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Research Paper

Reliability analysis of seismic bearing capacity of strip footing by stochastic slip lines method

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ABSTRACT

In this research, the reliability analysis of seismic ultimate bearing capacity of strip footing is assessed with implementing slip lines method coupled with random field theory. The probability density functions of seismic and static bearing capacities which are log-normal and nearly normal distribution respectively are compared to each other. The predicted Probability Density Function (PDF) of the seismic bearing capacity by slip line method is verified, with those of the Terzaghi equation and Monte Carlo simulation (MCs). For uncertainties analysis by Terzaghi equation the N_c, N_q and N_γ are assessed stochastically.

1. Introduction

Determination of seismic bearing capacity of foundations is an important problem for the safe design in the seismic zone. Due to seismic loading, foundations may experience a reduction in bearing capacity and increase in settlement. In the last years the seismic effect has increased in many national design codes of foundation according to recent records.

A rigorous seismic design of foundations can be done using seismic soil-structure interaction, which is capable to consider nonlinear soil behavior under dynamic loading. However, it is costly and time-consuming and is suitable only for important projects. Routine analysis of bearing capacity and the seismic response of the superstructure are decoupled. Base on this simplification, the methods for calculating the seismic bearing capacity of the strip footing can be classified into four major categories: limit equilibrium method [1–3], limit analysis [4–6], numerical methods [7,8] and the method of characteristics [9–12]. These methods with related important researches are explained briefly in subsections.

1.1. Limit equilibrium method

Limit equilibrium is the most common analysis method of bearing capacity. In this method, at the first a sliding surface is assumed. Then, to obtain the ultimate limit load, the equilibrium equations are solved. A major limitation of this method is caused by the absence of a stress strain relationship. This method is used usually on the soil slope stability analysis and is followed by many researchers to analyze the bearing capacity of foundations.

Sarma and Iossifelis [1] determined the seismic bearing capacity factors using the limit equilibrium technique of slope stability analysis with inclined slices. Their analysis showed that the factor N_q is dependent on the inertia of the surcharge load; the relationship between N_C and N_q given in the literature was found to be incorrect for inclined loads and the inertia of the soil mass certainly has an effect on N_γ. They showed the results of analysis in graphical forms as functions of the horizontal acceleration factor and of the angle of internal friction of the soil.

Richards [2] based on limit analysis and using coulomb mechanism including inertial forces in the soil and on the footing gave expressions for seismic bearing capacity factors that are directly related to their static counterparts. They found that reduction in foundation capacity was due to both the seismic degradation of soil strength and the lateral inertial forces transmitted by shear to the foundation through the structure and any surcharge. A straightforward sliding-block procedure with examples was also presented for computing these settlements due to loss of bearing capacity for short time periods.

Sarma and Iossifelis [1] and Richards et al. [2], had examined the reduction of static bearing capacity of cohesionless soils for horizontal accelerations of an earthquake. Budhu and Al-Karni [3] proposed the seismic bearing capacity factors with consideration of vertical acceleration and soil cohesion. They derived the seismic

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bearing capacity factors for a c-ϕ soil within the framework of the Mohr-Coulomb theory. The horizontal and vertical accelerations, the effects of inertia forces of the soil below and above the footing and applied loads, were considered in that research.

1.2. Limit analysis

The basis of limit analysis rests upon two upper bound and lower bound theorems. The correct answer is revealed by identical upper and lower bounds. In lower bound theorem any stress system in which the applied forces are just sufficient to cause yielding. Similarly, in upper bound any velocity field that can operate is associated with an upper bound solution. In limit analysis, ultimate bearing capacity of foundation is calculated using the stress-strain relationship and failure mechanism. Among important contributions are the following researches.

Soubra [4] calculated the seismic bearing capacity factors of shallow strip footings using the upper bound method of limit analysis. The pseudo-static approach was considered by taking into account static inertia forces. The solutions obtained were rigorous upper-bound ones in the framework of the limit analysis theory for an associated flow rule Coulomb material.

Soubra [5] investigated the static and seismic bearing capacity problem of shallow strip footings. Two kinematically admissible failure mechanisms separately for both static and seismic conditions in the framework of the upper bound theorem were considered. The numerical results of the static and seismic bearing capacity factors in the form of design charts for practical use in geotechnical engineering were presented.

