Computers and Geotechnics 56 (2014) 89–99

Contents lists available at ScienceDirect

Computers and Geotechnics

journal homepage: www.elsevier.com/locate/compgeo

Technical Communication

Case study and back analysis of a residential building damaged by expansive soils

Jie Li [a,*], Donald A. Cameron [b], Gang Ren [a]

[a] School of Civil, Environmental and Chemical Engineering, RMIT University, GPO Box 2476, Melbourne 3001, Australia
[b] School of Natural and Built Environments, University of South Australia, Mawson Lakes, SA 5095, Australia

ARTICLE INFO

Article history:
Received 14 February 2013
Received in revised form 8 September 2013
Accepted 18 November 2013
Available online 8 December 2013

Keywords:
Expansive soils
Case study
Back analysis
Finite element
Residential footing

ABSTRACT

This paper presents a case study of a residential house damaged by expansive soils. The field investigation revealed that the damage was most likely caused by excessive lawn watering and leaks of sewer pipe and/or stormwater pipe, which resulted in non-uniform soil moisture conditions. Three-dimensional back analysis of this distressed structure indicated that stresses were most critical at a re-entrant corner and that steel reinforcing bars in the beam in this area had yielded. The results of the back analysis also indicated that a stronger footing was required to limit differential deflection to an acceptable level and reduce stress in the footing. The case study has clearly shown that a leaking underground water pipe and/or excessive watering of a garden could cause more severe distortion to a single storey masonry veneer house than could be expected from seasonal moisture change and the deeper moisture re-distribution caused by the imposition of the house on seasonally dry reactive soil. Moreover it has been demonstrated that it would be extremely costly to design a footing for extreme, or abnormal, moisture changes.

1. Introduction

Expansive or reactive soil is any soil composed predominantly of clay, which undergoes appreciable volume change in response to changes in soil moisture content. This volume change occurs as swelling upon wetting, and shrinkage upon drying. Buildings constructed on expansive soils are frequently subjected to severe movement arising from non-uniform soil moisture changes, with consequent cracking and damage related to the distortion. These moisture changes may be induced by rainfall and evaporation, garden watering, leaking water pipes, or tree root activity.

Damage to lightly loaded structures founded on expansive soils has been widely reported in many countries such as Australia, China, India, Israel, South Africa, the United Kingdom and the United States of America. In the United States alone, total damage due to expansive soil is estimated to cost $US15 billion per year [13], more than twice the damage from floods, hurricanes, tornadoes, and earthquakes combined. The American Society of Civil Engineers estimates that one in four homes have some damage caused by expansive soils [13]. The annual cost of expansive soil damage in China is estimated to be approximately $US15 billion [17]. The Association of British Insurers has estimated that the average cost associated with damage due to expansive soil is over £400 million a year, making it the most damaging geohazard in the UK today [13]. The problems are particularly significant in Australia as approximately 20% of Australia is covered with expansive soils [6,19] and six out of eight of Australia's largest cities are significantly affected by expansive soils [10,9]. Before a national standard was introduced for site classification and design of footings, it was reported by Considine [8] more than 50,000 houses cracked each year in Australia, which accounted for approximately 80% of all housing insurance claims.

Over the last 40 years or so, much effort has been devoted to methods of analysing and designing structural footing systems on expansive soils. Since 1986, Australian footing design and construction practices have been guided by a national standard. The current Australian Standard for residential slabs and footings is the 2011 edition [3]. Common to the three versions of the Standard, sites are classified according to soil profile and regional climate influence on soil moisture state. Once a characteristic site surface movement has been estimated for a site and the type of house construction is known, a raft footing can be designed, usually based on two-dimensional approximations of true slab behaviour. Flexural strength, structural stiffness and section ductility are appraised so that the slab will keep differential deflections across the floor within tolerable limits. Section ductility is an important consideration to ensure that if ground movements are greater than anticipated, the reinforcing steel will not yield readily, and there

---

[*] Corresponding author. Tel.: +61 3 9925 3554; fax: +61 3 9639 0138.
E-mail address: jie.li@rmit.edu.au (J. Li).

0266-352X/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.compgeo.2013.11.005

remains the possibility that action may be taken to correct the cause of movement without the need to re-construct the building.

The Australian Residential Slabs and Footings Standard AS2870 provides simple and efficient design procedures, which assume that the moisture condition around the buildings will remain within reasonable limits. This means that owners should be aware of the need to make sure extreme soil moisture changes are avoided over the life of the house; maintenance of site drainage and prompt repair of leaking pipes are two actions which will help to achieve this aim.

There are a number of cases of residential structures which have experienced significant cracking, despite the design of the footing systems conforming to the Australia Standard for residential footing design [19,15]. In December 2011, the Housing Industry Association (HIA) estimated that more than 1000 new houses in the Western suburbs of Melbourne were damaged due to soil heave [18]. These new houses have all been built according to Australian Standards and the Building Code. There are many different factors to consider in assessing damage to residential building constructed on expansive soils, which include the adequacy of the site investigation, the scope of the design and inherent underlying assumptions, construction practices and post construction site maintenance. In order to obtain a better understanding of the problem and to improve the current practice, more research is needed to quantify the impact of these factors on the performance of residential footings.

