International Journal of Rock Mechanics & Mining Sciences 76 (2015) 68–77

Contents lists available at ScienceDirect

International Journal of Rock Mechanics & Mining Sciences

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

Displacement-based seismic design of a shallow strip footing positioned near the edge of a rock slope

Ernesto Ausilio*, Paolo Zimmaro

Department of Civil Engineering, University of Calabria, Arcavacata di Rende, CS, Italy

ARTICLE INFO

Article history:
Received 27 October 2014
Received in revised form
12 February 2015
Accepted 18 February 2015
Available online 18 March 2015

Keywords:
Seismic bearing capacity
Earthquake-induced displacement
Strip footing
Rock slope
Hoek–Brown failure criterion

ABSTRACT

This paper presents a displacement-based dynamic design of shallow strip footings located close to the edge of homogeneous and isotropic rock slopes. The analysis is conducted using the "generalized tangential" technique in which the Hoek–Brown strength is replaced by an "optimal" tangential Mohr–Coulomb domain within the framework of the kinematic approach of limit analysis theory. In order to better understand the influence of these factors including geometrical features, rock strength parameters and seismic loading, a parametric study is carried out. An expression is derived and used to obtain a least upper bound solution for the bearing capacity of a footing on a rock slope considering a kinematically admissible log-spiral failure mechanism. In addition, a similar expression of the horizontal yield seismic coefficient is derived for a given load acting on the foundation.

The assessment of earthquake-induced permanent displacement is performed by a simplified procedure. This requires the knowledge of a ground motion parameter that can be evaluated by site-specific seismic hazard analyses or ground motion prediction equations and that considers the actual sliding surface. The calculated displacement should not be greater than a selected limiting tolerable displacement for the specific case. An example is presented illustrating the application of the design procedure for the bridge foundations.

1. Introduction

There are many situations where the foundations are built on slopes or near the edges of slopes or excavations for example buildings and roads in hilly regions and footings for bridge abutments. When a shallow foundation is placed near the edge of a slope, the bearing capacity of the foundation can be significantly reduced, according to the location of the foundation with respect to the slope edge. In this case, the failure mechanism is influenced by the distance of the foundation from the edge of the slope. To design a footing on a slope requires a thorough understanding of mechanical behaviour both of the footing and of the slope. Several studies have been devoted to this purpose. Most of these investigations are based on the assumption that the geomaterial strength is governed by a linear Mohr–Coulomb (MC) failure criterion [1–6]. However, the strength envelope of almost all geomaterials is nonlinear and this nonlinearity is marked for most rocks over a wide range of normal stresses as emphasized by several experimental studies.

Various nonlinear failure criteria have been proposed in the literature and among them the Hoek–Brown (HB) failure criteria are considered to model reasonably well the strength properties of intact rock or heavily jointed rock masses that can be regarded as homogeneous and isotropic.

The modified Hoek–Brown criterion has been used by several authors to calculate the bearing capacity of a strip footing resting on a horizontal rock surface in static conditions [7–12] and the stability of rock slopes both under static [13–15] and seismic conditions [16–18].

More recently, the modified HB criterion has been also used to evaluate the seismic bearing capacity of strip foundations on rock slopes with two different approaches [19,20]. Yang [19] used the generalized tangential technique in which the modified Hoek–Brown strength is replaced by an "optimal" tangential Mohr–Coulomb domain in a limit analysis framework where the upper-bound solutions are obtained by optimization. In this work, the footing is located on the edge of the slope. In [20], the modified HB criterion was implemented in its original form also within the framework of the kinematic approach of limit analysis theory and considering several failure mechanisms. In both works mentioned above the seismic analysis is conducted adopting the conventional pseudo-static approach where the earthquake effects are represented in an approximate manner by constant and static forces acting only in the horizontal direction. The pseudo-static

* Correspondence to: Department of Civil Engineering, University of Calabria, Via Pietro Bucci, Cubo 44/B, Arcavacata di Rende 87036, CS, Italy. Tel.: +39 984 496527; fax: +39 984 496526.
E-mail address: ernesto.ausilio@unical.it (E. Ausilio).

http://dx.doi.org/10.1016/j.ijrmms.2015.02.010
1365-1609/

approach is generally considered conservative, since even when the bearing capacity drops below the load actually applied through the strip footing, the slope and therefore the same foundation could experience only a finite displacement rather than a complete failure. In such circumstances, it is rational to accept that the slope and the foundation are affected by a tolerable displacement and so it is necessary to use an alternative approach based on the assessment of earthquake-induced displacement.

This paper uses the modified nonlinear HB failure criterion by employing the generalized tangential technique, proposed by Yang [21], to investigate the seismic performance of shallow strip foundations located close to the crest of the homogeneous and isotropic rock slopes. The study applies the kinematic theorem of limit analysis set up within the framework of the pseudo-static method taking into account a mechanism which is assumed to start at the edge of the strip foundation far from the slope. After performing a comparison of the present results and those obtained in the literature, a parametric analysis is carried out to highlight the influence of the various parameters on the seismic limit load. The most important parameters taken into account are the geometrical aspects (slope angle, edge distance between the footing and the crest of the slope), rock strength parameters (uniaxial compressive strength or stresses at failure, intact rock yield parameter and geological strength index) and the seismic loadings (horizontal and vertical accelerations, rock mass inertia and structure inertia). The results of the parametric analysis are presented in the form of non-dimensional charts that can be used directly by practitioners for preliminary design.

