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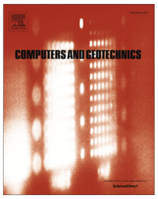

Research Paper

Optimised design of jet-grouted raft using response surface method

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ABSTRACT

The use of jet grouting as a foundation supporting element has brought about the need to define the design strategies for jet-grouted raft (JGR) system which differs from the traditional raft design due to the effects of jet-grouted columns (JGCs). Paper tackles this important aspect by combining the previously defined design strategies on piled raft and JGC to achieve an optimised design of complete JGR system. Initially, a single JGC has been analysed by means of three dimensional finite element (3D FE) analysis accounting for the previously measured actual trial JGC's geometrical variation with depth. The image processing technique allowing the complex 3D FE modelling of JGC system is utilised and the results are validated by the back-analysis of the well-known experimental results reported in the literature. In a parametric study, extension of the numerical analysis to the complete JGR system is accomplished by considering the mutual interaction between the foundation elements. The effects of design factors that are interlayer thickness, JGC spacing and lengths on the design responses of vertical stresses, bending moments, average and differential settlements are presented. Response Surface Method is utilised in the multi objective optimisation analysis to present the optimised design solution by accounting for the design constraints previously defined for the considered factors and the responses. The significance of design constraints and their relative influences on the optimised design of JGR are finally discussed.

1. Introduction

Jet grouting technique is based on the injection of high-pressure self-hardening grout through small-diameter nozzles to erode the surrounding soil and mix it with injected grout to form a quasi-cylindrical shaped soil–cement column named as jet-grouted column (JGC) [1]. Among its varieties of application in geotechnical engineering, this practical technique is utilised in foundation engineering as an alternative to piles to provide more economical solutions or it is preferred when the subsoil characteristics are unfavourable for the installation of piles. In the case of raft supported by isolated JGCs, if they are located by the centre-to-centre spacing greater than the diameter of the columns, this arrangement becomes similar to that of a piled raft and the foundation system is accordingly named as jet-grouted raft (JGR) [2]. JGR is a composite foundation consists of the four bearing elements that are JGCs, granular interlayer mat (cushion), raft and subsoil. Granular material is generally used as a cushion layer and it is placed between JGR and the soil surface, to adjust stress distribution on JGR. Therefore, the concept of JGR design differs from the traditional raft design due to the effects of JGCs.

An important potential difference between the traditional piled raft and JGR is the unique shape and properties of JGCs. Such difference could have a significant influence on the geotechnical design of JGRs. Many application of JGRs are reported in the literature for new buildings (e.g. [3–6]) and for underpinning of pre-existing structures (e.g. [7–9]). Although there are some acknowledged rules regarding the load transferring mechanism of JGCs [2], the design of JGR is still based on empirical, subjective and oversimplified methods in practice. The most important reason of this is the lack of commonly acknowledged design procedure that considers the dimensional variations of JGCs, the effects of various possible assemblages of JGCs and the rules consider the effects of uncertainties and the stress–strain properties of bearing elements.

Since many guidelines (e.g. [10,11]) highlights the importance of preliminary field trials for every jet grouting project to obtain the information such as the variation of diameter and properties of JGCs with depth, 3D FE modelling that closely represents the obtained JGC geometry unique to the project site is important to achieve the accurate results. For this purpose, 3D FE modelling of a complete JGR system with the complex geometrical shape of JGCs is conducted in this study using the robust image processing

