Settlement Analysis of Shallow Foundation on Frictional Soil Under Combined Effect of Static and Cyclic Load

Suvendu Kumar Sasmal and Rabi Narayan Behera

Abstract The settlement of a surface strip footing on dense sand due to long-term repetitive load (1 million cycles) is analyzed with the help of finite element method (FEM). The analysis is performed by applying both static and cyclic load on the center of footing, in the vertical direction and observing the corresponding settlement. The intensity of the static load is determined by dividing the ultimate static load by the factor of safety (*FS*). The static load is calculated for different values of *FS* i.e., 2, 2.5, 3, 3.5. The intensity of the dynamic load ($q_{d(\max)}$) is some percentage of the ultimate bearing capacity (q_u) of the foundation. Three values of ($q_{d(\max)}/q_u$) have been considered in the study, i.e., 5%, 10%, and 13%. Three different frequencies of cyclic load (0.5 Hz, 1 Hz, and 2 Hz) have also been considered. Based on the settlement pattern of the foundation, the critical number of load cycles (n_{cr}) for each case is determined beyond which the increase in settlement becomes insignificant for further load cycles. The study reveals that even a minor change in the frequency of loading can result in major variations in the n_{cr}.

Keywords Dense sand · Strip footing · Repetitive load · Settlement · Critical number of load cycles

1 Introduction

Foundations in the vicinity of industrial areas, generally apart from static loads from the superstructure, are subjected to dynamic forces in the form of machine-induced loads. In cases, such as the foundation beneath the railway track is generally subjected to long-term vertical cyclic loads. Other circumstances include the foundations under vertically oscillating machines. The behavior of these foundations is

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far different from that of the foundations under only static loads. The cyclic settlement response of footing was observed in the late 1970s by Raymond and Komos [1]. They concluded that the settlement is basically controlled by the cyclic load intensity and soil condition. A similar methodology was adapted by Das et al. [2] to study the settlement of square footing. Sawicki et al. [3] observed the response of circular footing under cyclic load. The response of footing under the incremental cyclic load was reported by Tafreshi et al. [4]. Apart from experimental models, various numerical methods are also available to study the actual footing response. When it comes to the numerical model for shallow foundations, the Winkler model predicts the foundation response with significant accuracy. With time, this model has evolved to capture the accurate nonlinear response of footing. The nonlinear responses were observed with the help of beam on nonlinear Winkler foundation (BNWF) model by researchers like [5–8].

The numerical analyses discussed mainly the seismic response. Also, the effect of change in frequency of loading has not been clearly defined in available studies. Rather than considering dynamic loads of small durations, the present study aims at studying the long-term response of footing with the help of numerical simulations. The foundation is modeled using BNWF method to study the response of the foundation. A large number of loading cycles, i.e., 10^6 cycles are applied to the center of the footing to study the long-term response. This type of loading condition generally takes place in the case of a railroad foundations. The work is further extended to observe the influence of possible change in frequency on the settlement response of footing. The phenomenon of near cessation of settlement after a certain load cycle is observed which is greatly controlled by the frequency of loading. The numerical methods and the obtained results are described in the following sections.

2 Numerical Modeling Approach

A finite element model (BNWF model) is adapted to observe the settlement of a strip footing of dimension 0.5 m × 0.1 m × 0.03 m (Length × Width × Thickness). The soil parameters used in the analysis are listed in Table 1. A schematic diagram of the foundation and loading system is shown in Fig. 1. The static load is the allowable load, determined by dividing the ultimate load by *FS*. The cyclic load is a vertical rectangular pulse load as shown in Fig. 1. In this study, 1 million cycles are considered to study the response of footing. The footing is divided into 100 equal parts

