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Research Paper

Simulating the behaviour of reactive soils and slab foundations using hydro-mechanical finite element modelling incorporating soil suction and moisture changes

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ABSTRACT

The main objective of this paper is to enhance the current design practice of stiffened slab foundations on reactive soils through an advanced numerical modelling study. The paper presents sophisticated three-dimensional (3D) hydro-mechanical finite element (FE) numerical models using coupled flow-deformation and stress analyses capable of simulating the complex behaviour of reactive soils and slab foundations. The decisive parameters of the developed FE models are described in detail and the modelling efficacy is verified through three case studies. The ability of the FE models to simulate the moisture diffusion and suction variations in relation to climate changes is validated through two case studies involving field observations. A third case study involving a hypothetical stiffened slab foundation on reactive soil is used for comparison with one of the traditional design methods. The developed FE models are found to perform well and overcome some of the most significant limitations of available traditional methods, leading to more reliable design outputs.

1. Introduction

Reactive (expansive) soils swell and shrink by increase and decrease of soil moisture between the wet and dry seasons, causing lightweight structures to suffer from different levels of structural damages due to foundation movements. The financial losses incurred due to damages caused to structures built on reactive soils are alarming; it has been estimated to be US$7 billion per year [1]. It was also reported that the annual losses in the United States could reach up to US$11 billion for houses and roads damaged by swelling of reactive soils [2]. The American Society of Civil Engineers estimated that nearly 25% of all homes in the United States suffered some damage due to reactive soils, with the financial losses exceeding those caused by natural disasters such as earthquakes, floods, hurricanes and tornadoes combined [3]. Similarly, reactive soils cover roughly 20% of Australia and cause structural cracks to nearly 50,000 houses each year, forming about 80% of all housing insurance claims [4].

Over the last 50 years or so, stiffened slab foundations have been used as a suitable foundation system for lightweight structures on reactive soils and have demonstrated historical success, despite the inherent shortcomings. The main premise underlying the design of stiffened slab foundations is to adopt idealised typical patterns of the slab foundation movements caused by soil heaves (edge or centre), assuming that these two heave scenarios (i.e. edge or centre) represent the worst loading cases among an infinite number of heave patterns, depending on the site boundary conditions. According to the extreme edge heave scenario, the stiffened slab foundation acts as a simple beam supported by the rising soil at the edges, assuming that the centre of the footing slab loses its contact with the soil. Conversely, in the centre heave scenario, the stiffened slab foundation acts as a double cantilever supported by the rising soil at the centre area while the edges of the slab lose their contact with the soil over a certain edge distance. Analysing the footing slabs over the distorted soil mounds enables the designers to obtain iteratively the required stiffness and the corresponding internal forces that maintain the foundation differential movements within certain acceptable limits. Many traditional design methods are available in the literature for the design of stiffened slab foundations on reactive soils, including the Building Research Advisory Board (BRAB) method [5], Lytton method [6], Walsh method [7], Mitchell method [8], Swinburne method [9], Post Tensioning Institute (PTI) method [10] and Wire Reinforcement Institute (WRI) method [11,12]. Out of these methods, Walsh method [7] and Mitchell method [8] are adopted by the Australian Standard AS2870 [13].

During the last few decades, several attempts have been made to

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enhance the well-established traditional methods by implementing numerical modelling techniques (i.e. finite element and finite difference). For example, Fraser and Wardle [14] carried out finite element analysis for stiffened rafts on a semi-infinite elastic soil, and the footing was analysed iteratively on a pre-formed soil mound based on Walsh method. Poulos [15] used the mound shapes proposed by Lytton method in the analysis of strip footings using the finite element method in which the soil was modelled as an isotropic, homogeneous elastic half-space. Sinha and Poulos [16] carried out a study using the finite element method and analysed slab foundations on the soil mound represented by the equations proposed by Lytton method. Li [17] adopted a coupled thermo-mechanical analogy and introduced this approach as an acceptable and relatively accurate methodology for simulating the moisture diffusion and soil shrink-swell movement in reactive soils. El-Garhy and Wray [18] and Wray et al. [19] used an uncoupled approach to model the suction distribution and the corresponding volume change and surface movement of expansive soils using the finite difference technique. Fredlund et al. [20] carried out a finite element analysis in an iterative, uncoupled procedure (that is difficult to utilise for routine design) to evaluate the separation distance under the footing edge in the case of the edge drop scenario. Abdelmalak [21] and Magbo [22] modified Mitchell's diffusion equation [8] to derive a more representative solution for the suction distribution under cover and estimated a more realistic distorted soil mound that was utilised as a predefined soil mound under a flat foundation in a finite element analysis. Dafalla et al. [23] proposed a simplified design concept for a rigid substructure foundation in the form of an inverted-T of a two-storey concrete frame structure on expansive soils, and the edge heave scenario was simulated, while the centre heave scenario was omitted from the analysis. Zhang et al. [24] carried out a coupled finite element transient analysis for isolated footings on expansive soils by adopting the thermal analogy, and the work focused on the prediction of soil movement due to the evapotranspiration of grass roots and crops, involving specific vegetation data, which in most cases would not be available to geotechnical engineers.

