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Riskiness of Size of Sinkhole Beneath the Center of Raft Foundation

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Abstract: Since, the collapsible soils covers considerable areas in Iraq, cavitations and sinkholes are likely to be formed. These phenomenapose a threat to stability of foundation of structures and infrastructures. The riskiness becomes more serious when losing a considerable supporting soil under foundations. Therefore, this study tried to understand the behavior of Raft Foundation when a sinkhole formed at its center with different sizes. The distribution of displacement and soil reaction were the main studied variables. SAFE 2014 (CSI) Software was employed to analysis the models. Winkler Model was adopted to simulate the soil-structure interaction. The results show that the position of maximum displacement and soil reaction were turned from corners in the case of basic model (no sinkhole) to the center of foundation. Moreover, the results display that the size of sinkhole to the size of foundation at which the failure occurred was 0.45 and above.

Key words: Raft Foundation, sinkhole, Winkler Model, SAFE 2014 (CSI), sizes, corners

INTRODUCTION

Sinkhole and cavitation due to karstic feature of some soils is of troubling problems to geotechnical engineers (Tan and Chow, 2006; Xeidakis *et al*., 2004). The soilsundergo to such phenomenainvolved limestone, dolomite, gypsum and anhydrite. They are classified as collapsible soil and possess solubility characterization and prospective of cavitation and sinkhole (Buck, 1992; Tan and Chow, 2006; Scheidt *et al*., 2005). In Iraq; karstified areas coverseveral parts as shown in Fig. 1. These areas consist mainly of limestone and gypsum. Therefore, sinkholes are likely to be formed in that area particularly near the movement of water (Sissakian and Al-Mousawi, 2007; Sissakian *et al*., 2011; Abdulameer, 2016).

There are many hazards associated to sinkhole formation. In addition to human life, the main hazards are environmental, economical and damage of structures and infrastructures (Scheidt *et al*., 2005; Sissakian and Al-Mousawi, 2007; Niu *et al*., 2015). The risk trend increased when the sinkhole formed under foundation after construction and precautions were not takenduring design stage. Hence, the behavior of shallow and deep foundationsface such situation should be studied extensively. Some studies have dealt with difficulties facing the geotechnical engineers due to karstic characteristics of deep foundation over limestone area. They discussed some design aspects and guidelines needed to be followed by designers and construction engineers (Tan and Chow, 2006). Richart and Zia (1963) studied the design of foundation in case of sinkhole formation under foundation. They suggested a useful curve to help the designer in such cases.

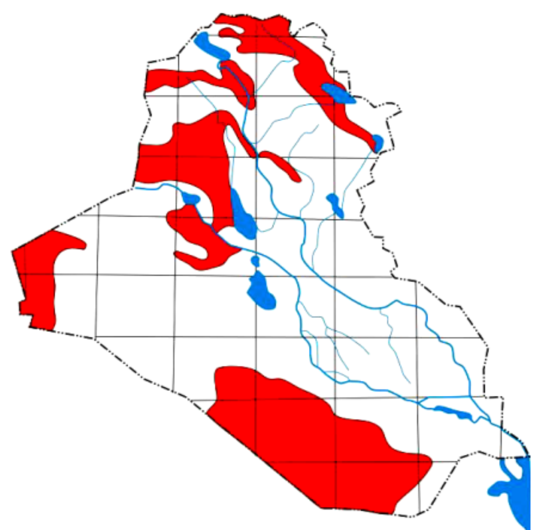

Fig. 1: Karstified areas (red color) in Iraq (Sissakian *et al*., 2011)

The current study involved the behavior of Raft Foundation under the effect sinkhole formation after construction. It takes into account the size of sinkhole located under the center of foundation aiming to observe the critical size of sinkhole and evolution of geotechnical behavior of raft foundation regarding the displacement and soil reaction.