Table 1 Soil properties

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)
69	40.8	14.36	55	0.35

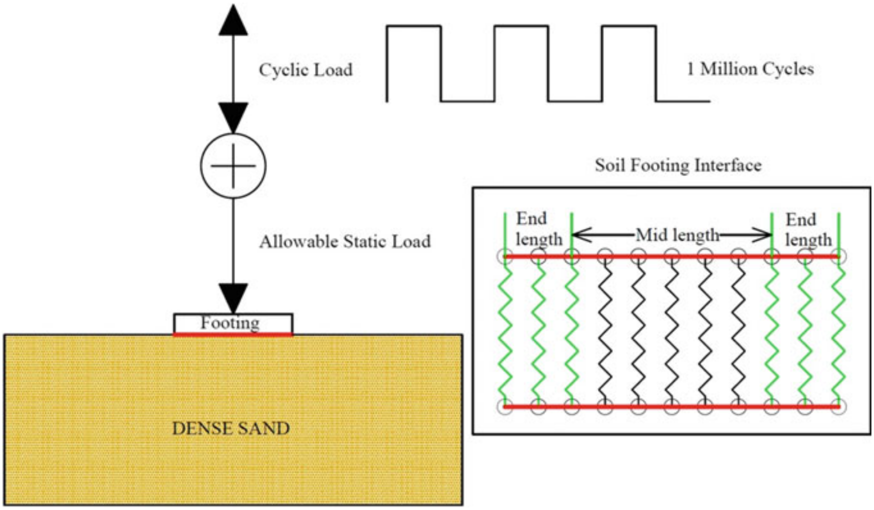

Fig. 1 Schematic diagram of the foundation and loading system

with the help of 101 nodes. The footing nodes having 3 degrees of freedom, DOF (2 translations and 1 rotation) are connected with the soil nodes (fixed, DOF = 0) using springs modeled as zero-length elements. The footing nodes are connected by using one-dimensional elastic beam-column elements defined with the help of area of cross-section, Young's modulus (E), and moment of inertia. Each spring consists of three components, i.e., elastic, plastic, and gap. The role of gap component (drag + closure) is to simulate soil-foundation separation behavior. Radiation damping is provided with the help of a damper parallel to the elastic component. Generally, for soil, a radiation damping value of 5% is applicable. The governing equations for spring behavior can be found in Boulanger [9]. The stiffnesses and capacities of the springs are determined according to Gazetas [10] and Meyerhof [11], respectively. FEMA 356:2000 [12] suggests assigning more stiffness at the end portion of the footing dimension considered (L_{end}). The end length ratio (End length/Total length) and stiffness intensity ratio (End portion stiffness/Mid portion stiffness) for the present model are selected as per Harden et al. [7]. The nonlinear properties for vertical springs are defined by *QzSimple2* material for shallow foundations according to Raychowdhury [13]. The *QzSimple2* springs used for capturing the vertical response have lesser strength in tension to simulate real soil type conditions. Apart from vertical springs, the sliding resistance of footing is considered using additional horizontal spring, defined as *TzSimple* material. The sliding capacity is calculated as

$$t_{\text{ult}} = W \tan \delta \tag{1}$$

Table 2 Details of the numerical model

FS	$q_{d(\max)}/q_u$, %	*f*, Hz
2	5	0.5
2.5	10	1
3	13	2
3.5		

where W = weight on footing, δ = soil-concrete interfacial friction angle = $0.66 \times \phi$.

The loading applied on the footing consists of 2 phases, application allowable static load followed by the cyclic load. Different amplitudes ($q_{d(\max)}/q_u$= 5%, 10%, and 13%) and frequencies (f = 0.5 Hz, 1 Hz, 2 Hz) of cyclic load are considered to observe the corresponding parametric variation effect on settlement. The parameters and corresponding numeric values used in the study are mentioned in Table 2. The D_r (%), ϕ, and γ are taken as the values considered in Patra et al. [14]. The E and ν are determined considering the values listed in EPRI [15]. The entire simulation is performed using numerical tool OpenSEES [16].

2.1 Validation of the Numerical Model

One of the key criterion to evaluate the accuracy of the model is to compare the outcome with that generated from a different constitutive model, for same soil conditions. The suitability from the present model has already been ascertained by comparing the static response of the foundation, for the same footing dimension and soil (dense sand) condition with the results obtained from Plaxis 3D [17]. The details of the validation study can be found in Sasmal and Behera [18] (Fig. 2).

3 Results and Discussions

The long-term settlement responses of footing following simulations of numerical model conditions are illustrated in Figs. 3, 4, 5 and 6 which are discussed in this section.

