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An Experimental Investigation of Ring Footings Resting on Granular Material Subject to Combined V-H-M Loading

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ABSTRACT: In some structures, such as oil platforms and wind turbines, depending on the type of utilization, the footing is subjected to combined vertical load, horizontal load, and bending moment (V-H-M). In this study, the behavior of the ring footings resting on sand subjected to combined V-H-M loading is experimentally investigated by conducting 100 tests using six load paths. Three values for the diameter ratio of the ring footing models are assumed, including n=0.2, 0.4, and 0.6, along with a circular foundation (n=0). The failure points were determined, on the basis of load-settlement diagrams, and by using the set of these points, the failure envelope was plotted in the vertical load-horizontal load, vertical load-bending moment, and horizontal-bending moment spaces. This failure envelope follows a parabolic curve in V-H and V-M/B spaces. The results indicate a parabolic curve for the failure envelope in V-H and V-M/B spaces which is dependent upon the diameter ratio. Moreover, the most efficient of a ring footing during eccentric or inclined loading takes place when n is within a range from 0.2 to 0.4.

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1. Introduction

Ring footing is a special type of shallow foundation which is circular and hollow. The ring footing sometimes can provide a larger bearing capacity in comparison to a circular footing with the same diameter. The ring footings are used for supporting telecommunication towers, silos, bridge piers, advertisement boards, coastal and offshore structures. Vertical bearing capacity and settlement of ring footings are considered by researchers with various methods [1-6]. Based on the type of structure, the foundation may be affected by the inclined or eccentric loading or both of them. Classical researchers have studied the bearing capacity of shallow foundations under the aforementioned loads and reported some empirical factors [7, 8]. The inclined or eccentric loading can be considered as a combination of vertical force (V), horizontal force (H), and moment (M). This combination can affect the footing behavior. Some researchers investigated the behavior of shallow footings under combined loading including V-H-M, to find the mechanism of soil failure. This allows the plot of the three-dimensional failure envelope for a shallow footing. The behavior of a shallow foundation under different loading paths can be evaluated using a 3D failure envelope. Each point inside the failure envelope represents a state of possible loading, and the points on the border indicate the state of failure occurrence. In addition, if a point is outside the failure envelope, it is considered an impossible point [9-15]. The aforementioned literature review indicates that researchers have focused on the effect of the diameter ratio upon settlement and bearing capacity of ring footings under vertical load. In addition, some studies were carried out to find the optimum diameter ratio when only a vertical load was applied on the ring footing. However, no attempt has been ever made to investigate the bearing capacity of a ring footing behavior that supports combined loading as V-H-M. Therefore, the current study investigates the bearing capacity of the ring footing under combined loading by considering various loading paths for different diameter ratios. The obtained results are used for plotting in the three-dimensional failure envelope of ring footings within V-H-M/B space.

2. Methodology

In this study, one circular and three-ring footings with a diameter ratio of 0.2, 0.4, and 0.6 were defined. The the outer diameter of all footings was 200-mm and made from 20-mm-thick steel. The footings model were located on the soil surface (Df = 0), and some sand was glued to the underside of each footing to get coarse, and thus to increase the interface friction. Drawing a failure envelope in V-H-M/B space for sandy soils needs to define various loading paths. By combining vertical and horizontal loads as well bending moment, six loading paths were tested as described below:

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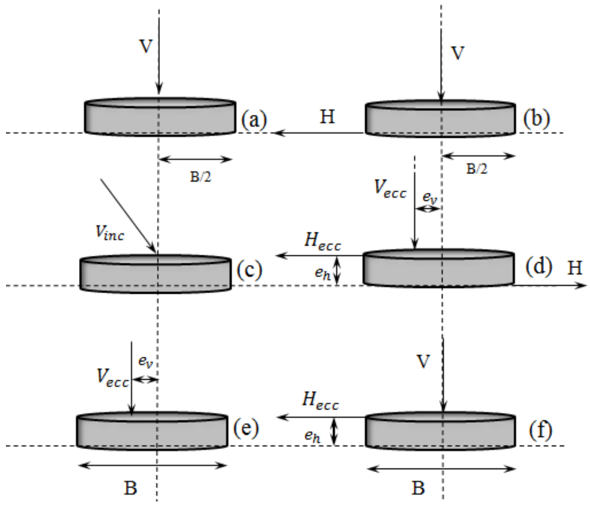

