS
1	1.5	0	29.05	33.68	CH
1	3.0	20	19.05	23.23	SC
2	3.0	20	21.92	24.80	SC
3	3.0	20	23.70	24.52	CH

3.2.5.8 Chemical Tests

Chemical tests were performed according to BS 1377,1990-2 on two soil samples and one water sample to determine chloride content, sulphate content and the pH value. The results are shown in Table 2 below. The results indicated alkaline soil and water of low contents of chloride and sulphate. Therefore, the building foundations are not expected to be affected by these low contents of chemical salts.

Table 2: Chemical Test Results

Sample No.	Sample Type	Location	Depth (m)	Chloride (%)	Sulphate (%)	pH
1	Soil	B.H. 2	2.0	0.2142	0.2513	5.27
2	Soil	B.H. 3	2.0	0.2213	0.1642	4.34
3	Water	-	-	0.2057	0.2043	5.10

3.2.6 Analysis of geotechnical results

It is evident from the soil profile that the top 4.0 to 5.5m layer of highly plastic silty clay (CH) and very loose to medium dense clayey sand (SC) was encountered. This is underlained by alternative layers of very stiff low plastic silty clay (CL) and very stiff low plastic silt (ML) and very stiff highly plastic silty clay (CH) extending down to the end of boreholes. No groundwater was encountered in boreholes during this investigation; it is expected to be far below the effective zone of the foundations. Although low values of swelling pressures were measured in the laboratory, the index properties of the investigated soil indicated high swelling potential for the clayey layers. The SPT N-values generally indicated soft to very stiff clays and very loose to medium dense sands, which reflects low to medium shear strength for the soil at the present site. The chemical test results showed acidic soils of high contents of harmful chemical salts. The building was constructed on isolated footing foundations placed at about 2.9-m depth below the ground surface level. At this depth the bearing capacity of the soil recommended to be 140 kN/m2.

The bearing capacity determination was based on soil classification and SPT results. Use SPT-N average value below the foundation level and maximum footing width of 4.5m for permissible settlement of 25mm at (Terzaghi and Peck Chart, Bowles, 1994).

3.3 Field and Lab. Testing of concretes

A combination of destructive core tests, ultrasonic pulse velocity and rebound hammer tests was performed to find the compressive strength and to assess the quality and uniformity of the concretes of the building.

3.3.1 Core test results

Six core specimens were extracted from the foundations and floor slabs using an electrical type core cutting machine. All core specimens were thoroughly inspected and prepared for the compression test. Visual inspection of the core specimens before compression tests revealed the following:

- Entrapped air voids were noticed in the core specimens which indicated that the concretes of different structural elements of the building were not properly vibrated and compacted.
- The concrete mix was found to be over sanded (i.e. the amount of cement was less than required).
- Many decayed aggregate particles were were noticed in the mix. Also the maximum size of aggregate found was less than 15mm and the grading observed was not uniform.
- After visual inspection the specimens were prepared and tested under uniaxial compression load, the average value of the strength results was 14N/mm2.

3.3.2 Ultrasonic pulse velocity tests results

Ultrasound pulse velocity was performed to assess the quality of concretes of columns and to evaluate the degree of compaction.

Ultrasonic pulse velocity test is usually performed for assessing the quality and integrity of concrete by passing ultrasound waves through the specimen or reinforced concrete member under test, This test can also be used to determine the presence of honeycombs, voids, cracks etc. The main strength of the method is in finding general changes in condition such as areas of weak concrete in a generally sound concrete. At the same time, the UPV technique is not always practicable in testing sound concrete. Especially in investigation of crack depth, it is ineffective if the crack is water filled. The performance is also often poor in very rough surfaces. Sometimes good contact requires the use of a coupling gel between the transducers and the structure. Sound energy above the audible frequency of 16,000 Hz is designated as ultrasonic (Song & Sarthawathy, 2007). The instrument consists of transmitter and receiver (two probes). The time of travel for the wave to pass from the transmitter to the receiver when kept opposite to each other is recorded in the ultrasonic instrument. The distance between the two probes (path length) can be physically measured. Hence ultrasonic pulse velocity = path length/time. This velocity in concrete can be related to its compressive strength. Different approaches have been published for classification of concrete quality based on the pulse velocity. In this study the Whitehurst (5) classification method was adopted. According to the Whitehurst classification method, the quality of concretes of the columns of different floors was found to be varying between poor (pulse velocity < 3Km/sec.) and doubtful (pulse velocity < 3.5 km/sec.), whereas some points were found to indicate very poor quality (pulse velocity < 2.5km/sec.).

