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Geotechnical Aspects of Light Structures on Expansive Soils

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Abstract :

The geotechnical behaviour of expansive clay soils is investigated by looking into the geomorphologic, geological and climatic conditions and mineralogical composition of the soils in the study area. The geotechnical results are linked with the performance of the foundation as well as structures.

Since swell potential and swell pressure are key properties of expansive soils, the swell parameters were measured by free swell tests and one-dimensional oedometer swell tests respectively.

Physical conditions of the surveyed properties in the area confirmed the hypothesis of building damages due to poor building materials triggered by expansive soils. In support of the obtained data, the actual behaviour of the foundations is supplemented with prototypes of strip foundations whose performances are to be monitored over a long period. Finally, suggested are the ways forward to solve the problem of foundation on expansive soil.

Key Words :

Expansive soils, soil properties, potential swell, Soil-Structure Interaction (SSI), and superstructure and substructure.

1. Introduction

Plastic clays termed as expansive soils or active soils exhibit volume change when subjected to moisture variations. The soil found in the case study is over-consolidated with the significant amount of expansive clay minerals (montmorillonite), mainly darkish grey colour. The case study being in Bairagarh in the semi-arid regions of Bhopal (M.P.) experiences two main seasons, the rainy and the dry seasons. During the rainy season, the expansive clay minerals attract water molecules resulting into massive change in volume.

Numerous masonry houses especially lightweight structures on these expansive soils in Bairagarh, have met with damages originating from differential heave. While the presence of expansive soil in the area can cause significant problem, the mere presence of it does not alone cause all the defects.

Apart from the expansive soil, the defects may originate from inadequate design, poor materials, poor job-site construction or multiple of the factors. In order to understand fully the problem behind the poor performance of buildings in the case study, a top agenda item is to build-up knowledge of expansive soils both as an entity in its own right, but particularly as a critical component with myriad linkages (Soil-Structure Interaction) to the whole structure, namely foundation and superstructure.

Generally, the structures include both superstructure (walls, floors and roofs) and substructure (foundation and soil). Foundations are in term divided into two main categories: deep and shallow foundations.

The structures most susceptible to swelling/shrinkage on expansive soils are those with foundations located at shallow depths. Damages experienced by these structures include cracks in the foundation and walls and jammed doors and windows. The degree of damage based on observed cracks ranges from hairline cracks, severe cracks, very severe cracks to total collapse. The pattern of the cracks depends on whether it is a dooming heave or a dish shaped lift heave. The dome effect results from the movement of the moisture from the perimeter to the centre of the house while the saucer effect results from the moisture moving from centre to the perimeter.

Apart from the soil and types of foundations, defects can start off from the pitiable design and poor quality of construction materials. Building materials come in many forms, different sizes and different qualities. The problems of heave are more common in un-reinforced concrete or masonry due to their brittleness. The type as well as standard of material is always behind the poor performance of structures on expansive soils. Many single-storey buildings in the case study are poor quality residential buildings.

Although the problem of expansive soil has caused damages with respect to serviceability in the actual area, little has been done to address the magnitude of the problem on the expansive soils. It is from the above facts that the primary goal of this study is to investigate the crucial properties of expansive soil, where the majority of the problems originate, but also on the building structures because the magnitude of the damage is related to the interaction between the soil and the structure.

The laboratory tests concentrated on the determination of the Atterberg limits (widely used index properties of soils), particle size analysis, swell test, and x-ray diffraction (XRD) test in order to identify the expansive clays. To gain a better insight into the swelling properties of the soil, detailed investigations and inspections were conducted at two buildings in Bairagarh, Bhopal, where damages were very apparent.

Statement of the Problem

The presence of the expansive soils, also known as shrink-swell or swelling soils in Bairagarh Bhopal where semi-arid clayey soils are predominant has caught many builders unawares.

Swelling or expansive clay soils are those that comprise swelling clay minerals such as montmorillonite, which expand when the moisture in the soil changes. In addition, expansive soils have high degree of shrink-swell reversibility with change in moisture content.

A large number of structures especially lightweight structures found on these expansive soils have met with widespread problems associated with serviceability performance mainly in the form of cracks or permanent deformation.

Objectives of the Study

The primary objectives of this study are to do the following:

- Study the engineering properties and mineralogical composition of the clay soils, together with their origin
- Study and understand the important soil properties for the soil swell/shrink potential
- Find out the causes of the swelling of the sub-grade soil.
- Study and evaluate the performance of existing buildings in Bairagarh Bhopal region and recommend appropriate measures.

Identification of Expansive Soils

Identification of potential swelling or shrinking subsoil problems is an important tool for selection of appropriate foundation (Hamilton, J. J., 1977 and Van Der Merwe D. H., 1964).