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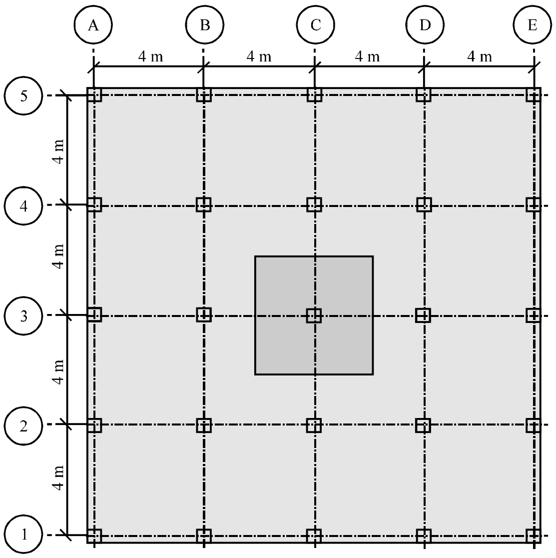

Fig. 2: Details of adopted raft foundationand position of sinkhole

MATERIALS AND METHODS

A Square Raft foundation of dimensions (16.5×16.5) m was adopted to study the above objectives. It is divided into four spans in each direction. The columns are also square of dimensions (500×500) mm. These details were shown in Fig. 2. The applied loads on the centers of columns were dead load of 350 kN and live load of 200 kN. The thickness of the Raft Foundation was selected according to punching shear requirement, so that, the Raft Foundation was preserved against any structural failure. The thickness of basic model (no sinkhole) was 600 mm with concrete strength of 35 kN/m^2. It is clear that the adopted model is symmetric in terms of geometry and loads. This is to easily observe any change in the behavior.

Various sizes of sinkhole under the center of the Raft Foundation were selected. It was denoted A' where A' is the area of sinkhole to the total area of raft foundation. The adopted strategy for selection of sinkhole size involves increasing the size progressively until reach the failure. Based on this strategy, it was found that 9 sizes of sinkhole were needed to reach the failure starting with A' of 0.1-0.45 with increment of 0.05 as presented in Table 1.

SAFE 2014 (CSI) Software was used for analyzing the model (CSI, SAP 2000, 2016). This software was built, so that, the finite element method is the base of analysisand designingthe slabs and foundations. Raft Foundation as a floor system can be modeled by shell element. This element could be three or four nods formulation as presented in Fig. 3 (CSI, SAP 2000, 2016).

Table 1: Relative size of sinkhole to the total area of Raft Foundation

Size of sinkhole	A' (m)
0.05	3.70×3.70
0.10	5.25×5.25
0.15	6.40×6.40
0.20	7.40×7.40
0.25	8.25×8.25
0.30	9.00×9.00
0.35	9.76×9.76
0.40	10.43×10.43
0.45	11.07×11.07

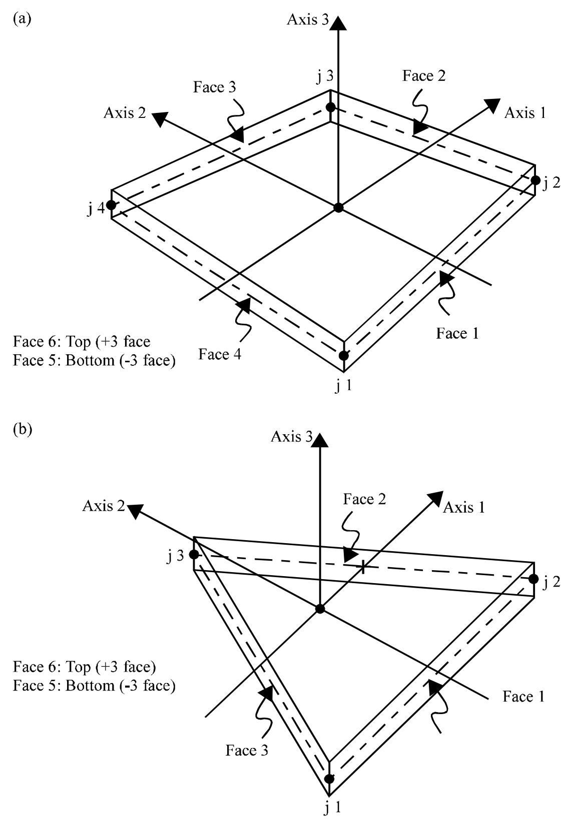

Fig. 3: Three and four nods shell element

On the other hand, Winkler Model was used to simulate the soil-structure interaction. This model exemplified the soil by a series of vertical springs. Each spring behaves isolatedly. Linear stress-strain relationship is assumed to be the behavior of soil. Although, this assumption of soil behavior doesn't present the actual behavior of soil under load action, Winkler model still reflects a good indication about the realistic soil behavior. By this model, the modulus of subgrade reaction (k) of soil is the main parameter which represents the soil behavior (Horvath and Colasanti, 2011) where $k = p/\delta$. Figure 4 presents the simulation of Raft-soil model.

