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Numerical Analysis of Interaction Between Earth and Large Foundations Regarding Size Effect

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Abstract: In this study, change in behaviors occurring beneath and around the foundation which caused by changes in foundation dimensions is studied numerically, by taking into account the interaction between earth and foundation. To do so, two dimensional and constant computational models with constant domain under uniform distributed load for both large and small foundation have been analyzed using ANSYS software, version 8.1. The results of this analysis clearly show that the earth beneath and around small foundations is shearing and general failure mechanism, which is the same as the predicted behavior and accepted failure mechanism most researchers believe in. But, based on the results obtained from this research, the earth located in the central areas as well as the earth under the large foundations is mainly bearing compressive and comprehensive stresses having hardening. Consequently, their endurance is gradually increasing. Hence, the stress concentrations as well as the deformations are directed toward this region. In case loading is constant, the regions outside the foundation and beneath (the sides) bear unloading (localization). While footing dimensions increase, rigid wedge angle will be increased up to 90°. Thus, the failure mechanism in large foundations is local and forming a resistant. Such resistance creates bearing column beneath the foundation and punching effect which happens between the earths under the vicinity of the foundation is clearly seen. Namely, if soil behavior and properties change, the foundation geometry will change as well. So, with regard to geometry increase and with the change in the behaviors of the earth material, the stiffness matrix changes which is in the form of coupled.

Key words: Soil behavior, failure mechanism, localization, modeling, large deformation

INTRODUCTION

At first Terzaghi (1943) studied change in the properties of soil behavior beneath and around the foundation (Terzaghi *et al.*, 1996; Meyerhof and Hanna, 1963). It is based ultimate bearing capacity theory for strip footing. This theory is explained by failure mechanism and width footing. Later on, Meyerhof and Hansen (1963) expanded Terzaghi theory. They considered other parameters to complete Terzaghi equation. More studies about bearing capacity are concentrated on the third coefficient bearing capacity ($N\gamma$) and failure mechanism is assumed general (Fig. 1), which is explained by Terzaghi (1943) and Bowles (1982).

Recently, Zhu *et al.* (2001) showed that bearing capacity and Terzaghi failure wedge position are related to width footing. According to studies, this researches for strip footing, while width increased from 0.1 to 10 m, ultimate bearing capacity calculated, increased from 620 to 12300 kPa and for circle footing ultimate bearing capacity increased from 290 kPa to 6730 kPa and wedge angel decreases from 57.9° to 52.2°. In later study performed by Junhwan *et al.* (2005), using finite elements method (FEM) on bearing capacity it was concluded that there are many uncertainties in the Terzaghi theory. More challenges concentrated on real development and explanation of bearing capacity parameters.

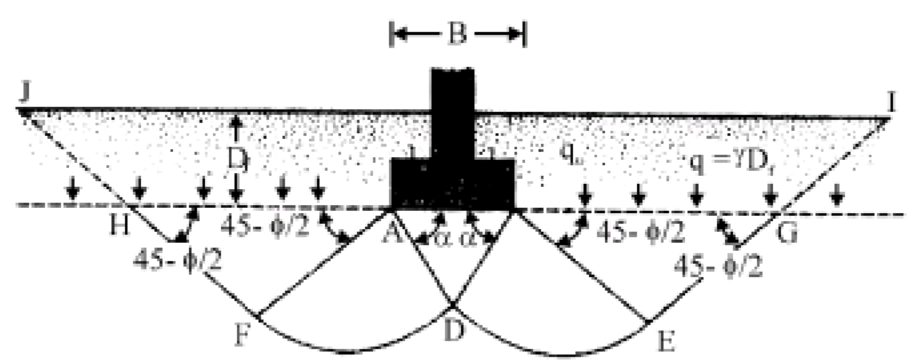

Fig. 1: Terzaghi failure mechanism

Another important subject, not considered in footing ultimate bearing capacity, is the interaction effects between earth and footing. In this paper first the different

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interaction types are both defined and classified and then considering the interaction, the behavior and role of earth under the small and large foundations are examined. Position of failure mechanism is also observed.

INTERACTION CLASSIFICATION

The interaction between the sections of structures is one of the most important and the most complex issue in engineering which is currently of particular interest to the researchers, designers and structural engineers; This is due to lack of information and insufficient knowledge in this area and the fact that this interaction has not yet been included in valid codes practice, generally do not take account of it. But due to the existing developments and more technological abilities as well as the owner's desire, studying and analyzing interaction is a must. To achieve this goal, the applicable solutions should be introduced which are in the hand of structural and geotechnical engineers. In general, three types (Zienkiewicz, 1991; Zienkiewicz and Taylor, 2000) of interactions including the geotechnical materials having high ductility, steel and concrete can be defined and studied:

Interaction in the form of compatibility in different material interface and contact surface (Compatibility equations contact): In this mode, the different material should be related to each other defining interface elements in contact surfaces. This element provides the compatibility and continuity conditions between the two continuums. This element contains material properties of the two media and can stand the stresses up to a certain limit, besides, stress transits between the two media continuously. After the stress reaches its final limit in the said element, the lateral elements are allowed to act independently causing segregation, i.e., in this stage the compatibility equations are not met.

Geometrical interaction (Large deformations and slipping on the contact surface): The displacement of match points of the two neighboring media is extremely noticeable and huge; so, it is likely that part of a medium is transferred and moved to another medium. Thus, we will have failure in some part of a medium. The stress-strain relations are not applicable to the boundary points of the two media and at the point of interface the geometrical behavior of the materials should be studied as non-linear.