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Nomenclature

a_c	cross-sectional area at a generic section of jet-grouted column (m^2)
a_f	cross-sectional area of the steel reinforcement (m^2)
B	breadth of raft (m)
c'	cohesion of soil (kPa)
E_c	Young's modulus of the cushion layer (kN/m^2)
E_{JG}	Young's modulus of the cemented soil (kN/m^2)
E_{ur}	unloading modulus (kN/m^2)
$E_{50\%}$	secant modulus (kN/m^2)
L_{JGCE}	length of JGC under the raft edge area (m)
L_{JGCC}	length of JGC under the raft core area (m)
$m_{r(\max)}$	maximum bending moment of raft without the jet-grouted column system (kN m/m)
$m^{JG}_{r(\max)}$	maximum bending moment of jet-grouted raft (kN m/m)
p	vertical stress at the JGC's base (kN/m^2)
$p^{JGCE}_{\max}$	maximum p value of JGCs under the raft edge area (kN/m^2)
$p^{JGCC}_{\max}$	maximum p value of JGCs under the raft core area (kN/m^2)
p_L	limit value of p (kN/m^2)
p_{L_d}	limit design value of p_L (kN/m^2)
q_c	tip unit resistance of CPTs (MPa)
q_u	uniaxial compressive strength of the jet-grouted material (kN/m^2)
$S, S_{\lim}$	axial load and its limit value at a generic section of JGC (kN)
s_{JGC}	centre to centre JGC spacing (m)
s_{ra}	average settlement of raft without the jet-grouted column system (m)
s^{JG}_{ra}	average settlement of jet-grouted raft (m)
s_{ra_d}	limit design value of s_{ra} (m)
t_c	thickness of the cushion layer (m)
γ	unit weight (kN/m^3)
γ'	buoyant unit weight (kN/m^3)
Δs_r	differential settlement of raft without the jet-grouted column system (m)
Δs^{JG}_r	differential settlement of jet-grouted raft (m)
Δs_{r_d}	limit design value of Δs_r (m)
ν	Poisson's ratio
σ_c	uniaxial compression strength at a generic section of jet-grouted column (kN/m^2)
σ_{c_d}	limit design value of σ_c (kN/m^2)
σ_f	compression strength of the steel reinforcement (kN/m^2)
$\sigma^{JGCE}_{z(\max)}$	maximum axial stress of jet-grouted columns under the raft edge area (kN/m^2)
$\sigma^{JGCC}_{z(\max)}$	maximum axial stress of jet-grouted columns under the raft core area (kN/m^2)
τ	vertical stress on the shaft of jet-grouted column (kN/m^2)
$\tau^{JGCE}_{\max}$	maximum τ value of jet-grouted columns under the raft edge area (kN/m^2)
$\tau^{JGCC}_{\max}$	maximum τ value of jet-grouted columns under the raft core area (kN/m^2)
τ_L	limit value of τ (kN/m^2)
τ_{L_d}	limit design value of τ_L (kN/m^2)
ζ_{asr}	coefficient for average settlement of jet-grouted raft
$\zeta_{\Delta sr}$	coefficient for differential settlement of jet-grouted raft
ζ_{mr}	coefficient for maximum bending moment of jet-grouted raft
ϕ'	angle of internal friction of soil (°)
ψ	dilatancy angle of soil (°)

technique. This modelling technique can be applied to any type of JGC shapes obtained from the preliminary field trials or the column integrity tests. Regardless of how complex the JGC geometries might be (i.e. including the inclination and axial deviation of JGCs), this presented technique can easily be applied for the design projects as long as the data are available on the geometry and orientation of JGCs. The parameters of interface between JGC and surrounding soil are obtained and validated using the performed back-analysis of the developed FE modelling with the well-known experimental results [12–14]. The geometrical variation of JGCs modelled in this study is adopted from the trial column in Amsterdam [15] as a representation of an actual geometrical shape of JGC. Three main 3D FE models developed to simulate the complete JGR systems are analysed to understand how the elements of JGR interact and affect the design responses in the varying levels of each factor.

The optimised design is defined as a design achieves the maximum economical solution by maintaining the satisfactory performance within the level of minimum cost in the installation of foundation [16]. Accordingly, the design strategies of JGR should also enable an optimised design having a paramount importance for an economic construction to be achieved. Several authors (e.g. [17–19]) have previously reported that the dependent variables of settlement, differential settlement and bending moment are important responding parameters for the optimum design of piled raft. Along these parameters, the design parameters of JGCs that are lateral interface stress, end-bearing load and axial column stress are included in the presented study. These parameters' previously set up constraints and limiting values for the piled raft [17] and JGC design [2] are considered in the presented optimisation analysis. Response Surface Method (RSM) that is used in the performed multi objective optimisation analysis allows a better understanding of the overall response system. RSM which is generally used in the empirical study of relationships between one or more dependent and independent variables [20] is applied to the results from the presented parametric study based on 3D FE analyses where each run regarded as an experiment. ANOVA is performed prior to RSM application ensuring that the system responses are rather well related to the considered factors that are cushion thickness, JGC spacing and length.

The aim of this paper is to demonstrate how 3D FE model representing the complex geometrical shape of JGC varies for each project can accurately be attained by using the image processing technique, how the previously defined design strategies on piled raft and JGC can be combined to achieve an optimised design of complete JGR system, how the confining design parameters can be used in practice to achieve an optimised design, how the mutual relationships between the considered design factors and responses may vary, and how the considered design constraints and limiting values influence the optimised design solution of JGR system.

2. Simulation of a single JGC

The most important initial step in any jet-grouted foundation project is probably the prediction of JGC diameter. JGC diameters are affected by soil properties and the treatment procedure to be employed [21]. Several authors (e.g. [22–30]) have presented the empirical correlations and alternatively some researchers [31–38] have proposed the theoretical models to predict JGC diameter. Ochmanski et al. [39] have recently presented an artificial neural