Factors Influencing Transient Response of Shallow Strip Footing on Granular Soil Subjected to Vertical Pulse Load

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Abstract The structures located near seashore and industrial areas, basically apart from static loads are subjected to dynamic loads in the form of natural wind, storm loads, and machine vibrations. Uncertainty in the time of occurrence is something that makes these dynamic loads dangerous. Normally before the arrival of dynamic load, the foundation remains in a stable (steady) state, the state which is distorted with a sudden change in loading, putting the foundation in a trauma state. In an attempt to observe the transient response, the present study uses a numerical technique based on Finite Element Method (FEM) to model a footing-soil interface system following the concept of Beam on Nonlinear Winkler Foundation (BNWF) to minutely observe the transient response of a strip footing, i.e., the settlement due to first load cycle. Significant amount of influencing parameters including four intensities of static load, three depths of embedment of footing, three intensities of cyclic load, and three different relative densities of sand have been considered to find out the settlement of the footing. The results obtained from the numerical model, created and analyzed by numerical programming tool *OpenSees* suggest that the transient settlement is significantly affected by soil, footing, and loading characteristics with the allowable static load being the most dominant factor. An empirical expression is also developed to estimate the settlement of strip footing due to first load cycle.

Keywords Strip footing · Cyclic load · Finite Element Method · Beam on Nonlinear Winkler Foundation · Settlement

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1 Introduction

The response of anything to a load that varies with time consists of two distinct parts; the transient response and the steady-state response. The transient response is the response of an object to sudden fluctuation in the state of that object. In the case of shallow foundations, these sudden changes of state generally take place when dynamic loads in the form of vibratory shocks from machines and earthquake-induced ground motions strike the foundation. Pulse load considered in the present study is in most cases generated from a rhythmically vibrating machine on the foundation or more specifically the load suffered by the railroad foundation. The analysis of the transient response of foundation is necessary keeping in view the fact that the behavior of footing directly affects any superstructure supported by it. When a pulse load is applied on the foundation, the first load cycle is something that distorts the state of the foundation which is previously loaded with only static load. As a response to the first load cycle, the foundation suddenly displaces from its original position and with the continuation of loading, the foundation attains the steady stage. Hence, the response of the footing to first load cycle, referred hereafter as the transient response is important in determining the magnitude of damage that the foundation will suffer.

The settlement of plane strain footing under the influence of cyclic load was observed by Raymond and Komos [15]. Their study indicated the importance of soil and loading parameters in determining the settlement of footing. Similar methodology was carried out by Das et al. [5] to study the response of a square footing. Sawicki et al. [17] studied the settlement of circular footing under the influence of cyclic load. Apart from different experimental techniques, the dynamic response of shallow foundation has been studied by using numerical model like Beam on Nonlinear Winkler Foundation (BNWF) model by various researchers like Allotey and Naggar [1], Harden et al. [8], Allotey and Naggar [2], Raychowdhury and Hutchinson [14].

The field of soil dynamics has always been dominated by steady-state response. However, a key concept of physics is that before the steady-state, a system behaves haphazardly in a response to external loads for a very small duration. In an attempt to prove the significance of transient response, in the present study, a shallow strip footing is taken as a physical system and its transient response to vertical pulse load is observed. Influencing parameters like allowable static load depending on the factor of safety (*FS*), embedment ratio (D_f/B), Intensity of pulse load $q_{d(\max)}$ and relative density of soil (D_r %) are considered to observe the settlement of footing due to first pulse load. A statistical model equation is also developed based on nonlinear regression to analyze the significance of the input parameters.