Behavioral interaction (Discontinuity of the material medium): In this case, it is possible to say that although the materials are constant and uniform, the behavioral properties are different at different points of the ambient material; this kind of interaction is conceptual and is only considered in overall modeling of the foundation system and the effective part of the earth (domain). However, in the interaction of earth and structure, beside structural system, the nonbearing members such as walls and fillers and should be considered as well. This results in the complexity of the analytical model and the modeling method.

Currently, most models are finite elements or boundary elements that their application will be commenced or the earth is considered as a set of springs with linear stiffness which has basic differences with the real state. Calculating the deformations, earth behavior should be taken in to account. In small deflections, the deflection effect on the finishing or partitions or fillers become important, while under the major deformations, especially during the earthquake, the location of the filler walls is due to mass distribution and creating rigidity and interfering with the stiffness matrix. Namely, in large deformations of the earth, the limit and the definition of the structure is changed owing to the entrance of non-structural elements to the structure. Here, new elements are also involving in which their interfering rate depends on their geometry, material and adherence (link) to the main structure. This change in the stiffness matrix as wall as the interference of the new elements are changed with respect to the rate of deformation and failure of the old elements which can be considered and estimated using failure mechanic. To compute the stresses and deformations, the earth is usually modeled as a continuous medium (semi- infinity). In this study, efforts have been made considering large deformations and interaction of foundation type (2-1) and part of the earth beneath and around it is modeled and foundation dimension variation effect on the earth behaviors under and around the foundations is studied and analyzed.

ANALYSIS METHOD OF EARTH AND FOOTING INTERACTION

There are generally two methods of analysis for analyzing earth and large footings interaction (Owen and Hinton, 1980; Zienkiewicz and Taylor, 2000; Khazaie and Amirshahkarami, 2007):

Bearing analysis using the limiting equilibrium method (failure analysis and determining the safety factor): In order to study and determine the safety factor regarding the behavior of the earth beneath the large foundations, the limiting state analysis should be conducted first. As for the limiting analysis method, it is usually necessary to define and have the failure mechanism, i.e., define and illustrate surface areas on which the material (medium) slips and fails. When loading the foundation, some segments (areas) are formed in the earth beneath and around the foundation including the foundation itself and these segments slide on each other. The above-mentioned failure mechanism has been defined by Terzaghi (1943) and is only true for the small foundations (spread and strap footing. The bearing capacity relations have been presented based on it; however, it seems that is not the case for foundations with large dimensions (Mat foundation).

Deformation analysis: This analysis is very complicated and difficult. Here, the quality of the footing behavior on the ground under the distributed load and effective parameters on the layers behavior and the earth elements are presented. What is very important is distinguishing and identifying behavioral differences between layers and the soil beneath the foundation depth in the earth under the foundation. Columns of soil located exactly in the middle and under the foundation there are different behaviors of soil columns around the footing. From analytical point of view, such behavior is only possible when numerical methods are used; that is, the base of analysis theory of deformations.

COMPUTATIONAL MODEL

The proposed model: In this study to predict and interpret the results obtained from ground behavior analysis beneath large and small foundations, softened continuous loops method of a conceptual model has been used to adjust the concentration of deformations (localization) and to interpret more real behavior of materials (Zienkiewicz and Taylor, 2000; Amirshahkarami, 1978-2007).

According to this model in the method of analysis based on deformations due to the uniformly assumption of chains behavior as well as uniformity of the load rate in them, the failures are similar to each other and total deformation equals sum of the deformations in all loops. To justify the concentration of deformations in Fig. 2 it is assumed that from behavioral point of view, five loops are not similar to each other and one of the loops -for instance loop No. 3 is weaker than the other loops. Before the behavior of loop No. 3 gets loops, the behavior of the system as well as the behavior of all loops is similar and from the moment loop No. 3 reaches loose state, the overall system acts in the feeling state caused by loop No. 3. In this mode, loop No. 3 is under load whereas loops No. 1, 2, 4 and 5 bear unloading mode and shrink (Fig. 3).