3.1 Effect of Intensity of Loading

It is obvious that the settlement of footing always increases with the increase in loading intensity (static and cyclic) which can be observed from Figs. 3, 4, 5 and 6. The role of the static load is found to be the major factor that controls the total settlement of footing. A decrease in the settlement is observed with an increase in

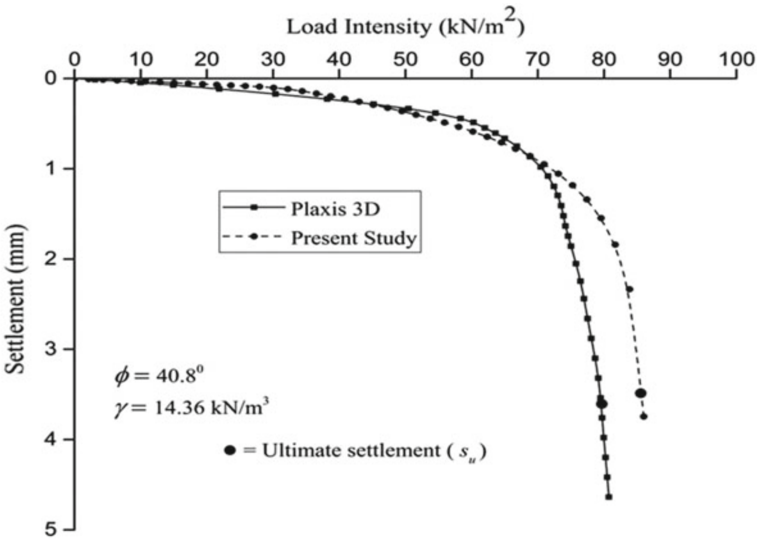

Fig. 2 Verification of accuracy of the present model [18]

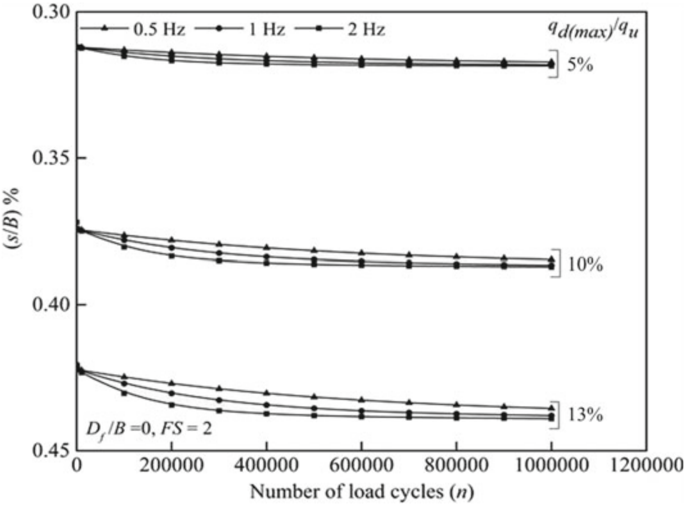

Fig. 3 Long-term settlement of footing under cyclic pulse ($FS = 2$)

the FS, keeping the intensity and frequency of cyclic load constant. It is attributed to the fact that the more the FS, the less is the amount of static load on the foundation. Hence, it can be inferred that the total settlement is directly proportional to intensity of both cyclic load and static load.