However, the purpose of this paper is to show a simple iterative procedure based on the assessment of earthquake-induced footing displacements for the design of a strip footing placed close to the crest of homogeneous and isotropic rock slope. The displacements can be evaluated by a ground motion parameter, Arias intensity, which can be obtained by site-specific seismic hazard analyses or empirical relationships.

In the serviceability limit state design of foundations, the estimated displacement should not be greater than a selected limiting tolerable displacement. The limiting tolerable displacement is influenced by many factors, including the type and size of the structure, the properties of the structural materials, the rock mass–foundation–structure interaction and the settlement characteristics.

2. Generalized tangential technique and upper bound analysis

The nonlinear criterion widely employed to estimate the strength of a rock mass is the modified HB failure criterion. However, this criterion is considered to model realistically well the strength properties of rock mass that behaves as a homogeneous and isotropic continuous medium. This is considered to be reasonably true for intact rock or a jointed rock mass that contains a sufficient number of randomly oriented discontinuities. The modified HB failure criterion is described by the following expression [22]:

$$\sigma_1 - \sigma_3 = \sigma_c \left[\frac{m\,\sigma_3}{\sigma_c} + s \right]^n \tag{1}$$

where σ_c is the uniaxial compressive stress of the rock at failure, σ_1 and σ_3 denote respectively the major and minor principal stresses at failure.

The parameters m, s and n depend on the geological strength index, GSI, which characterizes the rock mass quality and are determined using the following expressions:

$$\frac{m}{m_i} = \exp\left(\frac{GSI-100}{28-14D}\right) \tag{2}$$

$$s = \exp\left(\frac{GSI-100}{9-3D}\right) \tag{3}$$

$$n = \frac{1}{2} + \frac{1}{6}\left[\exp\left(-\frac{GSI}{15}\right) - \exp\left(-\frac{20}{3}\right)\right] \tag{4}$$

The GSI, according to the structure of the rock and the surface condition of the joints, ranges between 5 and 100. It assumes the value 5 for extremely poor rock mass and the value 100 for intact rock. Recommendations and suggestions on the use of GSI and on the values that this parameter can assume from geological observations are given in [23]. D is a disturbance coefficient that varies from 0, for the undisturbed in situ rock masses, to 1 for very disturbed rock masses (in this study is assumed $D=0$). The disturbance factor effect on the rock slope stability assessments was investigated by Li et al. [24]. The parameter m_i, which represents the value of m for intact rock, can be obtained from experiments and it ranges from 4, for very fine weak rock like claystone, to 33 for coarse igneous light-colored rock like granite. In the absence of experiment results, it can refer to the approximate values proposed by Hoek [25] for some typical rocks.

The tangential line to the curve that represents the modified HB failure criterion in the stress space is given by the following expression (Fig. 1):

$$\tau = c_t + \sigma_n \tan\varphi_t \tag{5}$$

where φ_t and c_t are the tangential friction angle and the intercept of the tangential line to the τ-axis, respectively. c_t is expressed as [21]:

$$\frac{c_t}{\sigma_c} = \frac{\cos\varphi_t}{2}\left[\frac{mn(1-\sin\varphi_t)}{2\sin\varphi_t}\right]^{(n/1-n)} - \frac{\tan\varphi_t}{m}\left(1+\frac{\sin\varphi_t}{n}\right)\left[\frac{mn(1-\sin\varphi_t)}{2\sin\varphi_t}\right]^{(1/1-n)} + \frac{s}{m}\tan\varphi_t \tag{6}$$

The slope of the tangential line exceeds or equals that of the modified HB failure criterion, corresponding to the same normal stress.

This work presents the kinematic theorem of the plasticity theory for calculating the bearing capacity of a strip foundation located near the edge of the rock slope using the linear MC failure criterion represented by a tangential line shown in Eq. (5) instead of the modified HB failure criterion. This generalized tangential technique, proposed by [21] and repeatedly applied by Yang and his coauthors [10,15,17–19], allows the use of the classic approach of the kinematic theorem for a geomaterial obeying the linear MC failure criterion with the important difference that in this case the value of φ_t is unknown and it must be determined.

In the pseudo-static approach, static horizontal and vertical inertial forces, which are intended to represent the destabilizing effects of the earthquake, are applied both to the foundation and to the potential sliding rock mass below the foundation. The inertial forces are calculated as the product of the seismic coefficients and the weight of the sliding rock mass, indicated as

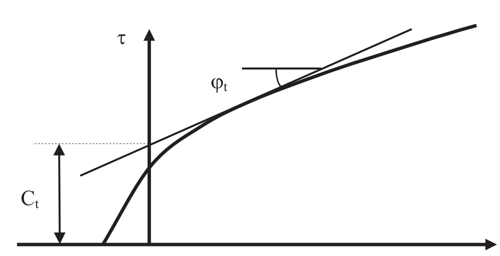

Fig. 1. Tangential line to the modified HB failure criterion (adapted from [10]).