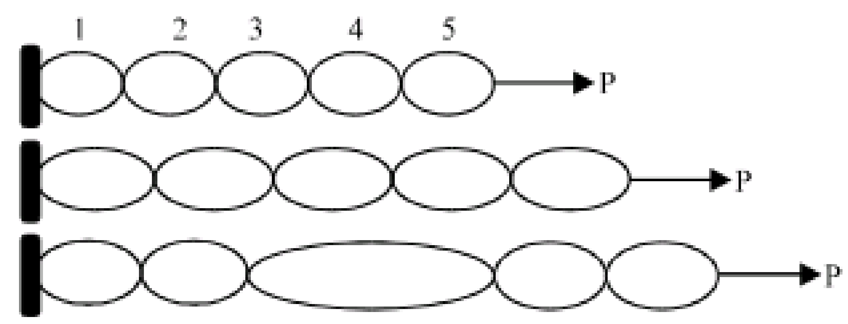

Fig. 2: Schematic diagram of softened continuous loops

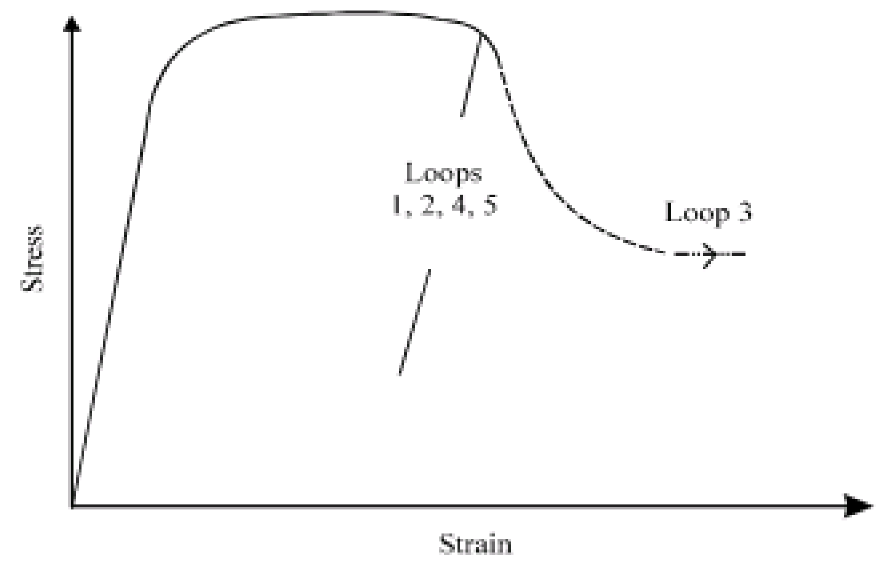

Fig. 3: Schematic curve of softened continuous loops behavior

Here, total strain of the system with respect to the strain in loop No. 3 which is in the feeling mode and also deducting, the amount of shrinkage in other loops, the following equation is obtained:

$$\Delta\delta_t = \Delta\delta_{P(3)} - \Delta\delta_{e(1)} - \Delta\delta_{e(2)} - \Delta\delta_{e(4)} - \Delta\delta_{e(5)} \tag{1}$$

If shrinkage rate in loops No.1, 2, 4 and 5 are equal, (then) we have:

$$\Delta\delta_t = \Delta\delta_{P(3)} - 4.\Delta s_{e(1)} \tag{2}$$

It can be observed that by applying loading, one loop starts noticeable deforming and ultimately fails while others tend to return to their initial form, namely, the deformations are concentrated on one loop and the rate of deformation in other loops is decreased, this phenomenon is know as deformation concentration (Localization).

Modeling: Modeling and finite analysis of elements have been performed in ANSYS software version 8.1. In this study in order to geometrically idealize according to Fig. 4, consider three types of interaction between foundation and ground. Constant media including the footing and part of the soil located under and around the footing which is effective in bearing and deformation (settlement) and is large enough (about 4B at sides and beneath the large footing) have been taken into account

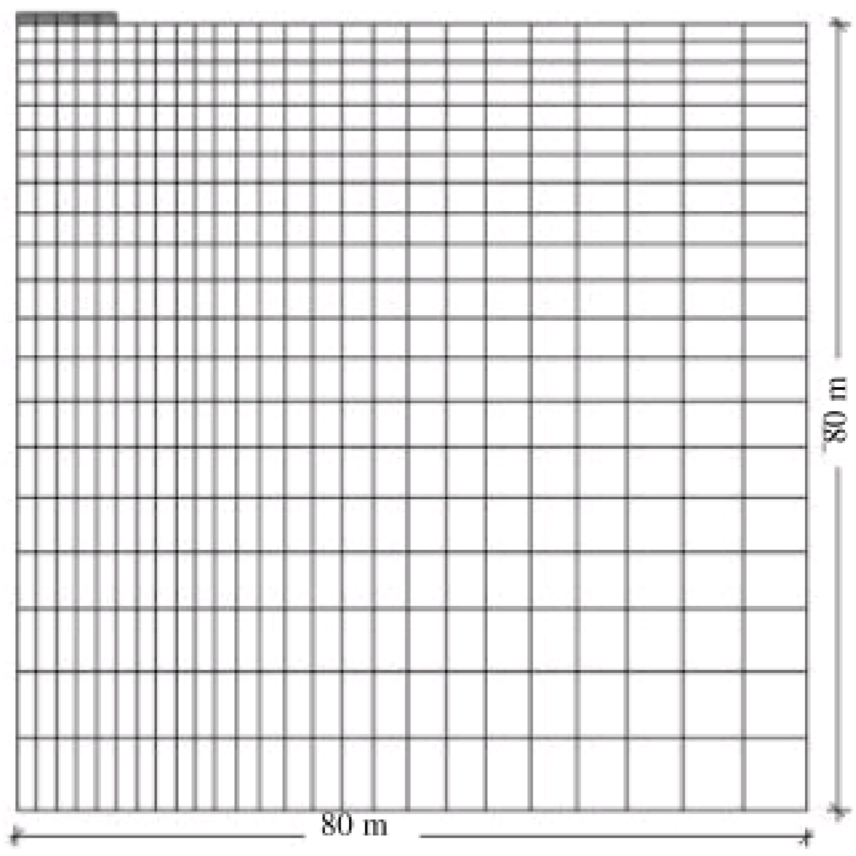

Fig. 4: Geometric modeling and domain characteristics of materials

a two-dimensional medium; Such that the boundaries of the media under study are far away enough from the point the footing is located and stress as well as deformations at those points are insignificant and negligible (Katsutoshi *et al.*, 1998, 2000). The constant grillage is independent from the footing dimensions in the studied media in order to avoid the effects of grillage change which is later followed in all large and small foundation models. The concrete footing and the soil with plane 82 elements have been modeled. This element is in the form of an eight-node and two-dimensional having three transitional degrees of freedom in each node and is able to take elasto-plastic behavior and large deformations in the plane strain state. To define the interaction between footing and ground, the 2-node contact element (contact 12) is used. This 2-node contact element; i.e., a node to node (contact), contains three transitional degrees of freedom in each node and has the ability of the initial distance. Pressure resistant in the axial direction and Coulomb frictional shear in the tangential direction are among the characteristics (features) of this element. The tangential and axial stiffness come into action when the initial distance is closed, the axial and tangential stiffness are defined based on stiffness of the contact surface and tangential resistance is also considered in the Coulomb frictional state applying the friction factor of the contact surface. It is worth mentioning that the grillage in footing and soil beneath footing have been conducted in a good manner so that for the contact elements, the corresponding nodes lie adjacent to each other.