2 Finite Element Model

A strip footing having dimension 0.5 m × 0.1 m × 0.03 m (Length × Width × Thickness) is divided into one hundred discrete elastic beam-column elements. The nonlinear springs used in the present BNWF model are for capturing the response of the footing-soil interface to applied external static and cyclic load. The footing consists of 100 elements and 101 nodes. The footing nodes are joined with the help of one-dimensional elastic beam-column. Each footing node is connected to soil node with the help of springs modeled as zero-length elements. The zero-length elements are one-dimensional nonlinear inelastic springs that are independent of each other and are modeled using QzSimple2, PySimple2, and TzSimple2 material models, and these spring elements simulate the vertical load displacement behavior, horizontal passive load displacement behavior against the side of the footing and horizontal shear sliding behavior at the base of the footing, respectively. The schematic diagram of the BNWF model is given by Fig. 1. Each footing node has three degrees of freedom (Two translations and one rotation). The soil nodes are fixed. The footing rests on free field soil and the springs capture the soil-footing interface response. The model is created using OpenSees [11].

The springs are distributed across the length of the footing according to Harden et al. [8]. The nonlinear properties are assigned to the springs as per Raychowdhury [13]. The stiffness of any spring is a function of soil strength parameters. Depending on the Shear modulus (G) and the Poisson's ratio (υ) of the soil, the stiffness of each spring is calculated as per Gazetas [7]. Procedures mentioned in Gazetas [7] are considered to include the effect of embedment, in case of embedded foundation. In all governing expressions, the shear modulus is calculated as $G = E/2(1 + \upsilon)$. To capture the passive resistance and the sliding resistance of footing, horizontal springs are provided in addition to vertical springs. The passive capacity is determined according to Rankine's method. The sliding resistance (t_{ult}) is calculated as

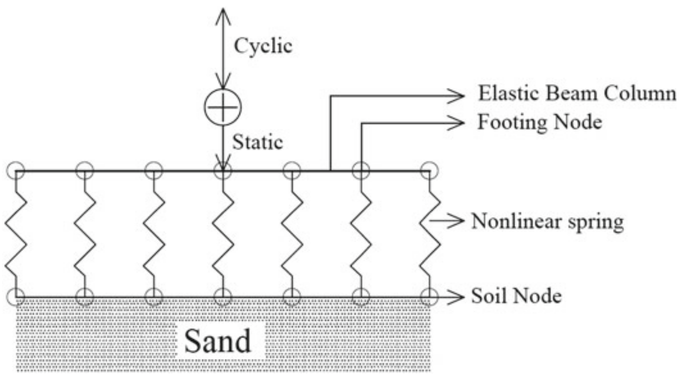

Fig. 1 Schematic diagram of the BNWF model and loading conditions

Table 1 Soil parameters used in the numerical model

Relative density (D_r, %)	Angle of internal friction (ϕ, degree)	Unit weight of soil (γ, kN/m^3)	Modulus of elasticity (E, MPa)	Poisson's ratio (υ)
35	34	13.34	20	0.3
51	37.5	13.97	36	0.32
69	40.8	14.36	55	0.35

$$t_{\text{ult}} = W \tan \delta \quad (1)$$

where W = weight on footing, δ = the soil-concrete interfacial friction angle = 0.66 × ϕ, ϕ = angle of internal friction of soil.

Three different embedment ratios (D_f/B) of footing are considered, i.e., 0, 0.5 and 1 along with three different intensities ($q_{d(\max)}/q_u$) of pulse load, i.e., 5, 10 and 13%. The intensity of pulse load is generally taken as some percentage of static failure load depending on the ultimate bearing capacity for corresponding soil and embedment condition. The different types of soil used in the present study and their strength defining parameters are provided in Table 1. The soil parameters like relative density(D_r), angle of internal friction (ϕ) and unit weight (γ) for dense and medium dense sand are taken as per Patra et al. [12]. The parameters for loose sand are taken as per Sahu et al. [16]. The modulus of elasticity (E) and Poisson's ratio (υ) are taken as per EPRI [6], considering the range of relative densities given in Das [4].

3 Results and Discussions

First, the present numerical model is validated for loose sand conditions with the results obtained from Plaxis 3D (Brinkgreve et al. [3]).