Despite the lack of standard definition of swell potential (Nelson, J. D. and Miller, D. J., 1992), there exist various geotechnical techniques to identify the swelling potential of soils. Surface examination, geological and geomorphological description can give indicators of expansive soils.

The morphological description includes a host of many things such as ground water table situation, colour of the soil, soil consistence, soil texture, soil structure, texture groups etc. Most of the relevant physical and mechanical properties to give indicators of swell potential are obtained by performing geotechnical index property tests such as Atterberg limits, unit weights and grain size distribution. Other tests direct tests) to determine the swell potential include volume change tests (free swell and swell in oedometer test), coefficient of linear extensibility (COLE) and mineralogical compositions by x-ray diffraction (XRD) test.

Criteria for describing consistency of in situ undisturbed fine-grained soils (ASTM D2488-00).

Degree of firmness	Pointer
Very soft	Thumb will penetrate soil more than 25 mm
Soft	Thumb will enter soil about 25 mm
Firm	Thumb will indent soil about 6 mm
Hard	Thumb will not indent soil but the thumbnail will readily indent it.
Very Hard	Thumbnail will not indent it

The direct methods consist essentially of laboratory swelling tests while indirect methods base on the correlation of certain physicochemical properties and mineralogical composition of the soils. Empirically correlating soil parameters like water content, Atterberg's limits, colloids etc. to the expansiveness is indirect method while tests like swell test and coefficient of linear extensibility (COLE) are direct methods.

Visual identification

Field estimates of shrink-swell potential can be made by observing desiccation cracks. The development of desiccation cracks in the ground surface is apparent during the dry periods. The degree of potential swell determines the size of the cracks (Day, R. W., 1999).

Great potential swell is indicated by large and more frequent polygon arrangements of cracks while low shrink/swell means that potential for shrinkage cracks developing is low. Soils containing expansive clays become very sticky and plastic when wet and adhere to soles of shoes or tires of vehicles. They are also relative easy to roll into small threads.

Consistency

Consistency is used to designate the degree of firmness or cohesion of intact fine grained soils (Day, R. W., 1999 and ASTM D2488-00, 2000) and it varies from 'very soft' to 'very hard' as indicated by the criteria in Table.

Particle size distribution (PSD)

The inherent swelling potential of soil is directly related to the total amount of clay-mineral particles (particles that are <2μ m in diameter) in it. The swelling potential increases with the increase of clay minerals. Moreover, particle size distribution of soil mineral separates are critical for getting hold of many soil properties such as water holding capacity, rate of movement of water through the soil, kind of structure of soil, bulk density and consistency of soil. All these are important in the identification of expansive soils.

Classification of the soils for engineering purpose depends very much on the system used. In this study, use is made of the two systems; the USCS and BS 1377. The grain size and grain size distribution are according to USCS, while the wet sieve is according to BS1377: Part 2: Clause 9.5: 1990. That means the distribution of particle sizes larger than 0.002 mm is determined by dry sieve, while a sedimentation process using a hydrometer determines the distribution of particle sizes smaller than 0.002 mm. For both systems, a cumulative frequency distribution is determined for each sample to characterize the grain size distribution.

Atterberg limits

In the year 1911 Atterberg proposed the limits (liquid limit LL , plastic limit PL and shrinkage limit SL) of consistency in an effort to classify the soils and understand the correlation between the limits and engineering properties like compressibility, shear strength and permeability (Casagrande, 1932). The limits represent the water holding capacity at different states of consistency.

The limits are the most popular procedures for gathering information on the expansive nature and mechanical behaviour of clay soils (Williams, A. A. B., 1958). The most useful classification data for identifying the relative swell potential are liquid limits (LL) and plasticity index (PI). The liquid limit is the water content at which a soil changes from the liquid state to a plastic state while the plastic limit is the water content at which a soil changes from the plastic state to a semisolid state. The plasticity index is calculated by subtracting the plastic limit (PL) from the liquid limit (LL). i.e., PI = LL - PL. It indicates the range over which the soils remain plastic. Soils that possess no clay minerals do not exhibit plasticity thus they pass directly from liquid limit (LL) to the semi-solid state when their moisture content is reduced.

Liquid limit (LL)

There are two methods to describe the liquid limit (LL) namely percussion cup method and fall cone method. In the percussion cup method, liquid limit is defined as the moisture content corresponding to a specified number of blows required to close a specified width of groove for a specified length (Casagrande, 1932 and 1958). The method however does not provide a uniform basis of comparison for fine-grained soils that differ in their reaction when subjected to a shrinking (dilatancy) test. Furthermore, there is a difficulty of cutting a groove in soils of low plasticity (i.e. silty soils) and the tendency of soil to slip rather than to flow.