Table 1: Mechanical properties and Characteristics of materials of the model

Material	E (kN m^{-2})	cv[2]	φ[3]	C[4]	γ[5]	Ks[6]	Kn[7]	μ[8]
				-----------(kN m^{-2})----------				
Soil-1 (Loose)	5E4	0.4	26	10	15	-	-	-
Soil-2	8E4	0.35	30	40	17	-	-	-
Soil-3 (Dense)	15E4	0.3	36	40	18	-	-	-
Concrete	2.6E7	0.15	-	-	24	-	-	-
Interface	-	-	-	-	-	8E4	8E4	0.7

[1]: Young's modulus soil, [2]: Poisson's ratio soil, [3]: Internal frictional angel soil, [4]: Cohesion soil, [5]: Unit weight soil, [6]: Sticking stiffness contact element, [7]: Normal stiffness contact element and [8]: Coefficient of friction contact element

In this study, the concrete behavioral model has been considered elastically and for soil, the Drucker-Prager behavioral model has been used which takes into account the material behavior elasto-plastically (Khazaie and Amirshahkarami, 2007). The mechanical properties and characteristics of the model materials have been shown in Table 1.

Boundary conditions and loading: With respect to the fact that the geometrical model has defined two-dimensional and is in the form of plane strain, the vertical boundaries have been limited such that the displacement is only possible in the vertical direction without friction and there is no horizontal transition. The horizontal boundary (bed) has been bounded such that it can only move horizontally. Loading on the large and small foundations have been carried out with uniform stress and small steps. The models then have been analyzed and compared with each other. In order to analyze non- linearly, the full Newton-Raphson step by step method applied and when the solution is converged in each sub-step, the outputs are stored in the nodes.

Analysis of the results with a view to the proposed model: As shown in Fig. 5a and b under the small footings, the ground beneath and around the footing both bear large deformation (failure) together. This is fully noted when studying the differential stresses and strains state in the ground under and around the small foundation which is clear from Fig. 5c and d, that complies with the Terzaghi theory. In large foundations, which can be observed from Fig. 6a and b, the earth deformations are mainly bound to the ground beneath the footing and to some extent to the punching or plastic deformation concentration mode takes place in the boundary ground between beneath and around the footing, Fig. 6d. This kind of failure mechanism is different from the failure mechanism proposed by Terzaghi on small foundations (strip footing) and the existing bearing capacity relations which have been obtained regarding the limit analysis (failure mechanism), are not valid for large footings.