In the present BNWF model, the behavior is controlled by the nonlinear springs. Nonlinear smooth backbone curves are used to define the springs rather than multi-linear material model. The Plaxis 3D model is created using Mohr–Coulomb constitutive model for the same soil and footing condition. The load-settlement curve obtained is then compared with that obtained from FEM analysis and the comparison seems to be reasonably good. The load-settlement curve in the static condition is given by Fig. 2. From Fig. 2. it can be inferred that the present model predicts the foundation response with reasonable accuracy. For the same soil condition and footing dimensions, theoretical ultimate bearing capacity as per Meyerhof [9] is found to be 22 kPa verifying the ultimate bearing capacity obtained from the present model.

Figures 3, 4 and 5 represent the response of footing for particular values of $q_{d(\max)}/q_{u,}$ i.e., 5, 10, and 13%, respectively, whereas all other parameters are varied within their specified ranges. It is observed that for a particular intensity of cyclic load, the total settlement after the striking of the cyclic load is dominated by the

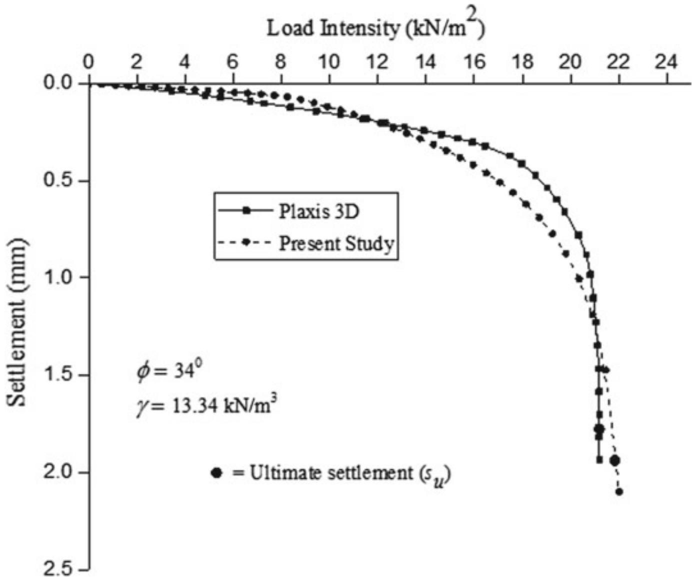

Fig. 2 Load-settlement curve for loose sand in static condition

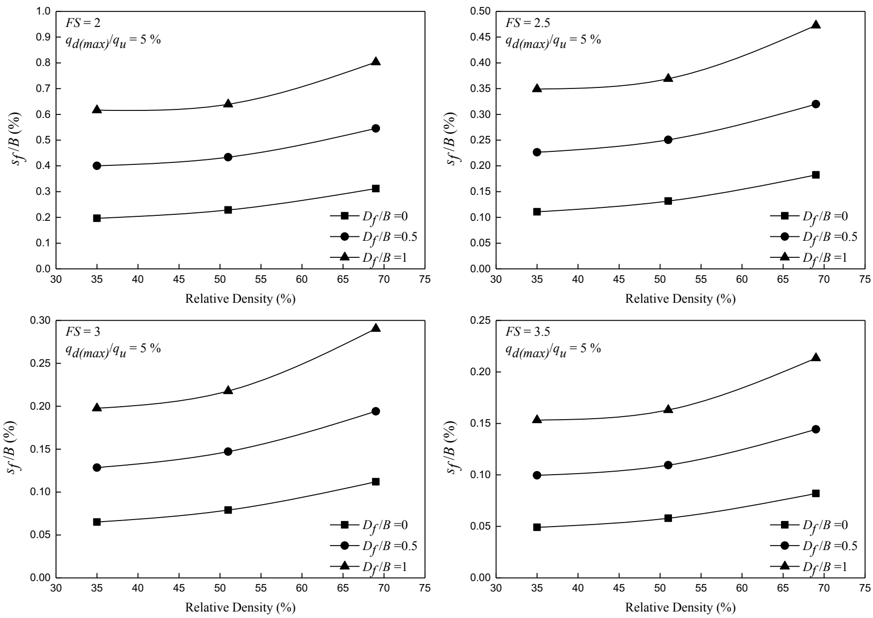

Fig. 3 Settlement of strip footing due to first load cycle ($q_{d(\max)}/q_u = 5\%$)

