Settlement of Surface Strip Foundation Resting on Soft Clay Subjected to Vertical Cyclic Load

Gobinda Das, Suvendu Kumar Sasmal, Devasish Sahu, and Rabi Narayan Behera(✉)

Department of Civil Engineering, National Institute of Technology, Rourkela, Rourkela, India
das.gvnd@gmail.com, suvendukumarsasmal@gmail.com, civilbydevasish@gmail.com, rnbehera82@gmail.com

Abstract. The nature of dynamic settlement of a shallow foundation is strongly influenced by the response of soil whereas the response of soil largely depends on the cyclic loading. Therefore, it is necessary to study the soil response due to cyclic loading. The present study focuses on investigating the settlement response of a surface strip foundation resting on soft clay subjected to vertical cyclic loading in the form of a rectangular pulse. A strip foundation-soil system is modeled and the settlement response is estimated using numerical programming tool Open System for Earthquake Engineering Simulation (*OpenSees*). Combinations of an allowable vertical static load and rectangular pulse with a frequency of one cycle per second are applied to the footing. The magnitude of the allowable static load and the amplitude of cyclic load are varied to observe the settlement response of the foundation. The effect of variation in the magnitude of static allowable load and increase in the amplitude of cyclic load on the behavior of the foundation is observed. Based on the results obtained from the numerical study, the critical number of load cycles (n_{cr}) after which the settlement becomes negligible for further cyclic loading, is estimated for each case. Furthermore, the effect of frequency of loading on the settlement response of the foundation-soil system for limited cases has been investigated considering two additional frequency of 0.5 Hz and 2 Hz.

1 Introduction

Foundation is the most essential part of any structure and the stability of any structure largely depends on the stability of the foundation on which it rests. The stability of the foundation depends on various factors such as the basic properties of the surrounding soil (cohesion, angle of shearing resistance, unit weight of soil, elastic modulus, shear modulus, Poisson's ratio), the dimensions of the foundation and the nature of load to which it is subjected. A foundation can be subjected to static as well as dynamic loads. Static loads include the weight of superstructure and the weight of the footing. Whereas the dynamic loads may be of various types. These may include slow cyclic loads or may be in the form of severe earthquakes. There are several structures that are subjected to both static as well as dynamic load as a combination. Such structures are the tall structures like tower, chimneys, and others subjected to wind loads, offshore

© Springer Nature Switzerland AG 2019
H. Shehata and B. Das (Eds.): GeoMEast 2018, SUCI, pp. 21–39, 2019.
https://doi.org/10.1007/978-3-030-01923-5_3

platforms, breakwaters and structures subjected to wave loading, structures and slopes subjected to earthquake loading, and foundation subjected to machine vibrations. The dynamic load can be the reason for the reduction of the strength of soil and may result in large settlement of the foundation. Therefore, investigating the behavior of the foundation i.e. settlement is an important aspect while designing a foundation subjected to dynamic load.

The settlement under cyclic load is hugely dependent on the loading and soil conditions. Raymond and Komos (1978) reported that the cyclic load (rectangular pulse) is generally generated from the train wheel passing over a railroad. They found a number of factors such as footing dimension, number of load cycles and amplitude of cyclic load that affect the settlement of any foundation. Das and Shin (1996) studied the settlement of foundation on clayey soil and concluded that the settlement is influenced by the intensity of static load and amplitude of cyclic load. Apart from different experimental techniques there exist a number of numerical methods to accurately predict the settlement of the foundation under cyclic load. When it comes to model a foundation numerically, the Winkler model has always been given importance by various researchers. The nonlinear cyclic settlement response of foundation, using Beam on Nonlinear Winkler Foundation model (BNWF), has been described by various researchers. Harden et al. (2005) described the finite element modelling procedures to estimate the settlement accurately using BNWF model. Gajan et al. (2008) using BNWF model provided the moment-rotation-settlement response of shallow foundation. Winkler model can satisfactorily capture all the cyclic response of a shallow foundation apart from permanent horizontal displacement (Allotey and Naggar 2008a, b). Raychowdhury (2008) found that the BNWF model is capable of predicting experimentally measured footing response in terms of moment, shear, settlement and rotation demands. Allotey and Naggar (2008a, b) reported that the soil structure interaction response can successfully be recorded by the BNWF model.

