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Research Paper

# Interaction of a rigid beam resting on a strong granular layer overlying weak granular soil: Multi-methodological investigations

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A B S T R A C T

In the geotechnical and terramechanical engineering applications, precise understandings are yet to be established on the off-road structures interacting with complex soil profiles. Several theoretical and experimental approaches have been used to measure the ultimate bearing capacity of the layered soil, but with a significant level of differences depending on the failure mechanisms assumed. Furthermore, local displacement fields in layered soils are not yet studied well. Here, the bearing capacity of a dense sand layer overlying loose sand beneath a rigid beam is studied under the plain-strain condition. The study employs using digital particle image velocimetry (DPIV) and finite element method (FEM) simulations. In the FEM, an experimentally characterised constitutive relation of the sand grains is fed as an input. The results of the displacement fields of the layered soil based DPIV and FEM simulations agreed well. From the DPIV experiments, a correlation between the slip surface angle and the thickness of the dense sand layer has been determined. Using this, a new and simple approach is proposed to predict theoretically the ultimate bearing capacity of the layered sand. The approach presented here could be extended more easily for analysing other complex soil profiles in the ground-structure interactions in future.



## 1. Introduction

In the terramechanical engineering applications, we often come across the foundation structures and rigid structural elements interacting with non-homogeneous soil profiles of complex nature. Layered soil profiles are often found either naturally or man-made. Due to the demands of the scarcity of the construction spaces, there is an increasing demand to construct structures on loose soils, which were previously considered as unsuitable for construction (Jahanger et al., 2010). Loose sand packings have high compressibility and low shear strength (Terzaghi et al., 1996). One of the methods to improve the strength of the weak soil is to construct a suitable layer of granular material to decrease the overall compressibility. For instance, oil storage tanks and diesel power stations may be found on a thin layer of compacted granular fill (Jahanger et al., 2010). Unpaved roads are also built on the weak soil where the treated layer of sub bases are used to spread the service loads applied by the passing vehicles (Jahanger et al., 2010). Shallow footings, when built on loose sandy soils, have a low load bearing capacity and undergo large settlements (Terzaghi et al., 1996). Construction on loose sands often requires the utilisation of ground improvement techniques (Das, 2009). Compacted soil layer is used under such foundation structures to improve the ultimate bearing capacity and limit the displacement in the soil. The ultimate bearing capacity equation for sand according to Terzaghi (1943) (as $q_{\text{ult}} = 0.5\gamma BN_{\gamma}$ where $\gamma$, $B$ and $N_{\gamma}$ are unit weight of the soil, the width of the footing and bearing capacity factor of the soil respectively) is not directly applicable for layered granular sand.

In a recent study, digital particle image velocimetry (DPIV) was used to understand the displacement fields of strip footing interacting with homogeneous sand bed of different packing densities (Jahanger et al., 2018). The experimental results compared favorably with finite element method (FEM) simulations, which used experimentally measured constitutive relations of the sand grains (Jahanger et al., 2018). The current study deals with the specific case of the bearing capacity of a rigid plane-strain surface beam placed on a layered sand consisting of a dense sand layer overlying a homogeneous bed of loose sand. The study is restricted to cases where the thickness of the top sand layer, $H$, is quantified in terms of the width of the beam, $B$. A discussion is given of the various

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**Nomenclature**

$B$ width of the beam (footing)
$\acute{B}$ projection of slip lines on the surface of the bottom layer (Fig. 4)
$c$ cohesion of the soil
$D_f$ depth of footing embedment
$D_r$ relative density of the soil
$D_{50}$ mean grain size of the soil
d depth of the region M under the beam (Fig. 4)
$E$ modulus of elasticity
$H$ thickness of the top layer of sand
Kp coefficient of passive earth pressure of the top layer of sand
$K_s$ coefficient of punching shear
$N_c$ bearing capacity factor due to soil cohesion
$N_q$ bearing capacity factor due to surcharge stress
$N_\gamma$ bearing capacity factor due to unit weight of soil
$P_p$ total passive earth pressure
$P_{ult\ layered}$ ultimate force for footing on layered soil
$q_{ult}$ ultimate bearing capacity
$q_{ult\ 1}$ ultimate bearing capacity of the top soil
$q_{ult\ 2}$ ultimate bearing capacity of the bottom soil
$q_{ult\ layered}$ ultimate bearing capacity for footing on layered soil
$q_c$ cone resistance
$s_c$ shape factor in the bearing capacity equation for shapes of footing other than a strip footing
$S_u$ ultimate vertical settlement of the beam
$s_u$ shear strength of the clay
$S_R$ resultant displacement
$S_v$ vertical displacement component
UBCR ultimate bearing capacity ratio
$z$ depth of the soil from the beam soil interface
$\alpha$ angle of plastic wedge vertices (slip planes) intersecting the horizontal
$\beta$ angle of the slip surface
$\gamma$ unit weight of the soil
$\gamma$ effective unit weight of the soil
$\delta_{bw}$ roughness of the side wall beam interface
$\delta_p$ roughness of the perspex wall
$\delta$ roughness angle of the material
$\theta$ angle of total passive earth pressure
$\nu$ Poisson's ratio
$\phi_1$ angle of internal friction of the top layer
$\phi_{mob}$ mobilized shear strength