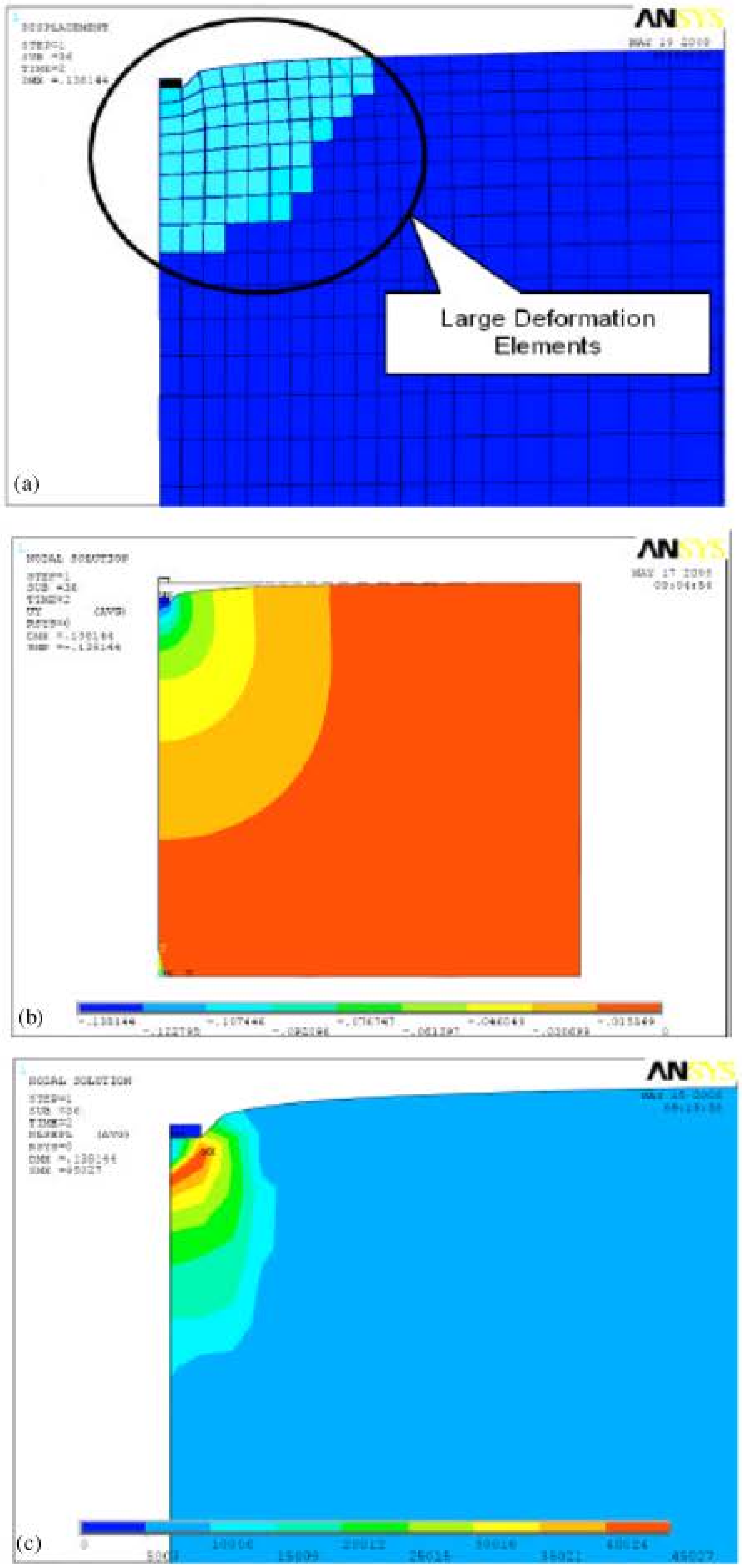

Fig. 5: Continued

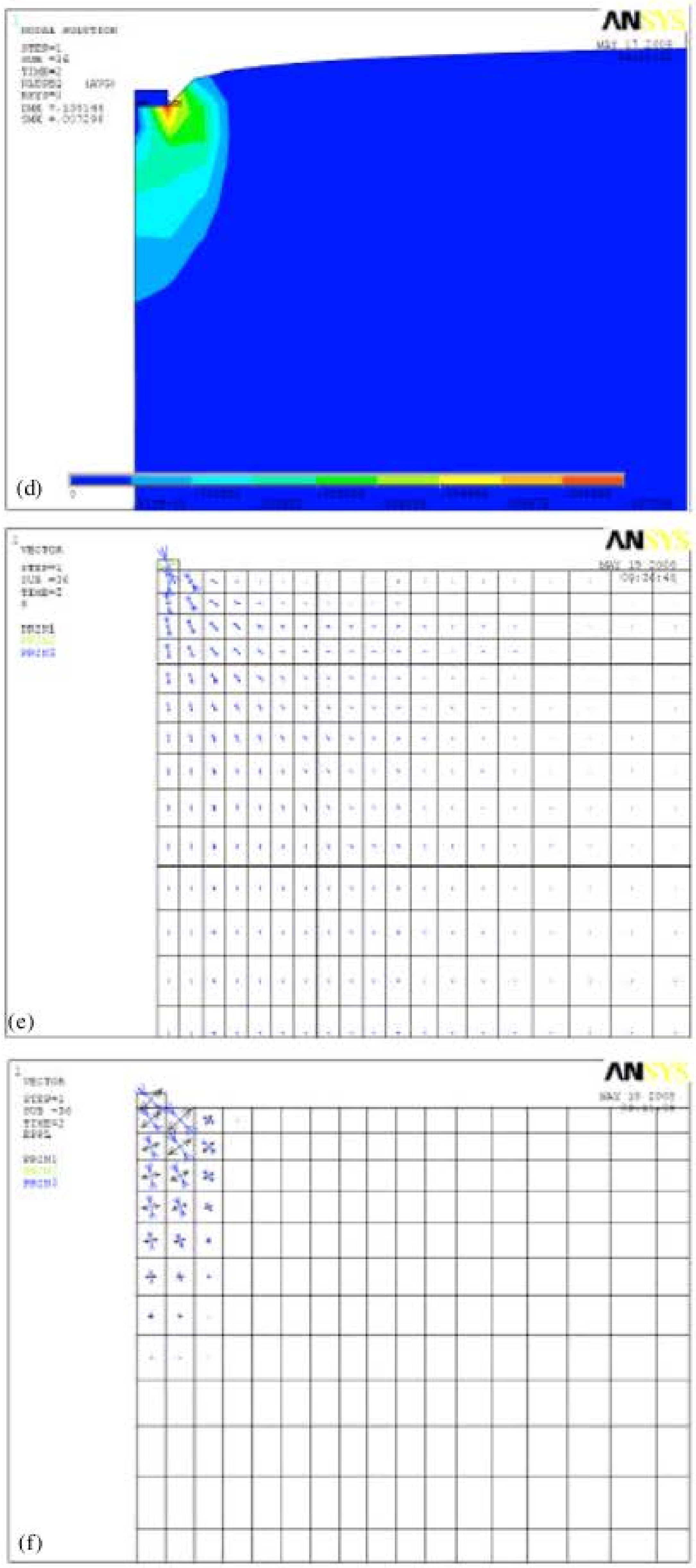

Fig. 5: Small footing (B = 2 m) under uniformly distributed load (a) Deformed Mesh, (b) Vertical Deformation cantor, (c) Von Misses equivalent plastic stress (deviatory), (d) Von Misses equivalent plastic strain (deviatory), (e) Principle stress vectors and (f): Principle plastic strain vectors

