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Ultimate bearing capacity analysis of strip footings on reinforced soil foundation

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Abstract

Reinforced soil foundations (RSFs) have been employed in engineering practice to increase the soil bearing capacity and to reduce the potential footing settlement. The aim of this study is to develop analytical solutions for estimating the ultimate bearing capacity of strip footings on RSFs. A general failure mode for RSFs was first proposed based on previous studies conducted by the authors and test results from literature study. A limit equilibrium stability analysis of RSFs was performed based on the proposed failure mechanism. New bearing capacity formulas, which consider both the confinement and the membrane effects of reinforcements on the increase in ultimate bearing capacity, were then developed for strip footings on RSFs. Several special cases of RSFs were presented and discussed. The proposed model was verified by the experimental data reported in the published literature. The predicted ultimate bearing capacity was in good agreement with the results of model tests reported in the literature. The study showed that the depth of the punching shear failure zone (D_P) depends on the relative strength of the reinforced soil layer and the underlying unreinforced soil layer, and is directly related to the reinforced ratio (R_r).

Keywords: Reinforced soil foundation; Ultimate bearing capacity; Failure mechanism; Limit equilibrium; Reinforced ratio

1. Introduction

The use of reinforced soils to support shallow foundations has recently received considerable attention. The benefits of including reinforcements in the soil mass to increase the bearing capacity and to reduce the settlement of the soil foundation have been widely recognized. However, the development of a rational design method and a theory for reinforced soil foundations (RSFs) is lagging in comparison to RSF applications. These restrictions, on the other hand, inhibit the further development of reinforcement technology. Therefore, it is essential to investigate the proper failure mechanisms for reinforced soil applications. During the past forty years, many experimental, numerical, and analytical studies have been performed to investigate the behavior of reinforced soil foundations (RSFs) for different soil types (e.g., Abu-Farsakh et al., 2008, 2013; Adams and Collin, 1997; Binquet and Lee, 1975a, 1975b; Chakraborty and Kumar, 2014; Chen et al., 2007, 2009; Demir et al., 2013; Huang and Tatsuoka, 1990; Kurian et al., 1997; Sharma et al., 2009).

The first experimental study reported in literature was conducted by Binquet and Lee (1975a) to evaluate the bearing capacity of sand reinforced by aluminum foil strips. Since then, several experimental studies have been conducted to evaluate the bearing capacity of footings on reinforced sandy soil (e.g., Abu-Farsakh et al., 2013; Adams and Collin, 1997; Akinmusuru and Akinbolade, 1981; Fragaszy and Lawton, 1984; Gabr et al.,

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List of symbols

B	width of footing
u	top layer spacing, i.e., spacing between top layer of reinforcement and bottom of footing
h	vertical spacing between reinforcement layers
l	length of reinforcement
d	total depth of reinforcement $=u+(N-1)h$.
N	number of reinforcement layers
N_p	number of reinforcement layers located in punching shear failure zone
N_T	number of reinforcement layers located above point c
T	tensile force in reinforcement
D_P	depth of punching shear failure zone
$q_{u(R)}$	ultimate bearing capacity of reinforced soil foundation
$q_{u(R)1}$	ultimate bearing capacity of punching shear failure zone
$q_{u(R)2}$	ultimate bearing capacity of underlying general shear failure zone
P_{p1}	total passive earth pressure on vertical punching failure surfaces aa' and bb'
δ	mobilized friction angle along vertical punching failure surfaces aa' and bb'
C_a	adhesive force acting on vertical punching failure surfaces aa' and bb', $=c_aD_P$
c_a	unit adhesion of soil along vertical punching failure surfaces aa' and bb',
T_1	tensile force acting on vertical punching failure surfaces aa' and bb'
α	angle of tensile force T_1 to horizontal
T_{1x}	horizontal component of tensile force T_1
T_{1y}	vertical component of tensile force T_1
γ	unit weight of soil
D_f	embedment depth of footing
K_{pH}	horizontal component of passive earth pressure coefficient
K_s	punching shear coefficient
ϕ	friction angle of soil
P_{p2}	passive force acting on faces ac and bc
C	cohesive force C acting on faces ac and bc
T_{2L}, T_2	tensile force acting on faces ac and bc
P_{pc}	passive force due to cohesion c,
P_{pq}	passive force due to surcharge q
$P_{p\gamma}$,	passive force due to weight of soil γ
c	cohesion of soil
q	surcharge load
P_{pT}	passive force due to tensile force of reinforcement T_{2L}
ξ	angle of tensile force T_{2L} to horizontal
T_{2Lx}, T_{2x}	horizontal component of tensile force T_{2L}
T_{2Ly}	vertical component of tensile force T_{2L}
T_{2R}	tensile force acting on face gd
η	angle of tensile force T_{2R} to horizontal
T_{2RX}	horizontal component of tensile force T_{2R}
T_{2Ry}	vertical component of tensile force T_{2R}
F	resisting force along log spiral cd
r	length of radial line of log spiral cd, $=r_0e^{\theta\tan\phi}$
r_0	length of bc
θ	angle between line bc and radial line of log spiral curve cd
X_{TR}	distance from center of footing to point where tensile force T_{2R} is applied
$q_{u(UR)}$	ultimate bearing capacity of unreinforced soil in general shear failure zone
N_c, N_q, and N_γ	bearing capacity factors
β	angle between σ_1 direction and bedding plane
ϕ_{design}	design friction angle of soil
ϕ_{peak}	peak friction angle of soil
ϕ_{cv}	residual design friction angle of soil
χ	percent of contribution of failure surfaces controlled by soil's peak friction angle
R_r	reinforced ratio
E_R	elastic modulus of reinforcement $=J/t_R$
J	tensile modulus of reinforcement
A_R	area of reinforcement per unit width $=Nt_R\times 1$
t_R	thickness of reinforcement
E_s	modulus of elasticity of soil
A_s	area of reinforced soil per unit width $=d\times 1$

1998; Guido et al., 1986; Huang and Tatsuoka, 1990; Latha and Somwanshi, 2009; Lavasan and Ghazavi, 2012; Omar et al. 1993a, 1993b; Yetimoglu et al. 1994), clayey soil (e.g., Abu-Farsakh et al., 2008; Chen et al., 2007; Chen and Abu-Farsakh, 2011; Das et al., 1994; Ingold and Miller, 1982; Mandal and Sah, 1992; Ramaswamy and Purushothaman (1992); Sakti and Das, 1987; Shin et al., 1993), aggregate (e.g., Chen et al., 2009; DeMerchant et al., 2002; James and Raymond, 2002), and pond ash (e.g., Bera et al., 2005; Ghosh et al., 2005). The aim of many of these research efforts was to investigate the parameters and variables that would contribute to the value of the bearing capacity ratio (BCR), which is defined as the ratio of the bearing capacity of the RSF to that of the unreinforced soil foundation. The results of the experimental studies showed that the bearing capacity of soil was improved when it was reinforced by reinforcements and that the amount of improvement was highly dependent on the layout of the reinforcements. Better improvements were obtained when the reinforcements were placed within a certain depth (or influence depth) beyond which no additional significant improvement occurred. In other words, the BCR value would approach a constant/limiting value with an increasing number of reinforcement layers.

From the experimental studies reported in the literature, two fundamental reinforcement mechanisms can be distinguished as contributing to the increase in bearing capacity of reinforced soil foundations (RSFs).

(1) *Confinement effect or lateral restraint effect:* With the applied load, the lateral forces are induced and the soil