Since, most of engineers are familiar with alloable bearing capacity (q_{all}) and allowable settlement (Δ_{all}), a corelation bwtween k and q_{all}, Δ_{all} was suggested by Bowels (1997) where:

$$k = \frac{FS \times q_{all}}{\Delta_{all}} \quad (1)$$

where, FS is a suitable factor of safety. So, if Δ_{all} for the Raft Foundation is 25 mm then:

$$k = \frac{FS \times q_{all}}{0.025} = 40 \times FS \times q_{all} \quad (2)$$

As per Eq. 2, subgrade reaction of 20000 kN/m^2/m (the value adopted in current study) corresponded to allawable bearing capacity of about 166.67 kN/m^2. This value is calculated based upon FS of 3.

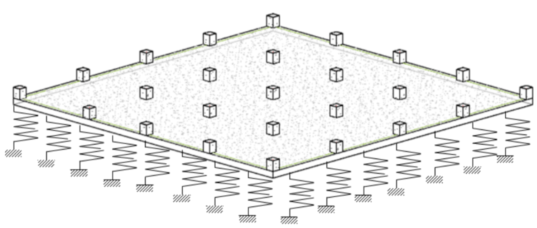

Fig. 4: Simulation of Raft-soil model

The distribution of displacement and soil reaction under the faundation are the main studied variables. The values of these variables were predicted at the center of foundation (center of sinkhole) and around the sinkholes (edges of sinkhole). In addition comparison was made between the distribution of mentioned variables in basic model and models with sinkholes. It is worth mentioning that each variable was presented under the effect of service load (i.e., DL+LL).

RESULTS AND DISCUSSION

Displacement evolution of Raft Foundation: Figure 5 displays the behavior of the Raft Foundation associated with displacement. Ten images can be seen in this figure. The first image shows the contour lines of displacement of original Raft Foundation (basic model). The contour lines of displacement of the raft foundation after sinkhole was generated beneath it can be illustrated in the other images in Fig. 5. Where, each image associated with different size of sinkhole. The color bands to the right of each image show gradient of displacement values. Where, the minimum values of were represented by blue colour gradients at the top of bands while the maximum values of were presented by purple colour gradients at the bottom of bands. In between values has been illustrated by gradient colours in the order of green, yellow, brown and red.