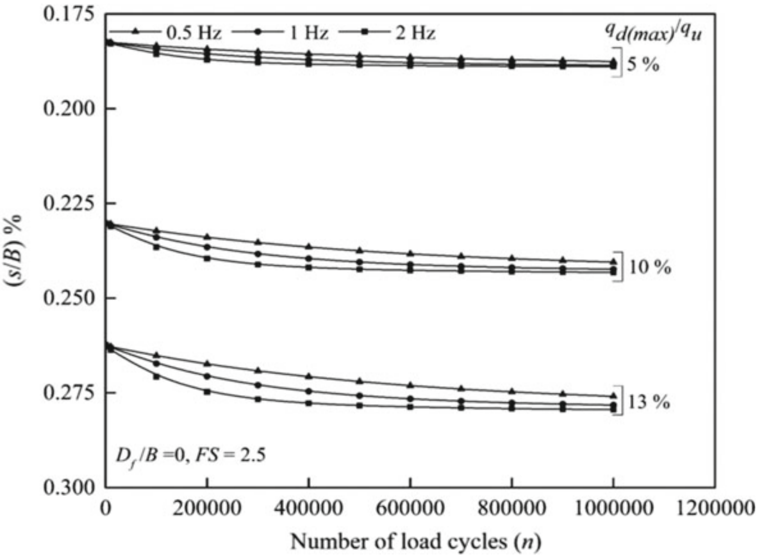

Fig. 4 Long-term settlement of footing under cyclic pulse ($FS = 2.5$)

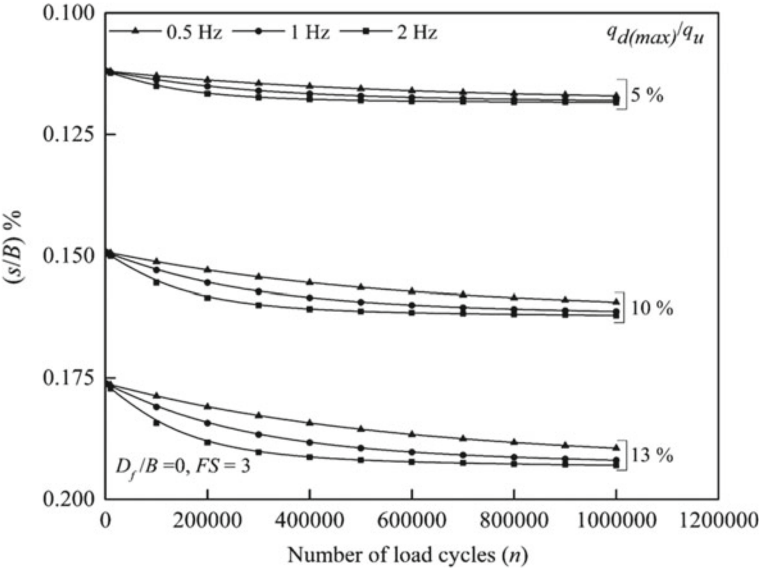

Fig. 5 Long-term settlement of footing under cyclic pulse ($FS = 3$)

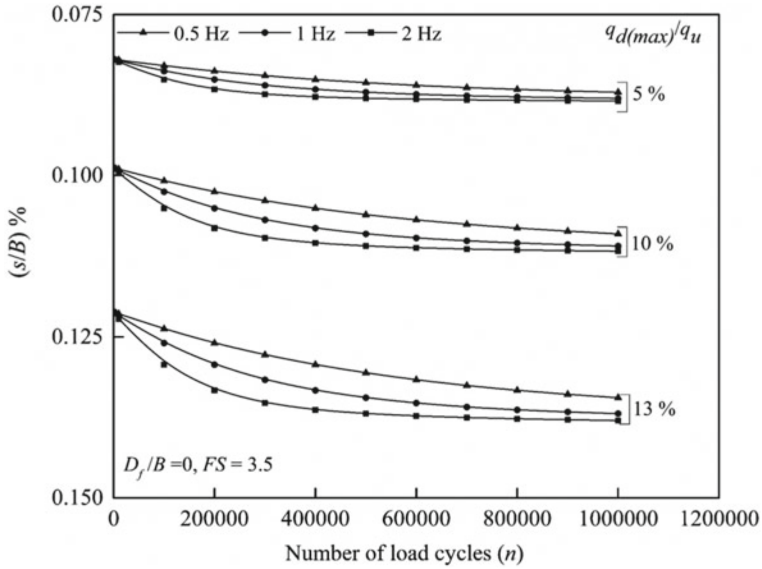

Fig. 6 Long-term settlement of footing under cyclic pulse ($FS = 3.5$)