Careful review of existing design methods and other studies on stiffened slab foundations on reactive soils revealed that a major assumption adopted by almost all methods involves simplifying the real, complex 3D moisture flow into a 2D problem, resulting in deformation incompatibility between the soil mound and supported footing. In addition, most existing methods use uncoupled approaches in which the footing is designed for stress analysis using pre-defined soil mound shapes obtained from a separate seepage analysis, with no consideration to the effect of slab loading on the formation of the soil mounds. Moreover, prediction of the soil mound shapes is determined using simple empirical equations, based on the best fit of minimal field observations. However, in reality, there is an infinite number of soil mound shapes depending on many factors, including soil suction, degree of saturation, permeability, site drainage conditions and irrigation/plantation events.

In this paper, an advanced 3D finite element (FE) numerical modelling is pursued to simulate the complex behaviour of stiffened slab foundations, which otherwise could not be realistically captured by the currently available design methods. Through a hydro-mechanical approach, the resulting FE modelling is capable of simulating the true performance of stiffened slab foundations on reactive soils, by: (1) involving a coupled flow-deformation analysis based on realistic moisture flow and suction evolution; and (2) inducing a realistic formation of the soil mound beneath the footing. The paper presents and discusses some important modelling aspects relating to unsaturated soils and the corresponding associated parameters. Development of the adopted FE numerical models is then explained and verified through three case studies.

2. Modelling aspects for unsaturated soils

2.1. Coupled versus uncoupled analyses

Design of stiffened slab foundations on reactive soils is typically a moisture transient, unsaturated soil problem [20]. Most studies carried out on this topic adopt uncoupled approaches in which the problem is solved via two phases, as follows. The first phase comprises an independent transient seepage analysis to obtain the distribution of the degree of saturation and/or the soil suction within the soil mass, for a certain time increment. The soil movement is then estimated using one of the available theories. A detailed description of the methods of estimating the soil movement can be found elsewhere [25]. By estimating the soil movement, the soil distorted mounds can be determined. In the second phase, a separate stress-deformation analysis is carried out for the soil structure interaction, by analysing the footing slab using pre-calculated distorted soil mounds obtained from the first phase. Although this approach is acceptable, the accuracy of results depends on the size of the selected time increment. In addition, the soil distorted mounds and the corresponding maximum differential movement are greatly affected by the stresses induced by the loaded footing, which is not considered in the seepage phase. Moreover, the soil properties in the stress phase is most often assumed to be constant; however, unsaturated soil properties are highly dependent on the moisture variation and the ensuing suction changes. Additionally, unlike the fully coupled flow-deformation analysis, the excess pore water pressure due to the load application in the uncoupled approach cannot be simulated [24]. Formation of the soil distorted mounds underneath the slab foundation in the coupled approach is thus correctly influenced by the combined effect of the suction evolution and the stresses induced by the footing loading. The abovementioned limitations indicate clearly that the uncoupled analysis oversimplifies the real situation compared with the coupled approach, and can thus inevitably lead to inaccurate design. To circumvent these limitations, this paper adopts a robust, fully coupled flow-deformation transient analysis for simulating the problem of stiffened slab foundations on reactive soils.

2.2. Mechanism of soil volume change

Fredlund et al. [26] described the volume change constitutive relations of unsaturated soils for a linear, elastic, isotropic material, as follows:

$$\varepsilon_x = \frac{(\sigma_x - u_w)}{E_1} - \frac{\mu_1}{E_1}(\sigma_y + \sigma_z - 2u_w) + \frac{(u_a - u_w)}{H_1} \tag{1}$$

where;

ε_x = normal strain in the x-direction;
E_1 = elastic modulus with respect to the change in effective stress $(\sigma - u_w)$;
μ_1 = Poisson's ratio with respect to the relative strains in x, y and z directions;
H_1 = elastic modulus with respect to the change in soil suction $(u_a - u_w)$;
σ = total normal stress;
u_a = air pressure; and
u_w = water pressure.

Similar equations can be written in the y- and z-directions. The soil volumetric strain is equal to the sum of the normal strain components, calculated as follows:

$$\varepsilon_v = C_t.\ \partial(\sigma - u_w) + C_a \partial(u_a - u_w) \tag{2}$$

where;

C_t = soil compressibility with respect to the change in the effective