Plastic Limit (PL)

Plastic limit is the water content at which the soil begins to crumble when rolled into 3 mm threads.

Shrinkage limit (SL)

The shrinkage limit is the water content dividing the semi-solid and the solid state of the soil. It is the water content at which further reduction in moisture content does not result into a decrease in volume of the soil mass.

Climate and Hydrological Conditions

Climate, hydrological conditions, and geology govern the formation and behaviour of soils. The climate in particular is one of the most important factors in soil profile development. It helps change parent material into soil. Climatic factors, such as precipitation, temperature, wind and sunlight accelerate the formation of the basic material of soil. Soil is a mixture of minerals, air, water, and organic materials. Soils differ depending on how much of these different ingredients they contain, and climate contributes to those differences.

Climate change will modify rainfall, actual evaporation, generation of runoff, groundwater level and soil moisture storage. Changes in total seasonal precipitation and in its pattern of variability are both important in the prediction of alternate cycles of swelling and shrinking.

The local effects of climate change on soil moisture, however, will vary not only with the degree of climate change but also with properties of soil. Heavy clay soils are thought to have higher water holding capacity than coarse-textured soils. The water-holding capacity of soil will affect possible changes in soil moisture deficits; the lower the capacity, the greater the sensitivity to climate change. That means coarse textured soils dry or drain more rapidly than fine-textured soils. The evaporation time-lag in fine-textured soils gives them chance to swell slightly before shrinkage. Thus, heaving of expansive clay may occur even without the presence of free water.

Structures (Super-Structures and Sub-structures)

Morphology of Structures

The major elements of a building include the structure system (foundation or sub-structure, and the superstructure including the exterior walls, interior walls, floors and roof) and service system. To understand the elements of a building the knowledge of the principle attributes of a structure such as building systems, materials, and loading is indispensable. This part focuses on the major parts of structures directly linked to Soil-Foundation-Structure Interaction, mainly foundations and walls.

A single-storey is the building in one floor or level, usually on the ground, whose full width and height can be utilised throughout for maximum garaging, storage, living or workspace.

The term multi-storey building encompasses a wide range of buildings that have more than one storey. However, for more clarity the building can be classified according to the levels it is built in. For example, a double-storey building is that built only in two levels or floors. Likewise, a three-storey building is that which has three floors or levels.

To simplify the classification, many buildings with multiple floors or levels are referred as multistorey. However, tall buildings with multiple floors equipped with elevators are singled out as high-rise buildings. Very tall buildings are referred as skyscrapers. Some of the skyscrapers in the world are taller than 400 m (Taipei 101 tower in Taipei, Taiwan, 509 metres; Sears tower in Chicago, 442 metres; Petronas twin towers in Kuala Lumpur, Malasia at 452 metres tall etc.).

The Sub-Structure (Foundation) Systems

There are two types of foundations used in construction: shallow and deep (Smith, G. N., 1992). Shallow foundation is that whose depth (D) below the finished ground surface is equal or less than the width (B). Strip footings, grade beam, pad footings and mat foundations fall into this category. Deep foundation is that whose depth is found very deep (depth greater than its least dimension) below the finished ground surface. They include caissons, piles, piers and micro-piles. Normally the types of foundation and importance or types of the structure determine the extent and type of soil exploration for geotechnical tests.

Identification of Damage in Structures

The most obvious identifications of damage to buildings are doors and windows that get jammed, uneven floors, and cracked foundations, floors, masonry walls and ceilings. Moreover, different crack patterns mean different causes for different foundation materials. In most cases, cracks due to shrinkage and expansive clay usually run from corner towards adjacent opening and are uniform in width or v-shaped, wider at the top than the foundation wall (Mika S. L. J and Desch S. C., 1998 and Ransom W. H., 1981). This pattern of cracks happens when the moisture movement is from the perimeter to the centre of the house. The typical crack pattern in the concrete slab-on-grade concrete due to centre heaving of expansive soils (Day, R. W., 1999).

In some cases, the cracks are wider at the bottom than the top due to dishing effect as opposed to dooming effect. This happens when the moisture moves from centre to the perimeter resulting into the saucer effect. In the dishing

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Table 2.10: Categorization of visible damages in structures (Burland, J. B., et al., 1977).