theoretical and the experimental work that have been proposed for this type of analysis.

## 2. Review of the previous work

Numerous researchers have investigated on the ultimate bearing capacity and settlement of the footings interacting with layered soil using theoretical and experimental approaches. Button (1953) was the first to analyse footings on the layered clayey soil. Likewise, many other investigations were conducted for the ultimate bearing capacity of a sand layer overlying a clay layer (Al-Shenawy and Al-Karni, 2005; Burd and Frydman, 1997; Fattah et al., 2011; Khing et al., 1994; Lee et al., 2013; Meyerhof, 1974; Michalowski and Shi, 1995; Oda and Win, 1990; Okamura et al. 1998; Ramadan and Hussein, 2015; Shoaei et al., 2012). Similar were also conducted for the cases of layered cohesion-friction soils (Azam et al., 1991; Purushothamaraj et al., 1974). Furthermore, researchers have studied theoretically and numerically on the bearing capacity of footings interacting with two-layered granular soils (Farah, 2004; Ghazavi and Eghbali, 2008). Some experimental studies, for example Hanna (1982) focused on the loose sand overlying on dense sand. Most of the aforementioned studies have used simplified failure mechanisms together with a reduction in the mobilized shear strength ($\phi_{mob}$) of sand in their corresponding limit analysis and finite element method based simulations. These simplified theoretical mechanisms comprise (i) projected area method (mode 1) that uses constant slip surface angle, β (Fig. 1) (ii) a punching shear failure (mode 2) which assumes zero slip surface angle (Fig. 2) (iii) the theory of bearing capacity by considering the top layer as surcharge (mode 3) and (iv) a variable slip surface method (modes 4 and 5) that assumes different values of β (Figs. 3 and 4). Large discrepancies between the measured and the predicted values of the ultimate bearing capacity were observed in the above studies. It is worth noting that existing studies either used a constant value of β (Yamaguchi, 1963) or set β = 0 (Meyerhof, 1974), but in both cases β is independent of the thickness of the top layer ($H$). However, other conclusions from the previously mentioned studies are that the ultimate bearing capacity

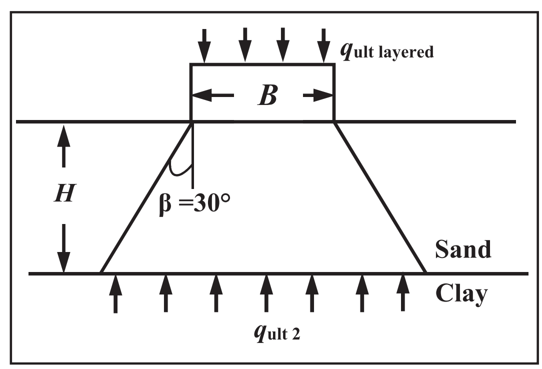


**Fig. 1.** Schematic illustration of the projected area method (Yamaguchi, 1963).

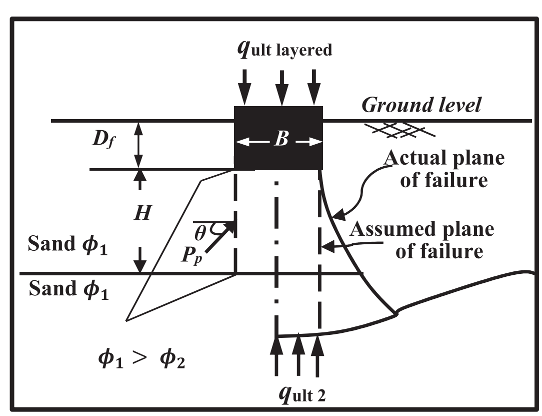


**Fig. 2.** Failure mode of dense sand overlying loose sand deposit (Hanna, 1981).

for the layered soils depends on the individual shear strength parameters of each layer, thickness of the top layer ($H$), the width of the footing ($B$), the shape and the depth of footing embedment