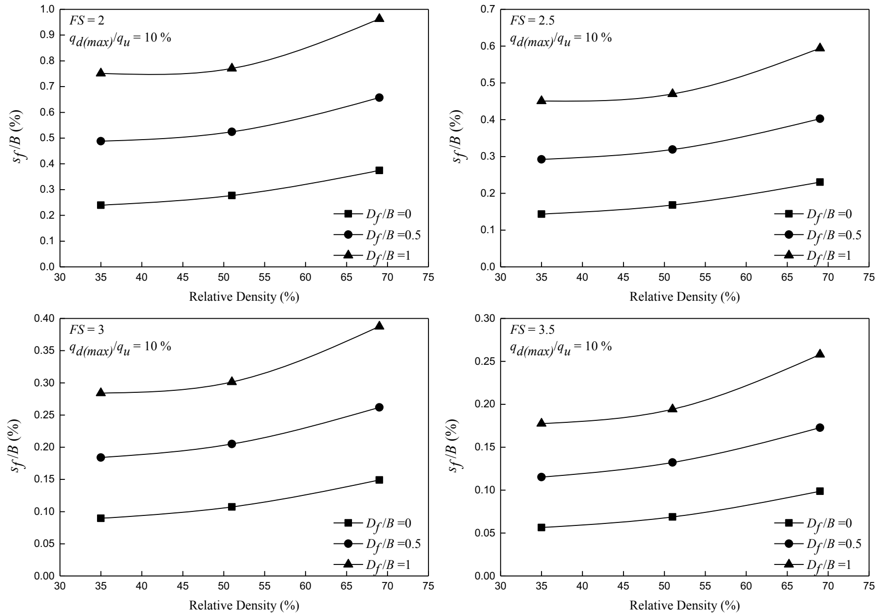

Fig. 4 Settlement of strip footing due to first load cycle ($q_{d(\max)}/q_u = 10\%$)

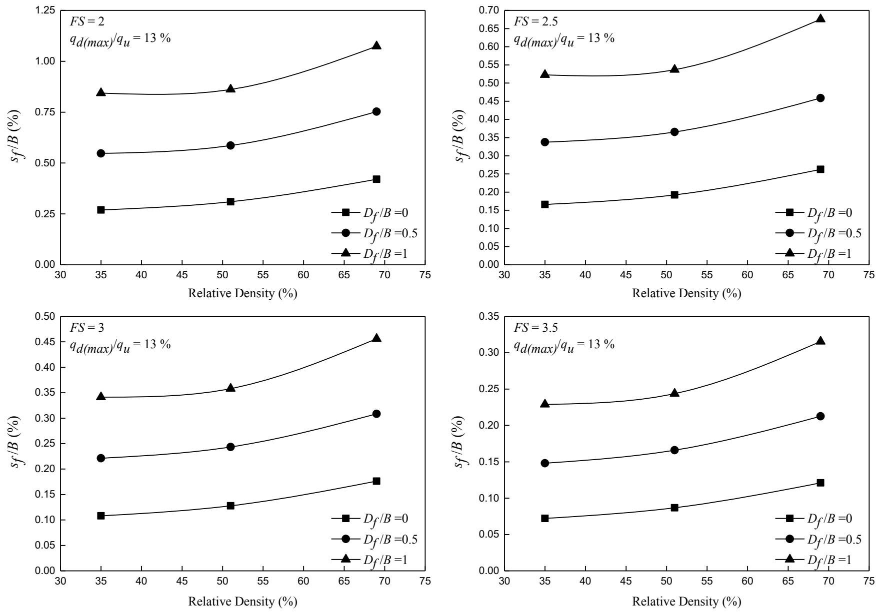

Fig. 5 Settlement of strip footing due to first load cycle ($q_{d(\max)}/q_u = 13\%$)