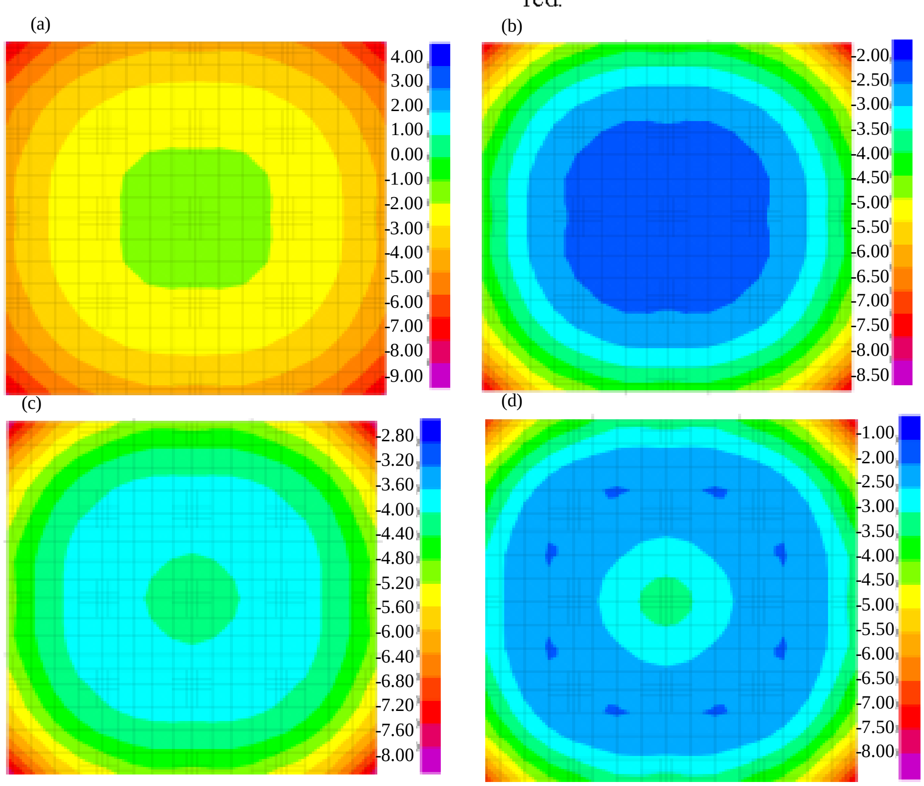

Fig. 5: Continue

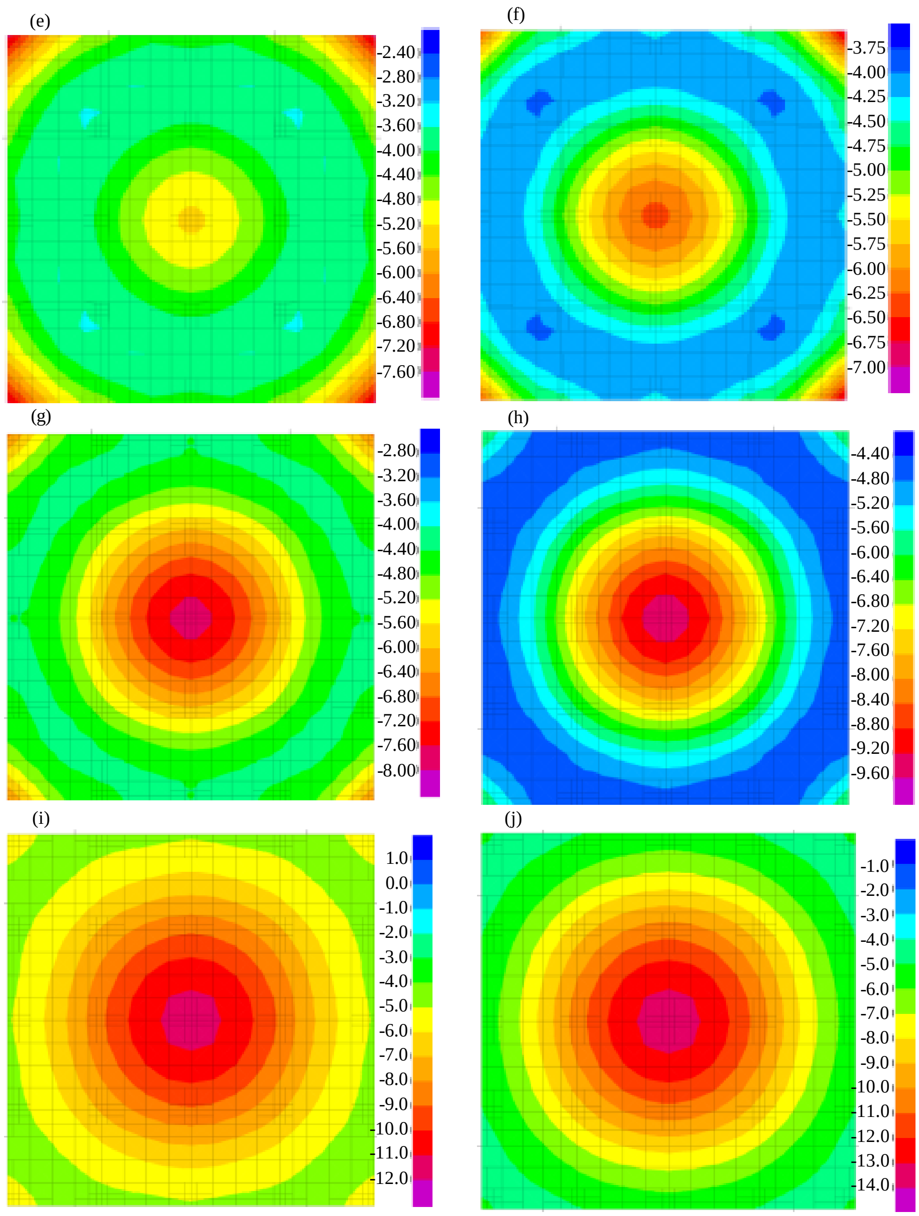

Fig. 5: Contour lines of displacement of the Raft Foundation; a) Displacement of basic model; b) Displacement of A' = 0.05; c) Displacement of A' = 0.1; d) Displacement of A' = 0.15; e) Displacement of A' = 0.2; f) Displacement of A' = 0.25; g) Displacement of A' = 0.3; h) Displacement of A' = 0.35; i) Displacement of A' = 0.4 and j) Displacement of A' = 0.45

Based on the above, for the basic model the minimum displacements located at the center of foundation (green color) and increases gradually passing through yellow and brown gradients toward the edges (corners) where the maximum values of displacement in red color. On the other hand, the images of Raft Foundation with sinkholes show that the displacement at the center increased gradually with increasing the size of sinkholes. Where the color of contour lines changes from blue in the case of A' of 0.05 passing through green, brown, red and purple colour in the cases of A' of 0.1, 0.15, 0.2, 0.25, 0.3, 0.35, 0.4 and 0.45, respectively.