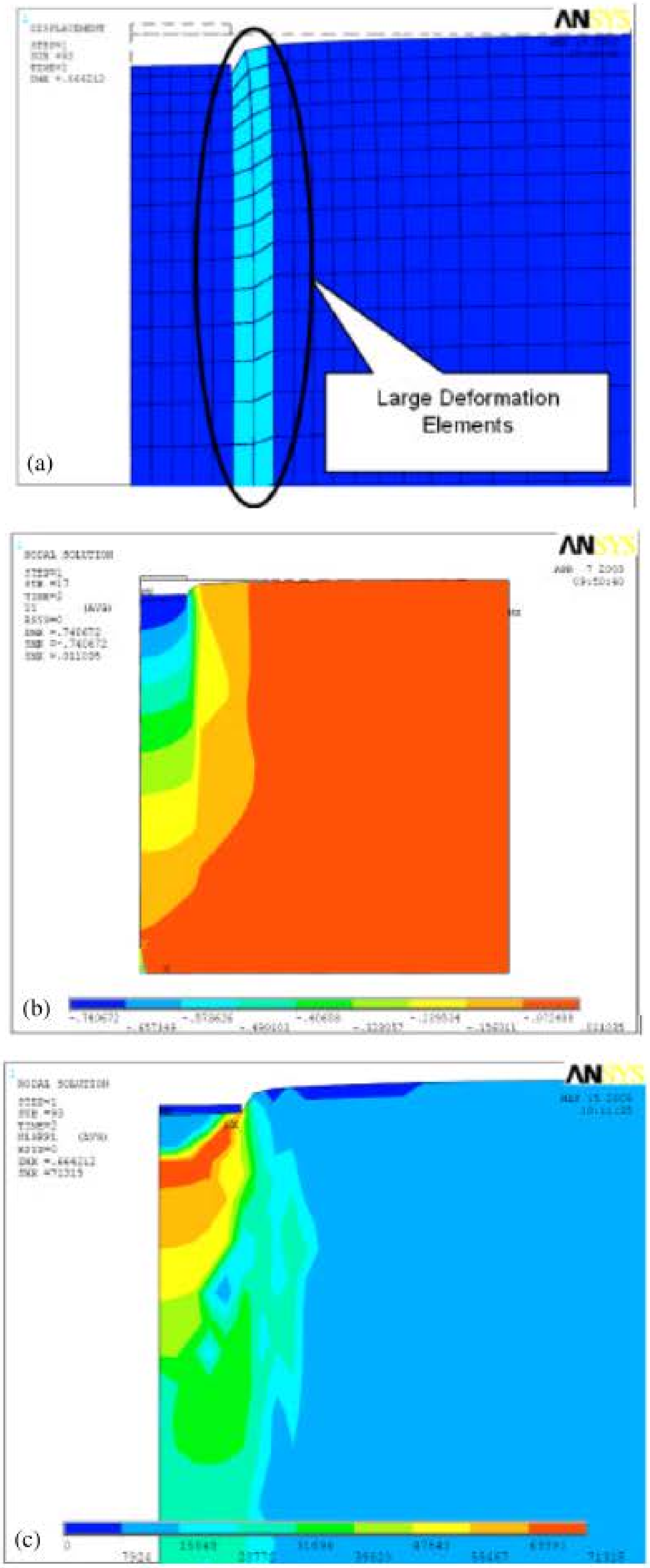

Fig. 6: Continued

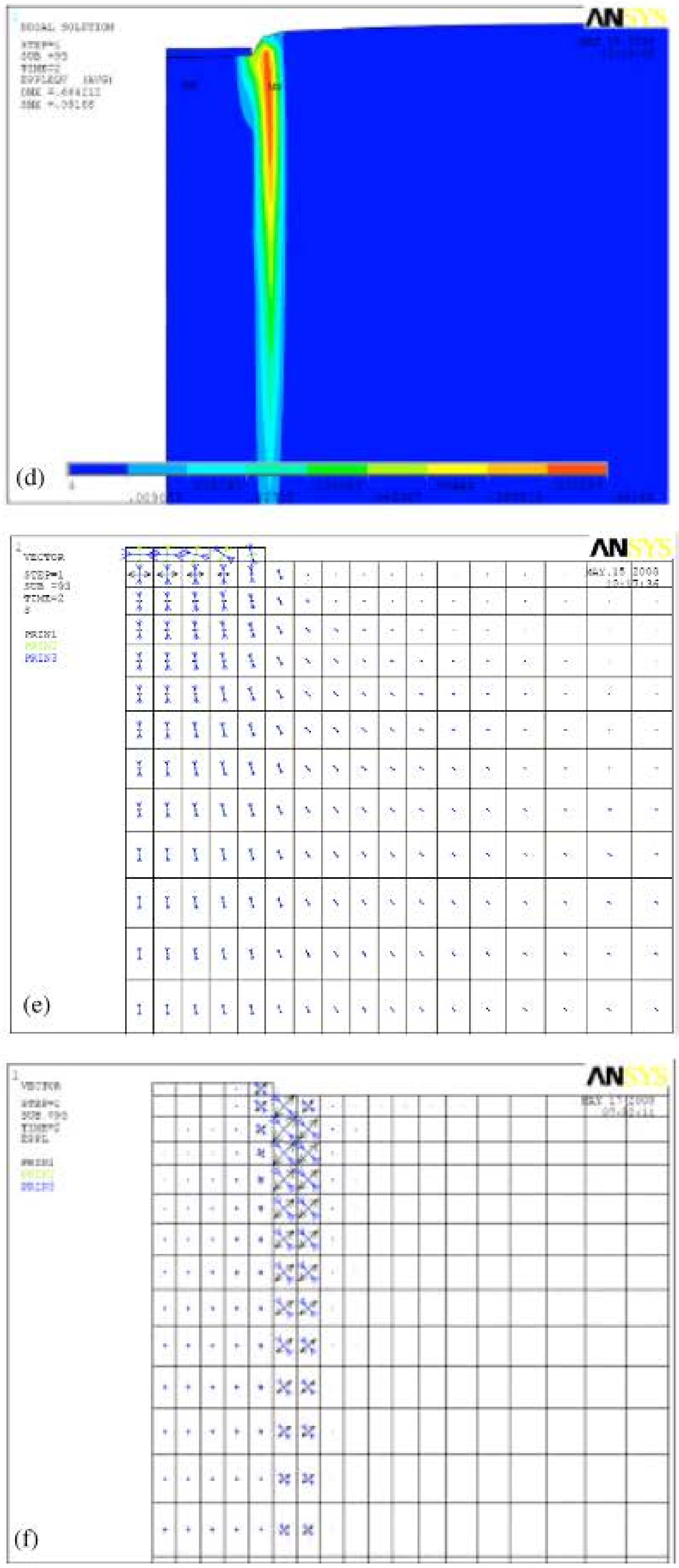

Fig. 6: Large footing (B = 20 m) under uniformly distributed load (a) Deformed Mesh, (b) Vertical Deformation cantor, (c) Von Misses equivalent plastic stress (deviatory), (d) Von Misses equivalent plastic strain (deviatory), (e) Principle stress vectors and (f) Principle plastic strain vectors

The failure mechanism in the soil beneath large footings is observed internally (a column of soil under the footing undergoes failure) thus swelling and movement of soil around the foundation is not seen (the passive zone is not distinguished/found clearly). This mechanism is different from what Terzaghi has proposed for small footings (limit width) on the soils with average and high compaction. Increasing lateral pressure (confining) the ground located under the footing will increase the pressure bearing in this region comparing regions outside this region (under the footing) which result in the formation of a column which resistant soil strongly (with high confining pressure) beneath the footing and it results in increasing the stress depth of influence and hence settlement would be higher, reasonable and expectable. According to the conventional failure mechanism, stress is distributed in the soil beneath and around the footing, so, the stress penetration depth decreases (formation of stress bubbles). This phenomenon is highly significant in settling the decline of small footing which is uniform and under loading.