Category of damage	Description of typical damage	Approximate width of individual crack (mm)
Negligible	Hairline cracks	<0.1
Very slight	Fine cracks that are easily treated during normal decoration. Isolated slight fracture in building and cracks in external brickwork visible on close inspection	1
Slight	Cracks which are easily filled and redecorated. Several slight fractures may appear inside of the building. Cracks are visible externally and repainting may be required to ensure weather-tightness. Doors and windows may stick	<5
Moderate	Cracks that require some opening up and patching by a mason. Recurrent cracks that can be masked by suitable linings. Re-pointing of exterior brickwork and possibly replacement of a small amount of brickwork. Doors and windows stick, service pipes may fracture and weather-tightness is often impaired	5 to 15 or a number of cracks
Severe	Large cracks calling for extensive repair work involving breaking-out and replacing sections of walls, especially over doors and windows. Windows and doorframes distort and floor slopes are noticeable. Leaning or bulging walls. Beams lose some bearing. Utility service disrupted	15 to 25 but also depends on the number of cracks
Very severe	Major repair job involving partial or complete rebuilding. Beams lose bearing, walls lean badly and require shoring and windows are broken with distortion. There is a danger of structural instability	>25

effect, the cracks are wider bottom than top because of the inwards tilt.

The identification is followed by the classification of the damage. The classification of the damage is very important to assess whether the building calls for strengthening, repair, renovation or demolition. Various researchers (Burland, J. B., *et al*., 1977, Boscardin M. D. and Cording E. J., 1989) put forward many definitions, specifications and guidelines for classification of damage in structures. Visible damages based on observed crack width as suggested by Burland and colleagues are reproduced.

Generally, the evaluation has to base on experience and knowledge of the history of the building, construction details (detailed building materials and structural survey), crack patterns, construction pathology and existing physical condition. This is possible by means of walk through inspection to identify and categorize both distinct and hidden damages. Unfortunately, the evaluation proposed by Burland and colleagues falls short of a link between deformation and critical strain criteria and damage category. Furthermore, the evaluation does not take into account the type of the building and the construction anatomy.

Site Response during Foundation and Structure Performance

An outbuilding to the church in a state of damage due to heaving. A wide-open horizontal crack developed between the ground slab and the external substructure wall. The inner substructure wall which is found deep into the estimated sensitive subsoil, experienced differential heave of the soil profile caused by differential water content from the liquid waste in the toilet, thus pushed the ground slab upward leaving behind the external shallow substructure wall. Effort to arrest the gap between the superstructure wall and the foundation with reinforcement proved futile. The gap opened further pulling the reinforcement apart. What happened is that, the wastewater percolated through under-lying expansive soil of the strip foundation of the internal wall making it too wet than that supporting the external wall. Since the structure is in semi-arid climates, the moisture differential was severe enough to differentially lift the slab. The consequences of the differential heave are seen also in the loss of verticality of the walls, misaligned doors and uneven floor of the toilet. This raises the doubt that the bottom of the pit-latrine was not provided with watertight slab. This case history is the classic demonstration of typical behaviour of light structures on expansive soils.

Foundation Depth

Most of the structures in the case study area are found on strip foundation. The results indicated strong correlation between minimum depth of foundations into the sub-soils and the damages.

Most buildings found about 1.0 m deep were more susceptible to damage than those found shallower or deeper than 1.0 m. The results confirmed the hypothesis that the more sensitive
stratum is located at about 1.0 m deep from the ground.

Construction Materials

Poor quality building materials are common in the case study area. The masonry walls and masonry infills are in some cases a hotchpotch of materials ranging from clay bricks to concrete blocks mostly of low quality.

Conclusions of the Study of Existing Buildings in Bairagarh, Bhopal Region

Many of the structural problems originate from improper design or construction, insufficient foundations and weak or inadequate materials triggered by the swelling soils. Other factors influencing the degree of likely damages include the climatic conditions, age, poor drainage and wet spots around the foundations, and neglected maintenance of the buildings. Taken together these factors underlying building damages are not mutually exclusive. The main challenge for any inspector is to investigate technically which one of these is predominant in any particular case.

General Conclusions

Expansive soils have been investigated in this study. The existence of expansive soils could damage foundations of above-ground structures. It is unfortunate that neither these soils were observed before nor had report been published regarding the characteristics of expansive soils and their adverse effects in the case study area. It is not therefore surprising that the side effect of expansive soils is ignored in both design and construction of structures.

This paper has helped identify the expansive soils and associated problems in the area. The more positive outcome of the research will be to sensitize the implementation of the proposed mitigation measures to prevent structural damages originating from the behaviour of expansive soils.

This awareness is a very positive development in terms of ensuring the durability of the properties in the area. The positive outcomes of this paper have the potential to improve the safety of the communities by assisting homeowners in promoting proper design, positive construction and maintenance altitudes.

Most of the damages caused by expansive soils are due to poor construction and lack of timely maintenance by the homeowners and are in most cases preventable, yet the communities have insufficient knowledge about the features and behaviour of the expansive soils.

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