It can be seen that the position of maximum displacement moves gradually with increasing the size of sinkhole toward the center of Raft Foundation. In agreement with above results, Fig. 6 displays the variation of displacement with different size of sinkholes. It is clear that the maximum displacement increased with increasing

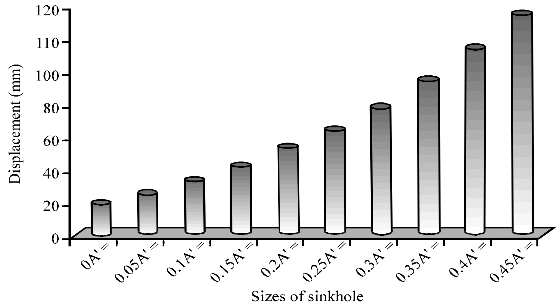

Fig. 6: Maximum displacements evolution with sizes of sinkhole

the size of sinkhole. Moreover, the position of maximum displacement moves gradually toward the center of foundation where the sinkhole was formed.

Evolution of soil reaction: The same color band with same color ramp of blue, green, yellow, brown, red and purple shows the change in soil reaction. This colour progression corresponds, respectively the minimum to maximum displacement over whole area of Raft Foundation. Figure 7 presents the soil reaction change under foundation. The basic model shows that the reaction at the center of foundation is the minimum value in green color. Moreover, moving toward the edge of

