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# Modeling of uniformly loaded circular raft resting on stone column-improved ground

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**Abstract**

In the present paper, a mechanical model has been developed to study the behavior of uniformly loaded circular raft resting on stone column-improved ground. The axi-symmetric condition was considered in the analysis. The raft was idealized by a circular plate. The soft foundation soil and granular fill were idealized as the spring-dashpot element and the Pasternak shear layer, respectively. The stone columns were modeled as stiff non-linear springs. To perform an axi-symmetric analysis, stone columns are converted into equivalent concentric rings with one stone column at the center. The finite difference method is used to solve the governing differential equations. The effect of different parameters on the behavior of the circular raft over stone column-reinforced ground was also studied. It was observed that the effect of the modular ratio on the rate of decrease of vertical settlement, radial and tangential moment and the rate of increase of shear force reduces sharply above the value of 40. The shear force developed at the edge of the stone column was critical when the spacing to diameter ratio was around 2.5.


*Keywords:* Stone column; Soft soil; Uniformly loaded circular raft; Axi-symmetric analysis

## 1. Introduction

Raft foundations are often preferred for tall and heavy structures constructed on highly compressible soil. Circular rafts are used for silos, chimneys, cylindrical storage tanks and other cylindrical structures. The most suitable foundation for such structures is circular raft because of the natural geometry. In many situations, geotechnical engineers design circular raft foundations for construction on stone column-improved ground. In such cases, understanding the behavior of stone column-improved ground is very significant for the design of the circular raft.

Many researchers have studied the behavior of circular plates or circular foundations resting on soil. Selvadurai (1979, 1980) used the fundamental theorem of minimization of total energy to study the interaction between a uniformly loaded thin circular plate and an isotropic elastic halfspace. Zheng and Zhou (1988) solved the large deflection problem of nonlinear thin circular plates using a concentrated load resting on an elastic foundation. The iterative method and a numerical procedure were used to obtain the solution. Zaman et al. (1988) developed a formulation based on an energy approach to solve the problem of a uniformly loaded thin circular plate resting in contact with the isotropic elastic halfspace. Mastrojannis et al. (1988) solved the linear elastic problem of adhesive contact between an axi-symmetrically loaded circular raft and foundation soil mass by modeling the circular raft as a thin circular elastic plate. Celep (1988) analyzed a thin uniformly loaded circular plate with an eccentric point load

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and a moment using energy approach. The behavior of the plate resting on a tensionless Winkler foundation has also been studied. Celep and Turhan (1990) and Güler and Celep (1995) worked further on circular plate resting on a tensionless elastic foundation to study the dynamic response. Melerski (1989) used an energy approach to find the effect of various axi-symmetric loading and support conditions on thin circular plates. A mixed-variational approach was used by Faruque and Zaman (1991) to predict the settlement and flexural moment of a thin circular plate in contact with an isotropic elastic halfspace. Zaman et al. (1990) adopted the same approach to investigate settlement, moment and shear force for a moderately thick circular plate resting on an isotropic elastic half-space. Vallabhan and Das (1991) analyzed the foundation of a circular tank foundation resting on soil. The bottom slab of the tank was assumed flexible enough to apply the linear plate theory. Güler (2004) developed a solution using the Galerkin method to show the response of a uniformly loaded thin circular plate with a concentrated load at the center, founded on a tensionless two-parameter Pasternak layer. Rad and Alibeigloo (2013) obtained the stress and displacement distribution using a differential quadrature method to study the interaction problem between an annular circular plate and a two-parameter linear elastic foundation.

All the reported works have been conducted to study the behavior of a circular plate or raft resting on existing ground without any treatment. However, many research works have also been conducted to understand the behavior of stone column-improved ground under axi-symmetric condition. Mitchell and Huber (1985) analyzed stone column-reinforced ground with an axi-symmetric approach assuming the existence of an equivalent model of concentric stone rings with a stone column at the center. The group of stone columns was substituted with an equivalent stone ring to keep the ratio of the stone column area at a constant for the total area. Lee and Pande (1998) proposed an axi-symmetric model to study the behavior of circular footing in contact with stone column-reinforced ground. Ambily and Gandhi (2007) conducted experimental as well as numerical studies on a single stone column and a group of stone columns to study the effect of parametric variation. Elshazly et al. (2008) developed an axi-symmetric finite element model keeping area replacement ratio constant to investigate the accuracy of the unit cell approach. The actual foundation has been idealized as concentric stone rings around the center column. Indraratna et al. (2008) analyzed a circular embankment resting on vertical drain improved soft ground by converting vertical drains into equivalent concentric rings. Deb et al. (2010) developed a mechanical model to understand the behavior of geosynthetic-reinforced granular fill on stone column-reinforced ground under the axi-symmetric condition. More recently, an analysis was carried out on the infinite beams resting over granular bed-stone column-reinforced earth beds under moving loads (Maheshwari and Khatri, 2012), and an analysis and design of floating stone columns was presented by Ng and Tan (2014). Sawada and Takemura (2014) conducted centrifuge model tests on piled raft foundations in sand subjected to lateral and moment loads.

Thus, the focus of most of the research was to study the behavior of stone column-improved ground without considering the circular raft or the circular raft/plate resting on untreated ground. A limited number of studies has been conducted to study the behavior of circular rafts resting on stone column-improved ground. The focus of the available studies has mainly been the settlement behavior of the improved ground. In the design of foundations, not only is settlement is a significant design factor, but the bending moment and shear force are also very important design factors. The flexural rigidity of foundations also plays a major role on its behavior. Thus, it is necessary to determine the settlement as well as bending moment and shear force of the raft foundation resting on stone column-improved soft ground.

Balaam and Booker (1981) presented solutions to evaluate settlement, moment and shear distribution of uniformly loaded rigid circular rafts resting on stone column-reinforced soil by adopting a unit cell approach. However, it has been observed that a unit cell approach can lead to erroneous estimations of the settlement of the foundation (Elshazly et al., 2008). Studies also show that the unit cell analysis is accurate when it is applied near the centerline of the embankment where no lateral displacement is observed (Indraratna et al., 1992). Chai and Miura (1999) reported that in many cases, the ground deformation patterns with vertical drain do not represent a unit cell condition. Thus, the present study investigates the behavior of a uniformly loaded circular raft resting on stone column-reinforced soft soil by considering all the stone columns in the analysis. The effects of different parameters on the settlement, bending moment and shear force of the circular raft are studied by using the developed model.

## 2. Modeling

In the present study, triangular and square arrangements of stone columns are taken into consideration because they are the two most common types of vertical drain arrangement. Fig. 1(a) shows the top view of the stone column distribution under a uniformly loaded circular raft. Stone columns were idealized as equivalent stone rings to analyze the soil-foundation system in the axi-symmetric condition. The stone columns were converted into equivalent stone rings using the equal area replacement technique as suggested by Mitchell and Huber (1985). Fig. 1(b) shows the typical top view of the idealized foundation system with equivalent stone rings. In this converted soil-foundation system, the center stone column is kept intact and the surrounding stone columns were converted into equivalent stone rings. Ambily and Gandhi (2007) and Elshazly et al. (2008) also adopted a similar model to carry out an axi-symmetric analysis of stone column-reinforced ground.

Circular raft was idealized as a thin circular plate. A granular layer was provided below the circular raft to facilitate drainage and distribution of the stresses coming from the raft. The granular layer was idealized as a Pasternak shear layer. The stone column and soft soil were idealized as nonlinear stiffer springs and a spring-dashpot system, respectively. The