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Seismic bearing capacity of surficial foundations on sloping cohesive ground

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ABSTRACT

Engineers often assume undrained conditions in stability calculations of shallow foundations resting on soil with fine content as this assumption yields conservative results. Calculation of undrained bearing capacity of shallow foundations on level ground is a well-defined problem and when the footing is located on or near slopes, empirical equations or design charts produced based on limit equilibrium, upper bound plasticity calculations or finite element method (FEM) analyses are used. On the other hand, available studies that consider seismic bearing capacity of foundations on cohesive soils do not consider the influences of all influential parameters. Therefore, their use in design practice is rather limited. Accordingly, this study attempts to develop design charts that consider the influences of all parameters that affect the undrained bearing capacity factor of surficial strip footings under seismic conditions (N_{cse}). These influences are footing width, slope angle, slope height, footing position, undrained shear strength and pseudo-static acceleration coefficient. As the number of parameters to be considered is high, a parametric study is conducted using FEM models. Obtained results are consistent with the results of available studies in literature. Proposed design charts allow the selection of problem specific N_{cse} values. A design procedure is defined and two design examples are presented for the calculation of the magnitude of undrained bearing capacity under seismic conditions.

1. Introduction

Design of shallow foundations requires the consideration of safety and serviceability. Safety check generally requires bearing capacity calculations, whereas serviceability calculations are done to keep the expected settlements within tolerable limits. However, a design that satisfies the serviceability criteria almost always satisfies the safety requirements. Then, the bearing capacity calculations are generally done for procedural purposes since they are compulsory in most design codes. But sometimes the combined influences of prevailing loading conditions and topography might reduce the bearing capacity of shallow foundations to critical levels and safety checks control geotechnical design. This is especially correct for the foundations of retaining structures, bridge abutments and transmission towers that rest on or near slopes within seismic zones. Under the influences of structural loads and earthquake accelerations, bearing capacity mechanism can induce slope instability which reduces the allowable bearing pressure in design. For projects that cover large distances, such as power transmission lines, many such foundations that support pylons and towers need to be designed. Thus, it is the goal of this study to develop simple design charts that allow the calculation of bearing capacity for different combinations of foundation dimensions, positions, soil properties, slope inclinations, crest heights and seismic accelerations. This study limits its scope to surficial shallow foundations resting on cohesive soils. The underlying reason for this preference is that sloping grounds generally have cohesive properties and the foundations of structures that are frequently built on sloping ground, such as retaining walls and transmission towers, are surficial shallow foundations. Accordingly, undrained behavior will be assumed as this corresponds to the most critical condition. Seismic loading will be defined using pseudo-static accelerations. Since there is no exact solution of the considered problem, it is essential to develop approximate solutions. For this purpose in this study, two-dimensional finite element method (FEM) is used for investigating the problem. As a shortcoming of the two-dimensional approach, modelled surficial foundations are always strip foundations. However, the applicability of the obtained results will be increased as the use of shape factors is adapted to seismic bearing capacity problems.

The problem of shallow foundations resting on or near slopes has attracted the attention of many researchers since late 1950s. These studies resulted in the development of several empirical equations and design charts [1–17,19,20]. Adopted methodologies of research are various and include limit equilibrium methods [6,7,15], upper bound [4,5,9,10,12,17,19] and lower bound analyses [20], method of stress characteristic [10,16], and finite elements method [8,10,16]. Additionally, recent studies used discontinuity layout optimization which

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is an upper bound limit state plasticity failure discretization scheme [13,14]. Yet, only a few studies consider the influence of seismicity and most of these emerged in the last two decades [7,12,15–20]. Among these, Sarma and Chen [15] studies slopes of cohesionless soils using limit equilibrium method. Similarly, Castelli and Motta [7] uses limit equilibrium method for studying the static and seismic bearing capacities of strip footings located situated near slopes. For this purpose, Castelli and Motta [7] assumes a circular failure mechanism and considers the influences of the sloping ground and soil inertia on bearing capacity using a pseudo-static approach. Georgiadis and Chrysouli [12], used an upper-bound plasticity solution for investigating the seismic bearing capacity of surficial strip footings on or near cohesive slopes. The kinematic mechanism proposed by Georgiadis [12] is extended for pseudo-static loading conditions by considering horizontal footing loads and the inertia of the soil body. On the other hand, Farzaneh et al. [20] employed finite element lower bound method to determine seismic bearing capacity of shallow foundations on cohesive slopes. Neglecting the changes to the geometry as the loading approaches collapse, the finite element lower bound models yielded lower bounds to the exact collapse load [20]. Among the studies that considered seismic bearing capacity of shallow foundations on or near cohesive slopes, Castelli and Motta [7], Farzeneh et al. [20] and Kumar and Rao [16] provided design charts, where Chrysouli and Georgiadis [12] provided an empirical equation based on the results obtained from the assumed kinematic mechanism.