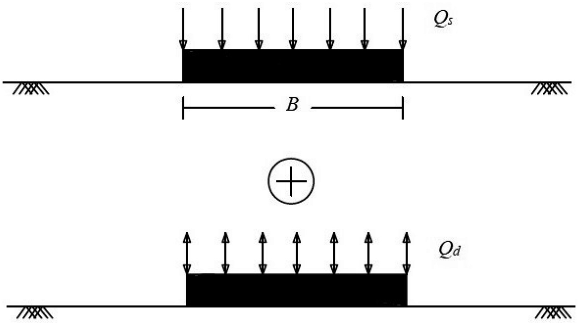
The experiments conducted by Raymond and Komos (1978), Das and Shin (1996) were unique in their category. However, there is lack of numerical procedures to study how a foundation at railroad behaves under wheel load. Hence, an attempt has been made in the present study to numerically model the foundation system and to study its settlement response under the influence of rectangular pulse. The present study focuses on analyzing the behavior of a strip footing resting on soft clay and subjected to a combination of a static load and vertical cyclic load. The foundation is modeled numerically using Open System for Earthquake Engineering Simulation (*OpenSees*) based on Beam-on-Nonlinear-Winkler foundation approach and the behavior of the foundation under static and cyclic load has been observed. The important factors affecting the cyclic settlement of foundation are highlighted and the critical number of load cycles (n_{cr}) after which the settlement of the foundation becomes negligible for further load cycles are found out for each case. The study will provide a brief idea regarding the settlement pattern of the foundation which will help in predicting the extent of damage and the lifetime of such foundations, which generally undergo a huge number of load cycles.

2 Methodology

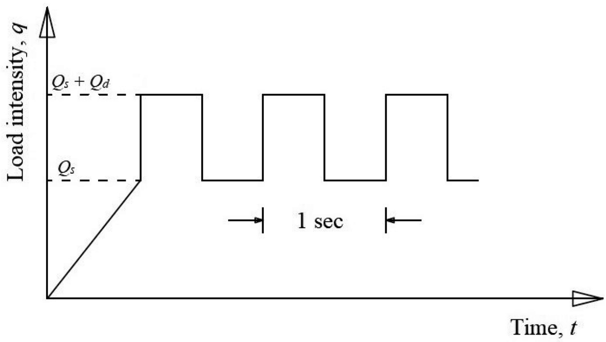
In the present study, a shallow strip foundation is modeled using Beam-On-Nonlinear-Winkler foundation (BNWF) model that is capable of capturing the nonlinear behavior of the soil-foundation system. The components of BNWF model are created using numerical programming tool Open System for Earthquake Engineering Simulation (*OpenSees*). The model consists of elastic beam-column elements that capture the behavior of the footing and zero-length elements which capture the soil-footing behavior. A BNWF model requires various input parameters such as soil type (clay or sand), bearing capacity of soil, Poisson's ratio (v), Young's modulus (E), shear modulus (G), vertical and lateral stiffness, radiation damping, tension capacity of soil, distribution and magnitude of vertical stiffness, spring spacing etc. The present model is developed for two-dimensional analyses. The foundation is created by connecting different one-dimensional elastic beam-column elements. Each element joins two nodes having three degrees-of-freedom per node. The zero-length elements are one-dimensional nonlinear inelastic springs that are independent of each other and are modeled using QzSimple1, PySimple1 and TzSimple1 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 above-mentioned springs are characterized by nonlinear backbone curves resembling a bilinear behavior and are implemented in *OpenSees* by Boulanger (2000). The vertical and lateral stiffness of the springs are calculated from the specified values of shear modulus (G), Poisson's ratio (v) and footing dimensions using the expressions by Gazetas (1991), the same supported by FEMA 356 - 2000. The ultimate bearing capacity (q_{ult}) assigned to the QzSimple1 material is calculated as per Meyerhof (1963) whereas the passive resisting force (p_{ult}) assigned to PySimple1 spring model is obtained as per Rankine (1857). The lateral sliding capacity assigned to the TzSimple1 material is the frictional resistance which is a function of the shear strength of the soil and the footing. The magnitude and distribution of vertical stiffness along the length of the footing is done by assigning suitable values of stiffness intensity ratio ($R_k = K_{end}/K_{mid}$) and end length ratio ($R_e = L_{end}/L$) according to Harden et al. (2005). The spring spacing is taken as a fraction (0.01) of the footing length (L), provided the fact that the smaller the spring spacing, the more accurate the result, when the Winkler model is concerned.

The model foundation has the measurements of 229 mm (length) × 76.1 mm (width) × 38.1 mm (thickness). The depth of embedment is zero since it is a surface foundation. The soil under the foundation is soft clay with a moisture content of 34.4%, moist unit weight of 18.58 kN/m^3 and undrained shear strength of 11.9 kN/m^2. The Young's modulus (E) and Poisson's ratio (v) are taken as 1500 kN/m^2 and 0.3 respectively according to EPRI 1990.