According to the proposed model in this paper, in order to predict and interpret the results obtained from numerical analysis, the deformation concentration phenomenon leads to the stress releasing (unloading) in parts of the media. When a large footing undergoes load up to a certain amount of loading, the behavior of the ground beneath and around the footing is similar and the whole system undergoes deformation (Fig. 7).

Increasing rate of loading, the earth separated to deferent zones: the soil column beneath the footing enters the plastic behavior range and hence the bearing capacity of the segment increases which results in concentration and increasing stress in this region and ultimately deformation and settlement increase. In the mean time, the behavior of the parts outside beneath the footing (around the footing) is elastic and under unloading. Therefore it can be inferred that the ground outside beneath the large footing does not have a significant influence on the footing bearing and zone of between this parts is in plastic deformation and shearing (Fig. 8). In the part of earth that located under the footing σ_1 (main stress) will be vertical and in the other parts it will be horizontal and in this parts the earth have a shear fracture and in the parts that maximum main stress vertical (σ_1), soil is bearing. So, in the parts that we have a horizontal (σ_1) the back part of this zone is passive which will be susceptible to breakage, but in the parts the σ_1 is vertical, zone is active and bearing, so if footing have a large zone of the vertical σ_1, this footing have a large bearing. In the small footing this zone is small and this zone will be progress by increase of footing dimension (Owen and Hinton, 1980; Zienkiewicz and Taylor, 2000; Khazaie and Amirshahkarami, 2007).