Fig. 1. Loading states

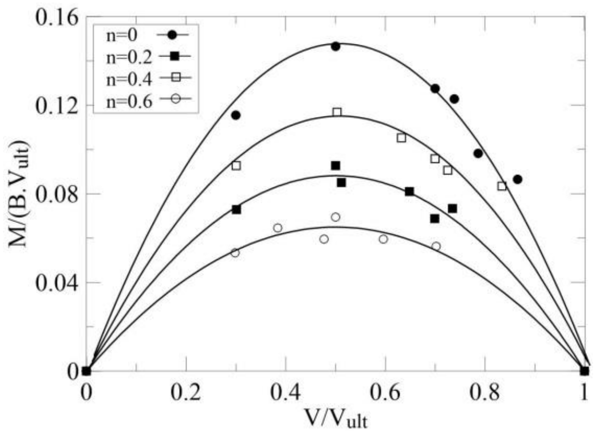

Fig. 3. Failure envelope of the ring footing in $M/(B.V_{ult})$-V/V_{ult} space

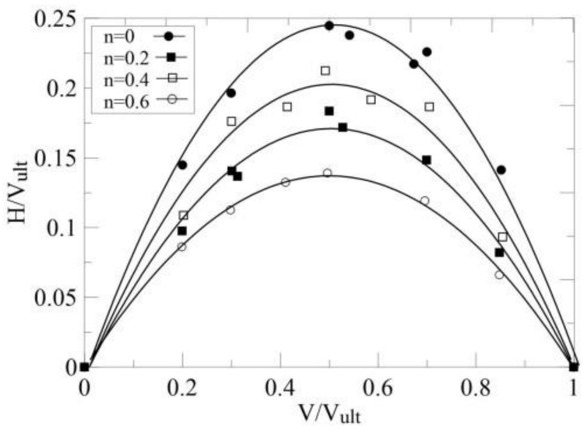

Fig. 2. Failure envelope of the ring footing in H/V_{ult}-V/V_{ult} space

V-C path: The purpose of this loading path was to obtain the bearing capacity of both ring and circular footings under the central vertical load (Vult) (Fig. 2(a)).

V-H path: Vertical loads of 0.2Vult, 0.3Vult, 0.5Vult, 0.7Vult, and 0.85Vult were applied on the footings model, while the vertical load keeps constant, horizontal loading was applied until reaching failure (Fig. 2(b)).

I-C path: The inclined load was applied at the center of each footing by a constant angle of α with respect to the vertical direction as shown in Fig. 2(d).

M-V path: The moment was applied on the footing as a couple. First, the ring footing was vertically loaded (0.3Vult, 0.5Vult, and 0.7Vult), then by keeping the vertical loads constant, the horizontal couples were applied.

E-V path: Vertical loading with a constant eccentricity (ev) applied until reaching failure Fig. 1(e).

V-H-M path: Vertical loading was applied on the footing until a constant value (0.3Vult, 0.5Vult, and 0.7Vult), then horizontal forces were applied with two certain eccentricities as shown in Fig. 1(f).

The failure criterion for the whole loading path is that the ultimate slope of each graph becomes zero. Since the sandy soil used in this study had a medium density, no maximum point was found in load-settlement curves.

The sand used in this research was chosen from Firuzkuh located in Tehran province, Iran. The internal friction angle of the soil was measured 36o by conducting a direct shear test. The specific gravity of the soil particles was determined 2.71 by the water pycnometer method. The pluviation system was employed to prepare medium sand with 70% relative density. Based on this density, dry unit weight was calculated as 15.2 kN/m3. The maximum and the minimum dry unit weights of the sand were found to be 16.38 and 14.05 kN/m3, respectively, using a vibratory table

3. Discussion and Results

Three spaces including V-H, M/B-V, and M/B-H are considered to investigate the shape of the failure envelope. Concerning the experimental observation, the failure envelope through V-H, M/B-V, and M/B-H spaces are investigated. It can be estimated as a parabolic curve for the failure envelope to predict the behavior of a ring footing. To compare the results, different failure envelopes are plotted in a dimensionless V/Vult-H/Vult space. This provides an investigation into parameters do not affect on ultimate load (see Fig. 2).