Ghosh [6] by considering the pseudo-dynamic approach, examined the effect of soil friction angle, horizontal and vertical seismic accelerations, soil amplification, shear and primary wave velocities travelling through the soil layer during earthquake on the seismic bearing capacity factor N_γ for a surface to very shallow strip footing. The result showed that the magnitude of N_γ decreases with the increase in soil amplification, shear and primary wave velocities, which cannot be predicted by the existing pseudo-static approach.

1.3. Numerical methods

The numerical methods such as Finite Difference Method (FDM), Finite Element Method (FEM) and Discrete Element Method (DEM) are used as conventional methods in geotechnical problems. These methods need more time to analyze but also offer the advantage that problems with complex geometries or complex constitutive models can be solved.

Shafiee and Jahanandish [7] used the finite element method to estimate the seismic bearing capacity of strip footings for a wide range of friction angles and seismic coefficients. Also, they presented curves relating seismic bearing capacity factors to earthquake acceleration.

Pane et al. [8] performed a finite difference numerical analysis aimed at evaluating the seismic effects on the ultimate bearing capacity of shallow strip foundations. Both structure inertia and soil inertia effects and possibility of superposition of these inertia effects are investigated. As results of their research, it was found that in some cases the soil inertia may play a significant role in the seismic capacity of the system, and that simple one-constant equations can be readily used in foundation design.

1.4. Method of characteristics

The method of characteristics avoids the assumption of arbitrary slip surfaces, and produces zones within which equilibrium and plastic yield are simultaneously satisfied for given boundary stresses. Furthermore, the effect of seismic forces on the bearing capacity of foundations can be entered into method of characteristics. Among important contributions are the research of Kumar and Mohan Rao [9], Keshavarz and Jahanandish [10].

Kumar and Mohan Rao [9] assessed the effect of horizontal earthquake body forces on the bearing capacity of foundations. They also investigated changes of the bearing capacity factors N_c, N_q and N_γ as functions of earthquake acceleration coefficient for different values of soil friction angle.

Keshavarz and Jahanandish [10] analyzed the seismic bearing capacity of reinforced soil slopes. For this purpose, the earthquake effect using horizontal and vertical pseudo-static seismic coefficients was considered. A number of graphs regarding critical load distribution for a uniformly reinforced slope, also a slope with linearly increasing reinforcement and a slope with linearly decreasing reinforcement in terms of variations in horizontal seismic coefficient were proposed.

Keshavarz et al. [11] analyzed the seismic bearing capacity of strip foundations situated on reinforced soils. They showed the ultimate bearing capacity increases due to reinforcement by introducing another bearing capacity factor, N_t.

Cascone and Casablanca [12] carried out the evaluation of static and seismic bearing capacity factors for a shallow strip footing using the method of characteristics, which was extended to the seismic condition by means of the pseudo-static approach. The results, for both smooth and rough foundations, were checked against those obtained through finite element analysis.

Vo and Russell [13] studied the bearing capacity of strip footings on unsaturated soils using slip line theory. The suction profiles was considered are non-uniform with depth and was correspond to vertical flow of water by infiltration or evaporation and suction influences was included using the effective stress concept. This paper showed the similar and independent effects of cohesion and the contribution of suction to the effective stress in the governing equations. It showed that the influence of a non-uniform suction profile on bearing capacity is significant, and the depth to the ground water table and the footing width have significant roles in how much suction influences the bearing capacity. Charts were presented that permit assessment of bearing capacity changes that may occur when changes to suction are expected, due to seasonal fluctuations of soil moisture, drought or flooding.

Analysis of seismic bearing capacity of strip footing is usually implemented with the assumption of homogeneous or averaged soil and earthquake properties. Therefore, the methods for calculating the bearing capacity of the shallow strip footing are restricted by the use of single valued parameters. Reliability analysis provides a means of evaluating the combined effects of uncertainties and offers a logical framework for choosing bearing capacity that are appropriate for the degree of uncertainty and the consequences of failure. Thus, as an alternative the deterministic assessment, a reliability assessment of bearing capacity would be useful in providing better engineering decisions.

Since three decades ago, many probabilistic methods have been devised for analysis of bearing capacity of strip footing. Fenton and Griffiths [14] modeled soil with spatially varying shear strengths using random field theory and elasto-plastic finite element method to evaluate bearing capacity. Theoretical predictions of the mean and standard deviation of bearing capacity were derived with independency of c and ϕ and using a geometric averaging model and then verified via Monte Carlo simulation.

Przewłócki [15] applied the method of characteristics to a strip footing based on the stochastic subsoil. The investigation was limited only for the special case of a purely cohesive material. It allowed determination of the influence of the spatial variability of cohesion on the variance of the collapse load of the bearing