It is the authors' belief that improvements of current design approach can be achieved by case studies of the performance of footings on expansive soils. In this study, the field investigation and back analysis of a residential building damaged by expansive soils were carried out. The purposes of this case study were: (a) to determine the causes of deformation and cracking, (b) to estimate the stress level in the deformed slab footing, (c) to estimate the soil mound shape underlying the footing, and (d) to find out what footing design could cope with the estimated ground movement. The last point is contrary to a basic philosophy of the existing Standard, but may serve to reinforce the potential waste of resources trying to design all houses for extreme moisture events. This paper presents the results of the case study.

2. Description of case study

The case study concerned a single storey, articulated masonry veneer dwelling, which was constructed in March 1992 (at the end of the dry season) in a northern suburb of Adelaide, Australia. The site was approximately 32 m long and 20 m wide and had a slight fall of approximately 2% towards the South (Fig. 1). Before construction, three boreholes were drilled to a depth of approximately 3 m at the site to estimate the shrinkage indices of the underlying soil profile using a visual-tactile method [12]. The classification of the site for potential ground movement following the Australian Standard, AS2870 was Class E (i.e., extremely reactive; refer Table 1). Site classification is based on y_s, the predicted design site surface movement, over the life of the house, which is based on design soil suction change profiles for different climatic regions of Australia. The value of y_s is determined by the following expression:

$$y_s = \frac{1}{100}\int_0^H I_{pt}\Delta u dh \tag{1}$$

where I_{pt} is the instability index of the soil, which is defined as the percent vertical strain per unit change in suction considering possible lateral restraint, Δu is the change in suction, in pF units in the soil layer under consideration, dh is the thickness of the soil layer and H is the design depth of suction change.

The stiffened raft slab was designed using the AS2870 recommended method, which generates empirically-based ground distortions or mound shapes from the design site surface movement. Two basic mound shapes are designed for: the short-term edge wetting distortion or "edge heave" mound, and the longer term central swelling and seasonal edge drying and distortion, or "centre" heave. The design then proceeds to limit footing deflections to levels tolerable for the supported building, by adding stiffening beams of sufficient depth and with adequate reinforcement. Interaction between the loaded footing and the soil is considered. Routine design however is based on simplified 2D analysis. In particular, the slab plan must be divided into fully overlapping rectangles, each rectangle being designed for centre heave and edge heave cylindrical mounds in both the short and long directions. One rectangle will dictate beam sizes for the whole slab.

For this case study, the footing layout is shown in Fig. 1. The external beams were 300 mm wide by 950 mm deep, reinforced with 8/Y16 bars, four at the top and four at the bottom. The internal beams were 250 mm wide by 950 mm deep, reinforced with 6/Y16 bars, three at the top and three at the bottom. A Y16 bar refers to a 16 mm nominal diameter deformed bar of yield strength, 400 MPa. The slab was 100 mm thick and was reinforced with F62 mesh placed 25 mm from the top surface of the slab. F62 refers to plain hard drawn steel fabric, of 6 mm nominal diameter and spaced at 200 mm centres in each direction, and having a yield strength of 450 MPa.

3. Post construction site investigation

After 6 years, the owner reported that the building was cracking. A site investigation was carried out by the authors in February (during the seasonally dry period in Adelaide, South Australia), to examine the cause of damage to the building. The investigation consisted of the following:

(1) A visual inspection of external walls and all internal areas of the building.
(2) Recording magnitude and location of cracking in wall, floor and ceiling.
(3) Examination of the beam depth, slab thickness and the properties of concrete.
(4) A level survey of the floor surface.
(5) Borehole used for evaluation of the physical properties and engineering characteristics of the subsurface soils.

The site inspection indicated that sewer pipe leaking had occurred at the front of the house, as well as stormwater pipe leaking at the back of bedroom 4 (Fig. 1). The inspection revealed there was a large well-watered lawn in the backyard, which sloped gently down towards the building. Water was observed ponding at the back of the building adjacent to the footing (see Fig. 1). Four small native shrubs were planted at the front of the property, approximately 5 m away from the building and adjacent to the footpath. The lawn in the front yard was well maintained as well. Damage to the house superstructure consisted of severe ceiling cracking (4–20 mm) in the family area (Fig. 2), and severe internal wall cracking (3–16 mm) in the dining room and lounge (Fig. 3), moderate external wall cracking (2–3 mm) under the window of bedroom 2 (Fig. 4), distortion of the cornice in the laundry (Fig. 5), and a slope on the floors in most rooms. The floor of the house was distorted into a complex pattern, involving both bending and twisting.

Three boreholes were drilled to approximately 4 m deep to evaluate the soil profile and the level of reactivity of soil types within the profile. The location of boreholes is shown in Fig. 1.