3.2 *Effect of Uncertainty in Loading Frequency*

A traditional way of observing the effect of the number of load cycles is to keep the loading frequency constant. However, in real world, the frequency of a certain type of loading is not same always. This is highly dependent on the source of load. In this study, results of the change in the settlement pattern of footing are presented altering the frequency of loading. It is noted that with a slight increase in the frequency of loading, the settlement of footing increases although not very significantly. The increase in settlement of footing with an increase in frequency is attributed to the fact that the more frequently the load strikes the footing the less time the foundation soil gets to recover from the effect of the previous load cycle. It can be observed from Figs. 3, 4, 5 and 6, as the factor of safety increases, the gap among settlement responses corresponding to three frequencies increases, whereas for a lower factor of safety the settlements for different frequencies have nearly similar values. Hence, the changing frequency of the loading controls the settlement response more for lower values of intensity of static load. It is also observed that, for all the conditions considered in the present study, the footing undergoes more settlement with an increase in the frequency of cyclic load for a higher values of intensity of cyclic load.

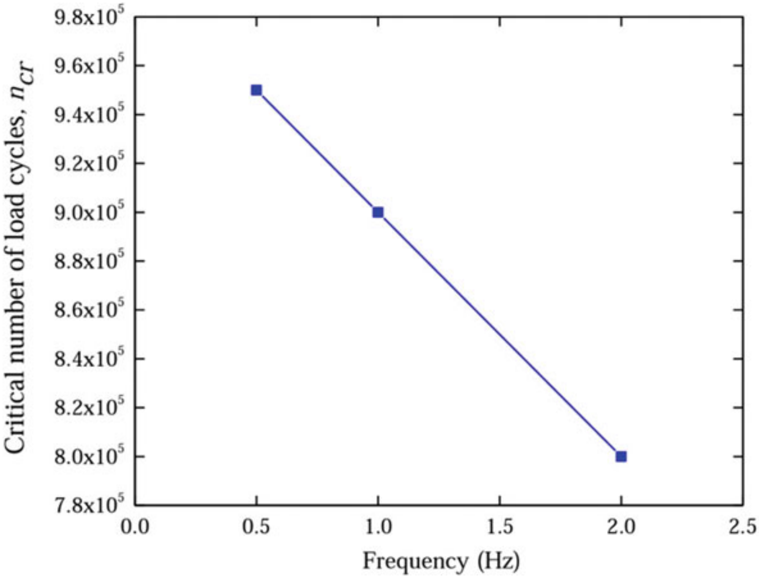

Fig. 7 Critical number of load cycles corresponding to different loading frequencies

3.3 Analysis of the Number of Load Cycles

Upon subjecting the footing to 1 million load cycles, it is observed from Figs. 3, 4, 5 and 6 that the rate of increase in the settlement with further loading cycles becomes very small or negligible after a particular value of the number of load cycles (n_{cr}). This number is dependent on the frequency of loading. This phenomenon takes place due to the increased strength of soil with increasing compression of soil mass with time. Similar outcomes have been presented in Das et al. [2].

Provided the fact that n_{cr} is a time-dependent parameter beneath the footing, its value is bound to be different for different frequencies of loading. n_{cr} takes lower value for higher values of loading frequency, justifying the fact that the more frequently the load compresses the soil mass, the less time is required to achieve sufficient strength so that further loading cannot cause any significant settlement. The n_{cr} values for different frequencies are presented in Fig. 7. It can be observed from Fig. 7 that the n_{cr} is linearly influenced by the frequency of the loading.

4 Conclusions

In the present work, the static-cyclic settlement response of a shallow foundation resting on a homogeneous layer of dense sand is discussed. Emphasis has been given to study the effect of uncertainty in the frequency of loading. Based on the finite element model and parametric analysis including four different intensities of static load, three intensities of cyclic load, and three frequencies of cyclic load, the following major conclusions are drawn;

- The settlement (s) of footing increases with an increase in $q_{d(\max)}/q_u$ (%) and a decrease in FS. The settlement becomes negligible after n_{cr}, which is highly influenced by the loading frequency. n_{cr} is lower for higher loading frequency.
- The variation in settlement increases with a change in frequency, for higher values of FS.
- Irrespective of the FS, the effect of frequency is more felt for higher values of $q_{d(\max)}/q_u$ (%).

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