To improve upon the existing literature, this study adopts a parametric approach employing numerical methods and deals with a more complete set of influences that control the behavior. These influences are soil strength, slope height, slope angle, seismic acceleration, soil strength, and foundation size and position relative to the slope. No single study in literature considered all of the above influences together for the ranges of variation examined in this study, therefore their practical applicability is relatively limited. The method of choice in this study is finite elements method since it allows the definition of different geometries and boundary conditions. This is especially important for the problem being considered as the mode of failure can change from a bearing capacity failure to slope instability as the material properties and geometrical conditions vary. Accordingly, in addition to the number and range of considered parameters, the novelty of the present study is that the combined influences of material properties, pseudo-static accelerations and problem configuration on the geometry of the failure mechanisms are considered with the use of FEM models.

Thus in this paper first the problem will be defined, followed by the presentation of the solution method. Then obtained results are compared with the results from available studies in literature and verified. Following, obtained results will be presented in the form of design charts. Then the results will be discussed and a design procedure is defined, followed by two design examples.

2. Definition of the problem and the details of the analyses

The problem of seismic bearing capacity of surficial foundations resting on or near cohesive slopes requires the consideration of a number of parameters and geometrical features. Changes in the configuration and geometry of the problem rather complicates the task of defining a general failure surface geometry. Finite element method requires no preliminary assumptions regarding the position and shape of the failure surface. This is especially important in case of footings located close to sloping ground as the mode of failure and its geometry is subject to change due to the combined influences of soil characteristics, problem geometry, and seismic accelerations. That is why finite element method which is a versatile tool that allows the consideration of different geometries is selected for this study. Furthermore, an important advantage of finite element over traditional limit equilibrium methods is that there is no need for the use of slices. This eliminates the need for assumptions regarding slice side forces as finite element

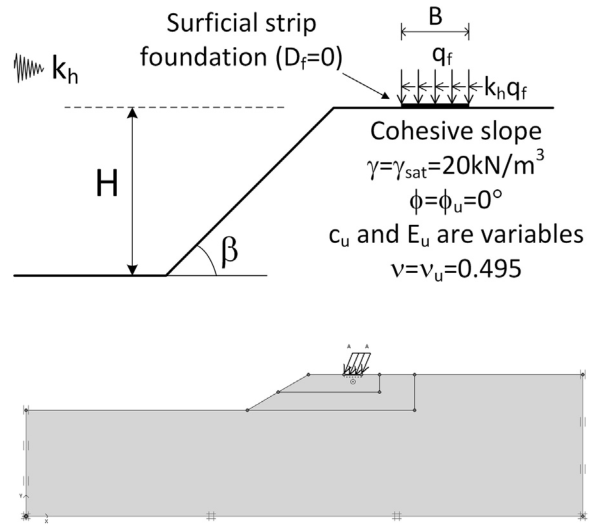

Fig. 1. General features of the problem and the corresponding model.

method preserves global equilibrium until failure state [21]. For this purpose, a commercial finite element software Plaxis 2D is used. Graphical representation of the problem and the corresponding model are illustrated in Fig. 1. Several assumptions were made towards the development of the model. Plane-strain conditions are assumed and the study considers surficial strip foundations. Therefore the influence of embedment on bearing capacity is ignored. The footing is represented by a rigid plate element and the interface is assumed to be rough. Pseudo-static approach is preferred for defining seismic effects and it is assumed that the inertia force of the structure acts at the base of the footing. Therefore, any moments due to inertia effects are neglected. A holistic pseudo-static approach is chosen in which horizontal seismic acceleration coefficients (k_h) used for calculating the inertia forces of the structure and the slope are assumed to be equal. By definition, seismic acceleration coefficients correspond to the ratio of seismic acceleration over gravitational acceleration (g). Moreover, horizontal accelerations ($k_h g$) are uniform throughout the entire model subjecting it to constant inertial forces. However, vertical component of the seismic acceleration is ignored ($k_v = 0$) owing to its insignificant influence on seismic bearing capacity [22]. Soil behavior is modelled as elastic – perfectly plastic with a Tresca failure criterion. Additionally, as illustrated in Fig. 1, slope and soil underlying it are uniform and soil properties do not vary with depth.

Seismic bearing capacity ($q_{ult,se}$) is defined using an appropriate seismic bearing capacity factor (N_{cse}) as shown in Eq. (1).

$$q_{ult,se} = N_{cse} c_u \tag{1}$$

Here, the value of N_{cse} is dependent on the collective influences of all variables and problem geometry. Considering that the measurement of undrained shear strength of cohesive soils is a straightforward task, the only requirement for the calculation of $q_{ult,se}$ is the determination of N_{cse}. Thus, the goal of this study is to prepare design charts for the selection of the value of N_{cse}. The first step in the development of design charts is the identification of influential factors. Following, the problem is solved numerically using different combinations of influential factors and obtained results are presented graphically for simplicity. Accordingly, factors that are defined as variables can be categorized into three groups. First group mainly involves factors that define the geometry of the problem. Geometry of the problem requires the definition of slope geometry, footing width and the position of the footing. Factors that define the geometry of the slope are height (H) and inclination (β). However by examining Fig. 1 it is possible to deduce that the influence of H on $q_{ult,se}$ must be measured relative to the width of the footing (B). So knowing the magnitudes of H/B and β is sufficient to define the