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Practical slip circle method of slices for calculation of bearing capacity factors

Takashi Tsuchida*, A.M.R.G. Athapaththu

Civil and Environmental Engineering, Institute of Engineering, Hiroshima University, 1-4-1 Kagamiyama, Higashi-Hiroshima, Hiroshima, Japan

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Abstract

The slip circle method of slices is commonly used in the analyses of slope stability and bearing capacity for multi-layered ground. However, in the case of ground consisting of horizontal sandy layer, it is known that modified Fellenius' method tends to underestimate the factor of safety, while simplified Bishop's method tends to overestimate the factor of safety. In this study, a new slip circle method was proposed for the purpose of improving the accuracy of the analysis for a ground consisting of sand and clay layers. In the proposed method, β of the ratio of inter-slice shear force to inter-slice normal force i.e $\tan(\beta\alpha_i)$ is assumed constant as 0.25 for all slices. This is named as circle bearing capacity factor (CBCF) method. It was found that the bearing capacity factors, N_c, N_q, and N_γ calculated for shallow foundation on horizontal ground from CBCF method agreed well with that obtained from the plastic solution. The back-analyses carried out for a few case studies on the stability of slopes on earth structures found in sand and clay layers showed that the factor of safety calculated from CBCF method explains the actual performance of earth structures well. The proposed CBCF method proves it reliability in calculating bearing capacity for shallow foundations. This was achieved from the results obtained from centrifugal model test, which were carried out for dense sand layer overlying soft clay with various conditions by Okamura et al. (1998). It was examined that the factor of safety calculated for the stability of slopes from CBCF method can explain the actual performance of geotechnical structures constructed on ground consisting of sand and clay layers.

Key words: Stability analysis; Slip circle; Bearing capacity; Soft ground

1. Introduction

Over the years, the slip circle method of slices is known to be the most popular among the designers and researches in the design works of earth structures. In this method, a potential failure mass is divided into number of finite vertical slices and the equilibrium of each slice is considered in determination of the factor of safety (Taylor, 1948; Tshebotarioff, 1951; Bishop, 1955). Fig. 1 illustrates a trial failure mass divided into number of slices and a slice with the unknown forces acting on it, including the resultants V_i and E_i' of shear and normal effective forces along sides of the slice, as well as the resultants T_i and N_i' of shear and normal effective forces, respectively. As the slip circle method of slices can be applied for various shapes or non-homogeneous

*Corresponding author.
E-mail address: ttuchida@hiroshima-u.ac.jp (T. Tsuchida).
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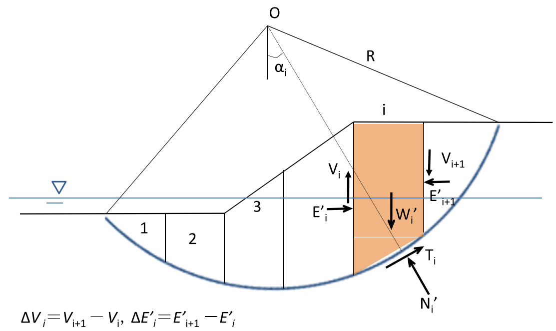

Fig. 1. Forces acting on a slice in the slip circle method.

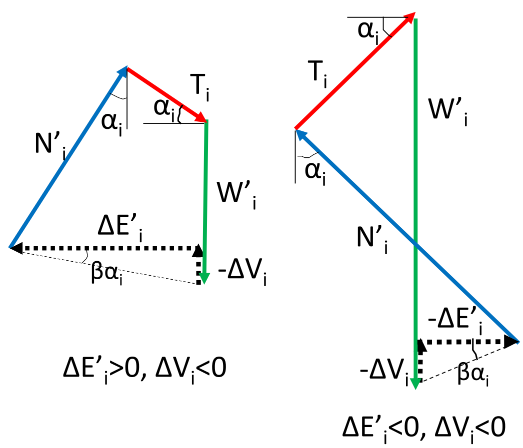

Fig. 2. Equilibrium of forces acting on a slice in the proposed method.

ground, this method has been used extensively in geotechnical engineering practice since its development, although more sophisticated methods such as a finite element method (Matsui and San, 1992; Noda et al., 2007) are available in the literature.

A number of methods are currently being applied to numerous slope stability problems based on the slip circle method of slices. However, each method is different from another and based on different assumptions on the forces acting upon the sides of the slices. In the simplest method of slices (known as Fellenius' method or Swedish method of slices), the resultant of all inter-slice forces is assumed to be consistent with the direction of failure arc for the slice. With this assumption, there are no resultant forces acting on the sides of a slice in the direction normal to the failure arc. Therefore, the factor of safety can be calculated without considering the forces acting on the sides of slices. In the modified Fellenius' method (M.F. method), the effective weight of slice is used for the slices where the potential slip surface is below the water table instead of considering the resultant of static pore water pressure along the failure arc (Nakase, 1967; Ugai and Hosobori, 1985). In the simplified Bishop's method (S.B. method), it is assumed that the forces acting on the sides of each slice have zero resultant in the vertical direction (Bishop, 1955). This method also used in the geotechnical practices by many designers and researchers over the years. Cheng et al., 2010 carried out extensive studies on inter-slice force function $f(x)$, the function of inter-slice normal and shear forces of the slices, and emphasis the importance of it in determining the factor of safety.

M.F. method has been used as a conventional method in design of geotechnical structures constructed on soft ground. In 1960s, Nakase carried out an extensive study on this method and successfully applied to large-scale slides of soft ground in the coastal areas (Nakase, 1967). However, when the ground consists of only sand or gravel or consists of upper sand layer and lower clay layer, it is known that M.F. method underestimates the factor of safety, while, S.B. method often overestimates the factor of safety (Turnbull and Hvorslev, 1967; Yamaguchi, 1984).

Similar shortcomings exist in calculation of bearing capacity for design of shallow foundations. The conventional formulas to calculate the bearing capacity of shallow foundations are derived for uniform ground with cohesion, c and friction angle, ϕ based on the limit state theory of plasticity. However, if the ground below the foundation is not uniform or changes with the depth as in many practical situations, the formulas cannot be readily applied (Brown and Meyerhof, 1969). To overcome this limitation, the method of slices used in slope stability has been successfully applied to calculate of the bearing capacity of strip footings on rather complicated inhomogeneous ground (Imaizumi and Yamaguchi, 1986). On the other hand, Cheng et al., 2013 used the slip line solution for a bearing capacity problem to determine inter-slice force function for a horizontal slope. To study the bearing capacity of concrete caisson on rubble mound, Terashi and Kitazume (1987) carried out a series of centrifuge model tests of a foundation on