The foundation is subjected to a combination of static safe load and cyclic load. The loading diagram is shown in Fig. 1. First, the static safe load (Q_s) is applied on the center of the foundation. Then, the cyclic load of amplitude (Q_d) is applied in the form of a rectangular pulse load at a frequency of 1 cycle/second (1 Hz). The static safe load is varied from 10% to 45% of the static failure load. The amplitude of cyclic load is varied from 2.5% to 20% of the static failure load of the foundation. Several combinations of both static load and cyclic load are applied to the foundation and the behavior of the foundation to the applied load combinations is observed.



(a)



(b)

Fig. 1. Details of loads applied on the foundation (a) static + cyclic load, (b) pattern of static + cyclic loading

3 Results and Discussion

The behavior of the foundation towards static load is observed first. The foundation is subjected to a static load equal to its ultimate load (Q_u) and the corresponding settlements are noted. A plot is drawn between the load per unit area (q) and the normalized settlement (s/B)% to determine the ultimate settlement (s_u) of the foundation. The above-obtained plot is compared with the plot obtained by Das and Shin (1996) and that obtained by using PLAXIS 2D software for the same soil conditions. From Fig. 2, it is observed that both the experimental and numerical results have good agreements, which justifies the ability of *OpenSees* to accurately capture the foundation behavior. Table 1 shows the corresponding ultimate bearing capacity (q_u) and normalized ultimate settlement [(s_u/B)%] obtained from the above-mentioned approaches.

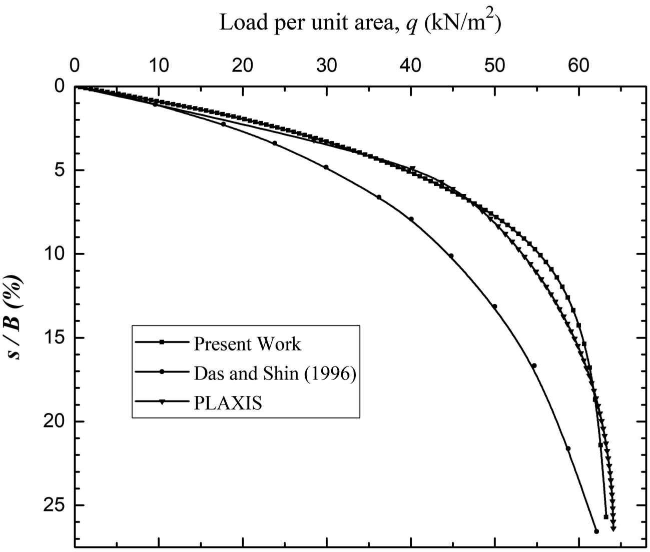


Fig. 2. Static load intensity (q) versus normalized settlement ($s/B\%$)

Table 1. Ultimate bearing capacity (q_u) and normalized ultimate settlement [s_u/B (%)] obtained from different approaches

Different approaches	Ultimate bearing capacity, q_u	Normalized ultimate settlement, $s_u/B(\%)$
Present work	61.5 kN/m^2	17.5
Das and Shin (1996)	58 kN/m^2	17
PLAXIS	62.5 kN/m^2	18.5

The response of the foundation to the cyclic load has been observed in the dynamic analysis where the foundation is subjected to a combination of static and cyclic load. A safe static load (Q_s) is applied to the footing followed by a rectangular pulse load of amplitude (Q_d) for 200000 cycles at a frequency of 1 cycle/second and the settlement for the corresponding number of cycles is noted. Figures 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16 and 17 represent the plots between the normalized dynamic settlement (s_d/B)% (where s_d = settlement due to only cyclic load, B = width of the foundation) and the number of cycles of load (n) for various combinations of Q_s/Q_u and Q_d/Q_u. It is observed that the variation of settlement with increasing load cycles has a definite pattern. The variation of the pattern of (s_d/B)% with n is shown in Fig. 18 as a straight line approximation. It can be observed that the settlement occurs in three stages:

- A primary rapid settlement: $s_{d(r)}$
- A secondary slower settlement that ceases at a critical number of cycles (n_{cr}) of loading: $s_{d(s)}$
- Beyond $n_{cr,}$ the settlement is very small which can be neglected

From Figs. 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16 and 17, it can be observed that the primary rapid settlement occurs within 10–20 cycles whereas the secondary settlement ceases within 20,000 cycles i.e. critical number of load cycles (n_{cr}) lies between 10,000 and 20,000 cycles which is independent of the Q_s/Q_u and Q_d/Q_u combination. When $n \geq n_{cr,}$ the settlement is very less or say negligible. For a given (Q_s/Q_u), the total permanent settlement due to cyclic loading increases with the increase of the amplitude of cyclic load intensity.