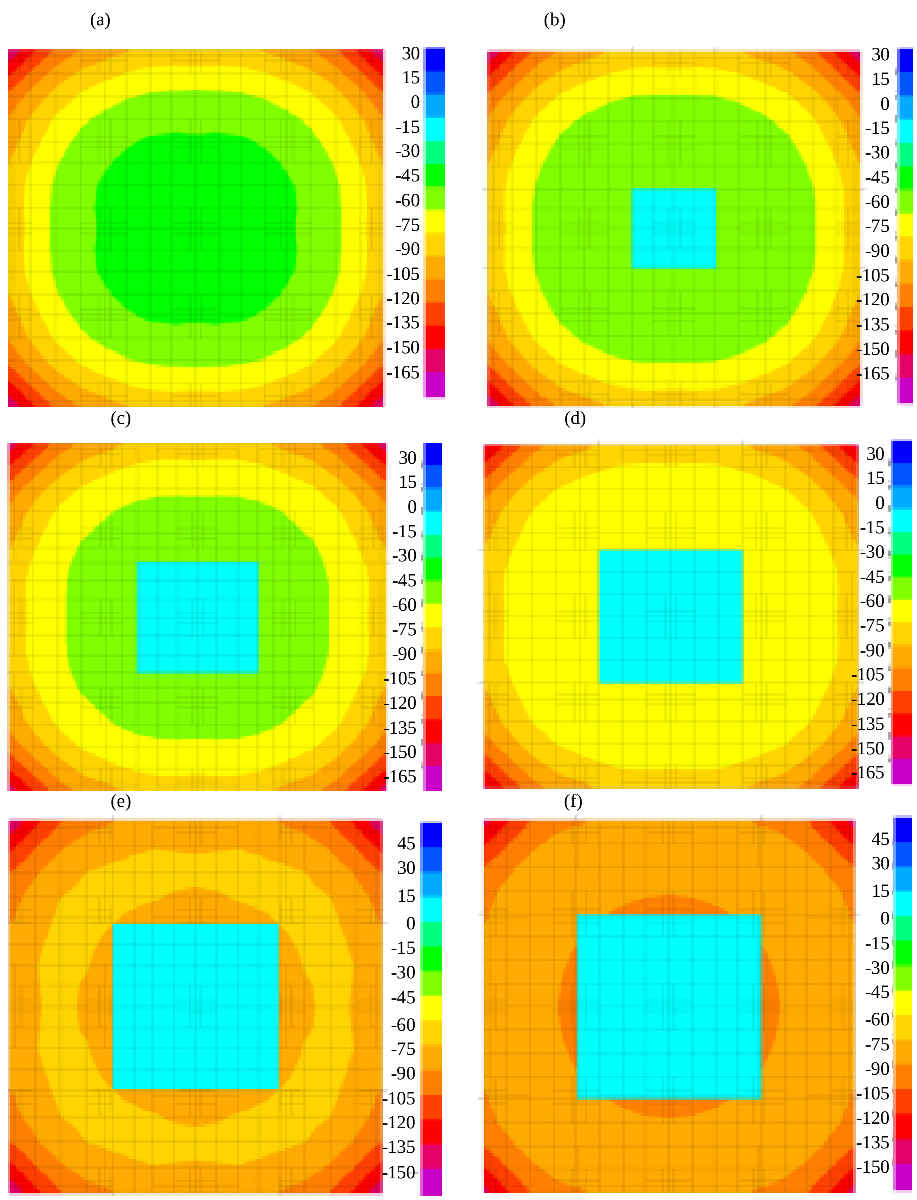

Fig. 7: Continue

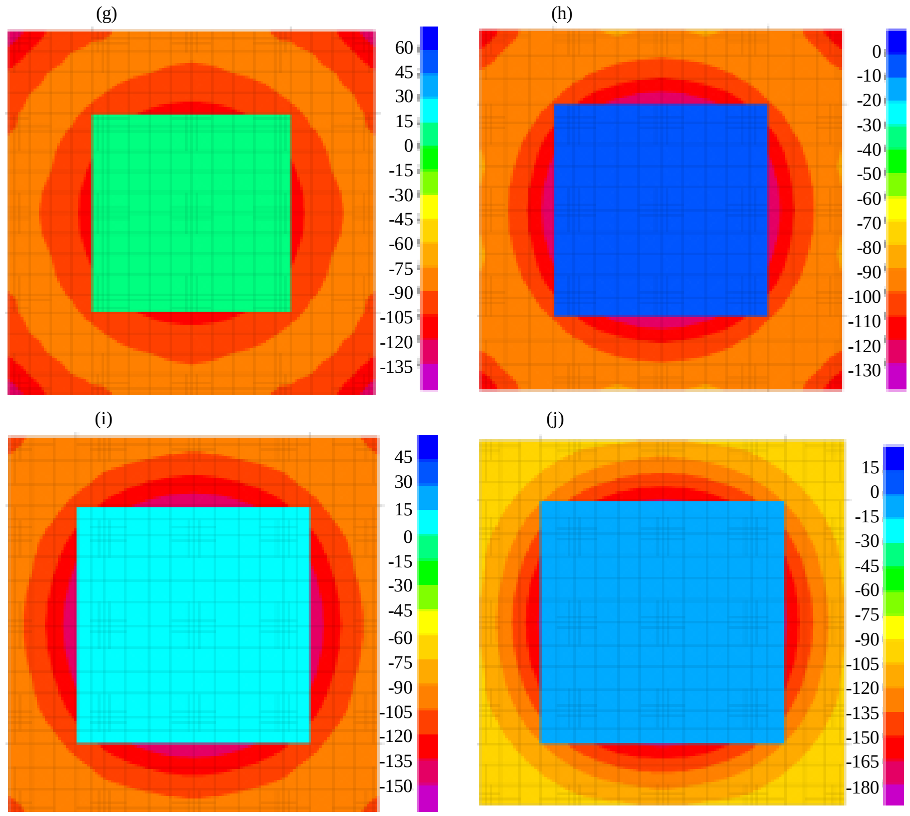

Fig. 7: Contour lines of soil reaction under the raft foundation; a) Soil reaction of basic model; b) Soil reaction of A' = 0.05; c) Soil reaction of A' = 0.1; d) Soil reaction of A' = 0.15; e) Soil reaction of A' = 0.2; f) Soil reaction of A' = 0.25; g) Soil reaction of A' = 0.3; h) Soil reaction of A' = 0.35; i) Soil reaction of A' = 0.4 and j) Soil reaction of A' = 0.45

foundation, soil reaction increases progressively to attain maximum value at the corners. Where, the counters lines turned in the order of green (at the center), yellow, brown and red gradients (at the corners).

The Raft Foundation with sinkholes experiences changes in values of soil reaction. Furthermore, the soil reaction decreases at the corners and increases at the center of foundation (around the sinkhole). This action becomes increasingly obvious with increasing the size of sinkhole. Where, the contour lines turned from green in the case of basic model and models of small size sinkholes of A' of 0.05 and 0.1 to yellow, brown and red gradient in the case of A' of 0.15, 0.2, 0.25, 0.3, 0.35, 0.4 and 0.45, respectively.

Figure 8 exhibits the progression of soil reaction at the corners and around the sinkhole sunder the raft foundation with increasing the size of sinkhole. The general trend of this column chart shows that the reaction at the corners decreases with increasing the sinkhole size. This behavior accompanied with increasing the reaction around the sinkhole at the center of foundation. It can be

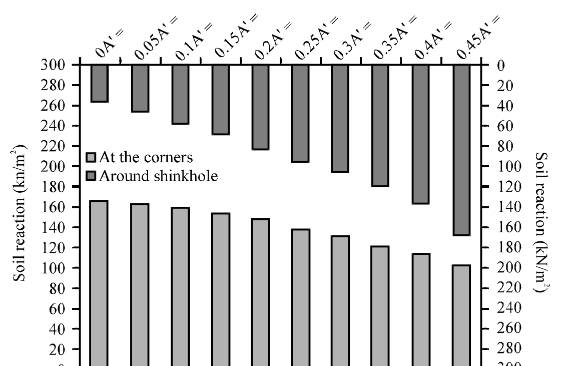

Fig. 8: Change of soil reaction at the corners and around sinkholes

observed that that in the case of A' of 0.45 the soil reaction reaches a value of 167.85 kN/m². This value exceeds the allowable soil pressure of 166.67 kN/m² by a little bit. So, it is expected that the failure could be occurred at A' of 0.45 and above.

CONCLUSION

Based on the obtained results, the sinkhole formed at the center of raft foundation inducessub stantially changes in geotechnical behavior of Raft Foundation. The following conclusions can be drawn:

For basic model (without sinkhole), the distribution of displacement under the foundation shows minimum values at the center area and increased gradually toward the corners. This behavior reversed when the sinkhole formed at the center of foundation. Where, the displacement at the corners decreased dramatically with the size of sinkholes and tends to increase in the direction of the center. This behavior continued until the maximum displacement will be at the center (the position of sinkhole) and the minimum values turned to be at the corners.

The soil reaction distribution displays maximum range near and at the corners of basic model and declined toward the center. On the other hand while the size of sinkhole increased, the soil reaction decreased progressively at the corners and growth on the way to the center of the foundation.

The failure is expected to be occurred in the case of sinkhole area to the area of Raft Foundation of 0.45 and above. Where the soil reaction exceeds the permissible soil pressure value.

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