allowable static load on the foundation. It is also observed that keeping all the influencing parameters constant, as the intensity of cyclic load increases the settlement of footing also increases. The intensity of cyclic load is a function of ultimate bearing capacity (q_u) which in turn is directly related to the relative density of soil (D_r) and the embedment ratio (D_f/B). An increase in both the parameters results in a higher value of q_u, leading to an increase in $q_{d(\max)}$ which is attributed to larger settlement of footing as observed from Figs. 3, 4, and 5. As the settlement is a combined response of footing due to the allowable static load and the cyclic load, as *FS* decreases the corresponding settlement of footing increases thanks to larger amount of static load.

3.1 Development of Empirical Equation for Nondimensional Settlement

To develop an empirical expression for finding the normalized settlement due to the first load cycle, i.e., s_f/s_u (%), 108 number of data set containing inputs and corresponding output are considered, the statistical values of which are shown in Table 2. The term s_f indicates the settlement due to allowable static load + first load cycle, i.e., called as transient settlement whereas (s_u) is the ultimate settlement of footing in static condition. The study indicates that a significant portion of the total settlement of footing occurs due to the first load cycle. Up to 14% of ultimate static settlement (s_u) takes place at this stage.

A statistical model is developed incorporating four input parameters to find out the settlement due to the first cycle of loading. The model equation is developed using Nonlinear regression analysis program NLREG [10]. The equation is assumed in the following form;

$$s_f/s_u(\%) = a \times FS + b \times \exp\left(D_f/B\right) + c \times \left(q_{d(\max)}/q_u(\%)\right) + d \times (D_r(\%))^e \quad (2)$$

The numerical values of the parameters are mentioned in Table 3. The R^2 obtained from the regression analysis is 0.91. Without affecting the accuracy of the model, the numerical values of the coefficients are approximated as shown in Column3 of Table 3. The final equation can be expressed as Eq. (3).

Table 2 Statistical values of input and output parameters

Parameter	Maximum value	Minimum value	Average value	Standard deviation
FS	3.5	2	2.8	0.6
D_f/B	1	0	0.5	0.4
$q_{d(\max)}/q_u$ (%)	13	5	9	3
D_r (%)	69	35	52	14
s_f/s_u (%)	14.02	1.82	5.93	3.17

Table 3 Numeric values of coefficients obtained from regression analysis

Coefficients (1)	Numeric value (Regression) (2)	Approximated value (3)
a	−5.13	−5
b	−0.28	−0.3
c	0.26	0.3
d	21.58	21
e	−0.045	−0.05

$$s_f/s_u(\%) = -5 \times FS - 0.3 \times \exp\left(D_f/B\right) + 0.3 \times \left(q_{d(\max)}/q_u(\%)\right) + 21 \times \left(D_r(\%)\right)^{-0.05} \quad (3)$$

Comparison between the observed output and predicted output (using Eq. (3)) is shown in Fig. 6. It can be concluded that the developed empirical expression can estimate the transient settlement of footing with reasonable accuracy having R^2 equal to 0.91, with majority of data lying inside ± 10% deviation lines.