The failure envelope for each diameter ratio is drawn in M/B-V space. By drawing the failure envelope in a dimensionless space such as M/BVult-V/Vult, it is found that the graph maximum occurs at 0.5Vult. In addition, the most value of the envelope depends on the diameter ratio of the ring footing as shown in Fig. 3.

Three failure envelopes are drawn in H/Vult-M/BVult space for each diameter ratio using three plates with constant vertical loads of 0.3Vult, 0.5Vult, and 0.7Vult. Fig. 4 depicts three failure envelopes through H/Vult-M/BVult space for a ring footing with n=0.4. The results indicate that the biggest failure envelope in H/Vult-M/BVult space is related to V=0.5Vult.

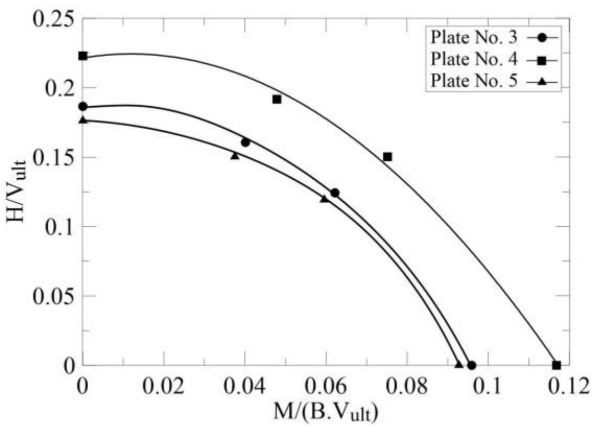

Fig. 4. Failure envelope of the ring footing in H/V_{ult}-$M/(B.V_{ult})$ space

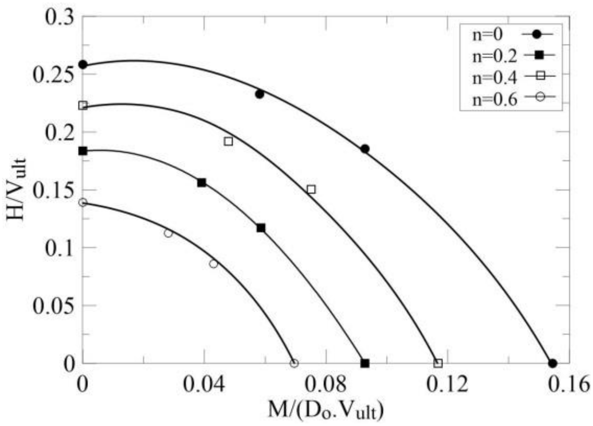

Fig. 5. Influence of diameter ratio of the ring footing on the size of plate 4 in H/V_{ult}-M/BV_{ult} space

Fig. 5 shows the effect of the diameter ratio on the failure envelopes in H/Vult-M/BVult space.

Combining the results derived for the failure envelopes in 2D space leads to an equation that expresses the 3D shape of the failure envelope as follows:

$$\left(\frac{H}{\beta_1 V_{ult}}\right)^2 + \left(\frac{M}{\beta_3 B V_{ult}}\right)^2 + c\frac{H}{\beta_1 V_{ult}}\frac{M}{\beta_3 B V_{ult}} = \left(\frac{V}{V_{ult}}\left(1-\frac{V}{V_{ult}}\right)\right)^2 \tag{1}$$

Equation (1) describes the geometrical shape of a rugby ball, which is the shape of a ring footing failure envelope.

4. Conclusions

In this study, 100 experimental tests are performed to investigate the behavior of the ring footings resting on sandy soils under combined loading. Due to this, eight loading paths are considered and the obtained results are summarized as follows:

(1) Increase in the vertical load does not increase the horizontal bearing capacity of a ring footing all the time.

(2) The failure envelopes in H-V and M/B-V spaces are governed by a parabola, in which the maximum position of the curve occurs at 0.5Vult.

(3) The failure state is independent of the loading path and it is enough to touch the failure envelope through an arbitrary path.

(4) The geometrical shape of the failure envelope in M/BVult-H/Vult-V/Vult space is quite similar to a rugby ball, regardless of the other parameters of footing and soil. The volume of this 3D envelope varies with the ring footing diameter ratio.

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