3.3.3 Rebound hammer test results

This test is basically a surface hardness test and should be used only where the surface has not carbonated as the results tend to be very high and unrealistic on carbonated surfaces. It is also possible to evaluate the degree of uniformity of concrete through statistical analysis of test results (ACI, 1195).

The building under consideration was constructed four years ago so little carbonation effect is possible. Rebound hammer values obtained from different columns at different floor levels showed low surface hardness (average rebound number 14) and high variability (standard deviation of rebound number 12.5) in the properties of concretes of columns.

3.4 Structural analysis

A structural analysis of the concrete frame was performed based on the actual dimensions of the building and main findings of field and laboratory tests results. The structural analysis showed that all the basement columns, second floor columns and the basement cover slab were stressed beyond the ultimate limits. While the bearing capacity of foundations were found to far less than the applied axial and bending forces of basement columns, the uplift pressures of soil didn't affect the punching shear strength of foundations.

4. SUGGESTED STRENGTHENING METHODS

After a comparative socio-economic feasibility study of the two options of demolishing and strengthening, it was decided by the different consultancies and authorities involved to strengthen the building. Time was critical since the hospital building had to be restored to provide medical services. Based on the findings of the assessment program, it was clear that the building required faster major and minor strengthening and retrofitting. It was also critical for building and strengthening works to be implemented before the rainy season, so as to prevent any moisture variation in soils and to stop any further movement of the building skeleton. Five different major structural strengthening techniques were suggested and implemented.

4.1 Modification of foundation system

It was suggested that the isolated footings of the foundation to be strengthened and connected using reinforced concrete beams fixed on top of footings. This will increase the stiffness and tightness of the foundation; hence redistribute the bearing stresses and the non-uniform uplift soil pressures. Also this will eliminate any stress concentrations and prevent any further increase in differential movement of underneath soils (Fig.6). This was performed after restoring the affected footings to their initial levels. Soils beneath the footings affected by the uplift pressures were removed and the footings were allowed to restore gradually to the initial levels under the existing dead loads. Wherever needed, additional surcharge loads were applied to push the footings down to their initial levels. For damaged short columns, shoring of upper floors was sometimes needed to reduce the applied loads, strengthen the columns and restore the footings.

Figure 6. Modification of foundation and concrete jacketing of short columns

4.2 Concrete jacketing of short columns

Strengthening of basement columns using concrete jacketing was apparent since the load carrying capacities of these columns were much less than the applied axial forces and bending moments. Shear connectors were first inserted and fixed in the old concrete columns using a carefully selected epoxy binder. The surfaces of the old concrete columns were roughened and a suitable epoxy binder was distributed before the additional reinforcement was placed (Hollaway and Leeming, 2005). After that additional flexure and shear reinforcements were fixed around the columns before final concreting.

4.3 Metal jacketing of columns

In order to increase the load carrying capacity of the second floor columns while maintaining the same cross-section, metal jacketing was the best solution. The columns were strengthened using four channel sections at the four corners along the columns, connected via horizontal steel strips at a suitable spacing (Fig. 7). The gaps between the concrete and the added steel frame were filled with a suitable epoxy mortar.

Figure 7. Metal jacketing of second floor columns

4.4 CFRP for basement cover slabs

The basement cover slab (total area 1350 sq.m) was strengthened using carbon fiber reinforced polymer laminates fixed at the soffit of the concrete slab using selected epoxy resin (Bank, 2006). This technique was the best solution to remedy the two deficiencies of the slab; structural cracks due to foundation movements and corrosion of reinforcements due to chemical attack (Fig. 8).

Figure 8. *CFRP* for basement cover slabs

4.5 Shear wall installation

To enhance the stability of the building and to rectify the openings at the expansion joints caused by the differential movement of the foundations, concrete shear walls were installed at both sides of each expansion joint along the total height of the building (Fig. 9).

Figure 9. Installation of shear walls at expansion joints

5. CONCLUDING REMARKS

This case study highlights the following facts:

- Clever combination between different strengthening and retrofitting techniques can save a lot of money and time.
- When considering the strengthening and rehabilitation of structures, it is essential to establish the nature of the problems, extent, severity and exact causes. If this is not done the symptoms could be treated rather than the causes.
- There is no substitute for following sound design and construction principles when constructing structures on expansive soils.
- Careful and continuous monitoring during and after installation of strengthening and retrofitting works is vital to evaluate the efficiency of such works.

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