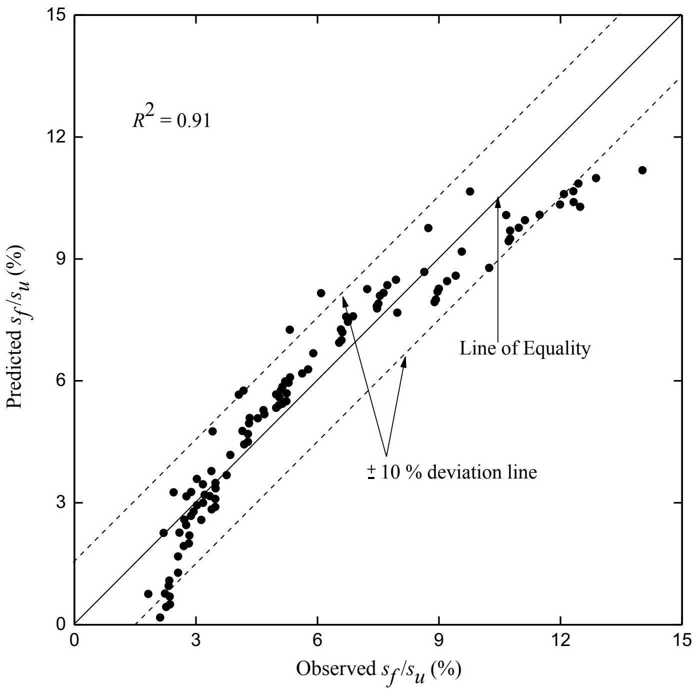

Fig. 6 Comparison between observed s_f/s_u (%) and predicted s_f/s_u (%)

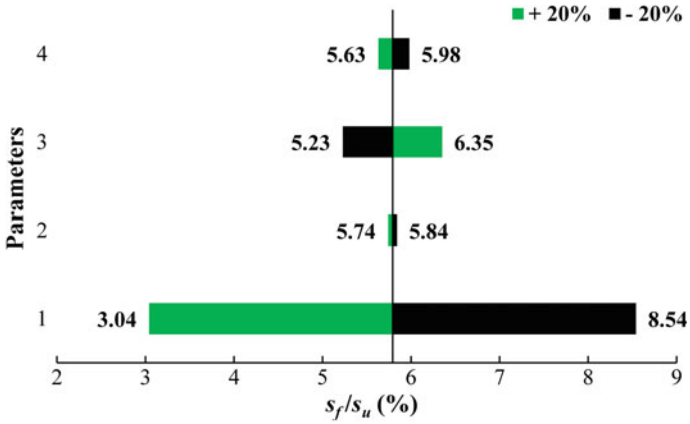

Fig. 7 Tornado plot showing variation of normalized settlement

3.1.1 Sensitivity Analysis

The sensitivity of input parameters toward determining the output is studied with the help of a tornado plot as shown in Fig. 7.

First, the output is determined for mean values of input parameters. Then the mean values of the input parameters are perturbed, one at a time by ± 20%, keeping all other parameters untouched, to observe the variation of the output. In Fig. 7. Parameters 1, 2, 3, 4 represent *FS*, D_f/B, $q_{d(\max)}/q_u$ (%), and D_r (%), respectively. It is observed that apart from $q_{d(\max)}/q_u$ (%), for all other input parameters, a positive perturbation results in decrease in (s_f/s_u) % and vice versa. Hence, it can be inferred that among all the input variables only $q_{d(\max)}/q_u$ (%) directly affects the output. *FS*, D_f/B, *and* D_r (%) inversely affect the (s_f/s_u) %. Depending on the range of variation of the output, as observed from Fig. 7, *FS* is the most influencing parameter followed by $q_{d(\max)}/q_u$ (%), D_r (%) and D_f/B.

4 Conclusions

Based on the numerical and statistical analyses carried out in the present study to estimate the transient settlement of shallow strip footing due to the initiation of dynamic loading in the form of a vertical pulse, the following major inferences are drawn;

- The transient settlement (s_f) due to the first load cycle can be up to 14% of the settlement of the footing under static failure load (s_u).
- With the decrease in *FS* and increase in D_r (%), $q_{d(\max)}/q_u$ (%), D_f/B, the transient settlement (s_f) of the footing increases. However, the normalized settlement (s_f/s_u) % decreases with increase in *FS*, D_r (%), D_f/B and decrease in $q_{d(\max)}/q_u$ (%).

- An empirical equation in the form of Eq. (3) is developed to predict the normalized settlement (s_f/s_u) % of the footing with reasonable accuracy.
- *FS* is the most significant parameter controlling transient response followed by $q_{d(\max)}/q_u$ (%), D_r (%) and D_f/B.

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