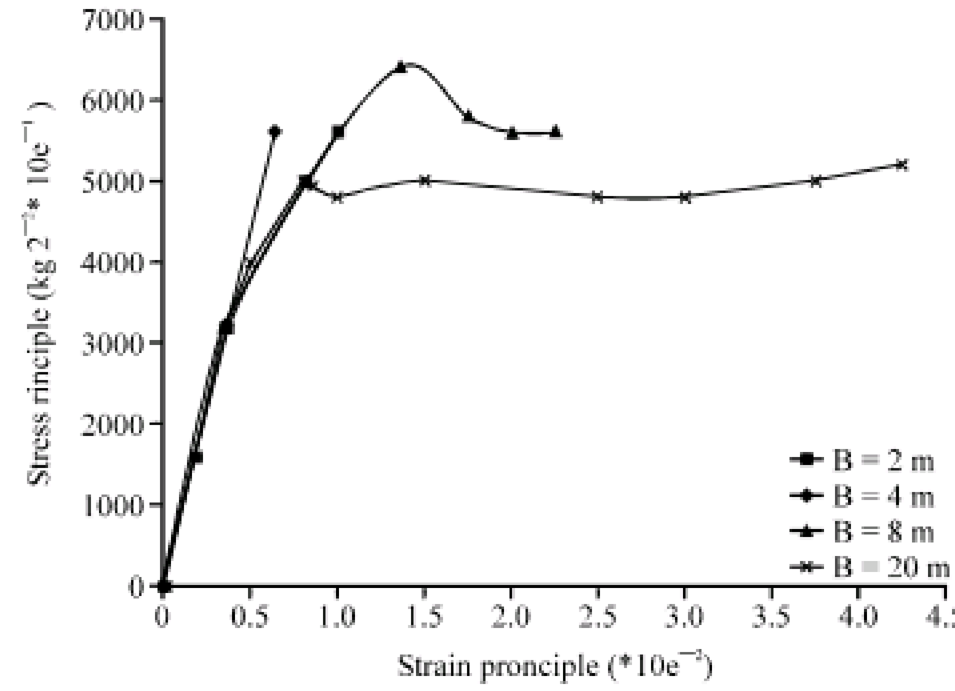

Fig. 7: Stress-strain curve in domain

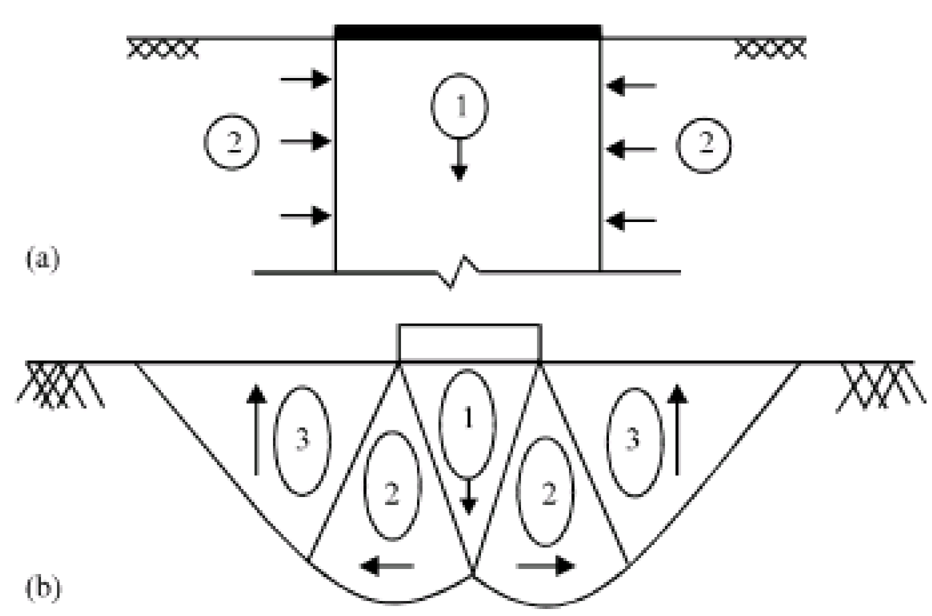

Fig. 8: Failure mechanism, (a) Large footing and (b)Small footing

In the large footing due to the increasing the confined zone that located under the foundation and decreasing deviatory stress in this zone bearing on the footing can increase. Also this agent cause the increase of reaction earth in the middle of footing compared to the edges. In region 1 the reaction of soil is less than the region 2, then by drawing the soil reaction curve and determining the inclination point we could separate two regions. Therefore when the earth is put under the vertical pressure the confined pressure will increase and it can effects to the region 1. Due to this pressure, region 1 want to move toward the edges or move up, according to the boundary conditions, none of these moves are possible for these regions then this will react as confined pressure. The confined pressure that acts from region 1 to region 2 will cause reduction of deviatory stress and breakage from shear state in the region 2. In the small footing region 1 under pressure of region 2 move up and shear fracturing will occur.

CONCLUSION

Based on the results obtained in this research, the failure mechanism for small foundations, proposed by Terzaghi and other researchers are not applicable to design large foundations in which the failure mechanism occurs regionally within the interface between the earths around and underneath them and rigid wedge angle will be increased up to 90°. Also by considering the change of property and distinction between soil behavior when it is placed under small and large foundations, predicting suitable tests in study of earth and finally selecting the best improvement method for earth underneath the foundation regarding foundation dimensions is a very important subject. On the other hand, the settlement of control problem taking into account the increase of stress in depth and in large foundations is more important than small foundations. It's obvious that the 3-D modeling can offer more accurate results and it's being prepared by the author. But the real modeling in lab is proposed by other researchers.

REFERENCES

Amirshahkarami, S.A., 1978-2007. Soil-structure interaction note. Lecture in Department of Civil Engineering, Tehran Polytechnic University.

Bowles, J.E., 1982. Foundation Analysis and Design. 3rd Edn., McGraw- Hill, New York, ISBN: 0-07-006770-8, pp: 816-816.

Junhwan, L., R. Salgado and S. Kim, 2005. Bearing capacity of circular footings under surcharge using state-dependent finite element analysis. Comput. Geotech., 32: 445-457.

Katsutoshi, U., M. Kinya and M. Yoshito, 1998. Prediction of ultimate bearing capacity of surface footings with regard to size effect. Soils Foundations, 38: 165-178.

Katsutoshi, U., M. Kinya, K. Osamu and N. Migitoshi, 2001. Reappraisal of size effect of bearing capacity from plastic solution. J. Geotechn. Geoenviron. Eng., 127: 275-281.

Khazaie, J. and S.A. Amirshahkarami, 2007. Mat foundations size effect in soil density behavior regard to the elasto-plastic models (*Shahkarami model*). Proceeding of 3rd Iranian Rock Mechanics Conference, Oct. 16-18, Amirkabir University of Technology, Tehran, Iran, pp: 21-26.

Meyerhof, G.G., 1963. Some recent research on the bearing capacity of foundations. Can. Geotech. J., 1: 224-229.

Owen, D.R.J. and E. Hinton, 1980. Finite Elements in Plasticity: Theory and Practice. 1st Edn., Pineridge Press Ltd., Swansea.

Terzaghi, K., 1943. Theoretical Soil Mechanics. 1st Edn., Wiley, New York, ISBN: 978-0-471-85305-3, pp: 528.

Zhu, F., J.I. Clark and R. Phillips, 2001. Scale effect of strip and circular footings resting on dense sand. J. Geotech. Geoenviron. Eng., 127: 613-621.

Zienkiewicz, O.C., 1991. The Finite Element Method in the 1990's. 1st Edn., Springer-Verlag, New York, ISBN: 84-87867-04-9.

Zienkiewicz, O.C. and R.L. Taylor, 2000. The Finite Element Method. 5th Edn. Butterworth-Heinemann, Oxford, UK., ISBN-10: 0340759844.