The magnitudes of primary rapid settlement $s_{d(r)}$ and total settlement due to cyclic load $s_{d(t)}$ are determined from the straight line approximation for various combinations of Q_s/Q_u and Q_d/Q_u. Figures 19 and 20 show the variations of $s_{d(r)}/s_u$ and $s_{d(t)}/s_u$ against Q_d/Q_u respectively for various Q_s/Q_u. It can be observed that for a particular Q_s/Q_u, both $s_{d(r)}/s_u$ and $s_{d(t)}/s_u$ bear a non-linear relationship with Q_d/Q_u and the rate of increment of $s_{d(r)}/s_u$ and $s_{d(t)}/s_u$ increases with the Q_d/Q_u. Figure 21 shows the plot of $s_{d(r)}/s_{d(t)}$ versus Q_d/Q_u for various Q_d/Q_u. It can be observed that $s_{d(r)}/s_{d(t)}$ bears an approximately linear relationship with Q_d/Q_u.

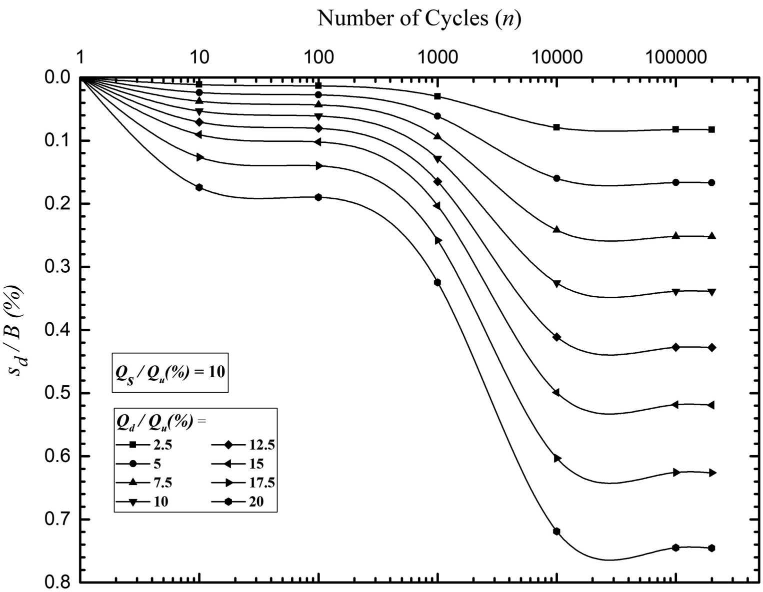


Fig. 3. Normalized settlement (s_d/B) due to only cyclic load with increasing load cycles (Q_s/Q_u = 10%)

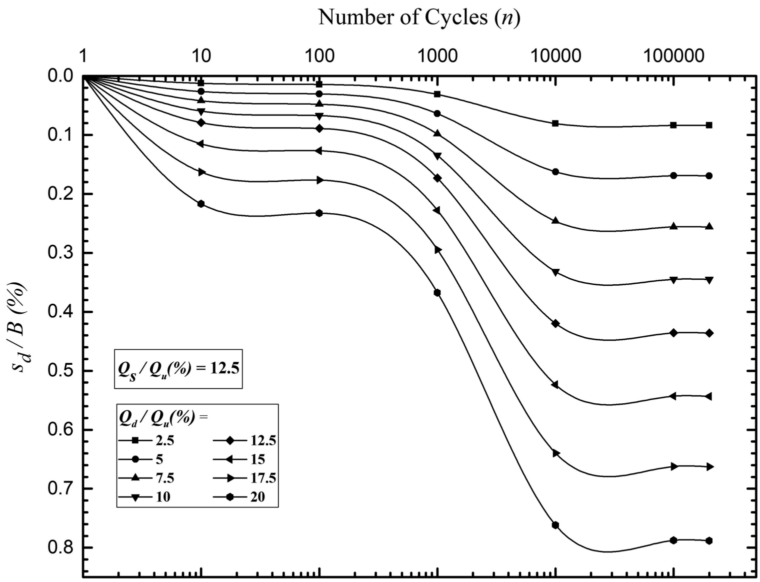


Fig. 4. Normalized settlement (s_d/B) due to only cyclic load with increasing load cycles (Q_s/Q_u = 12.5%)

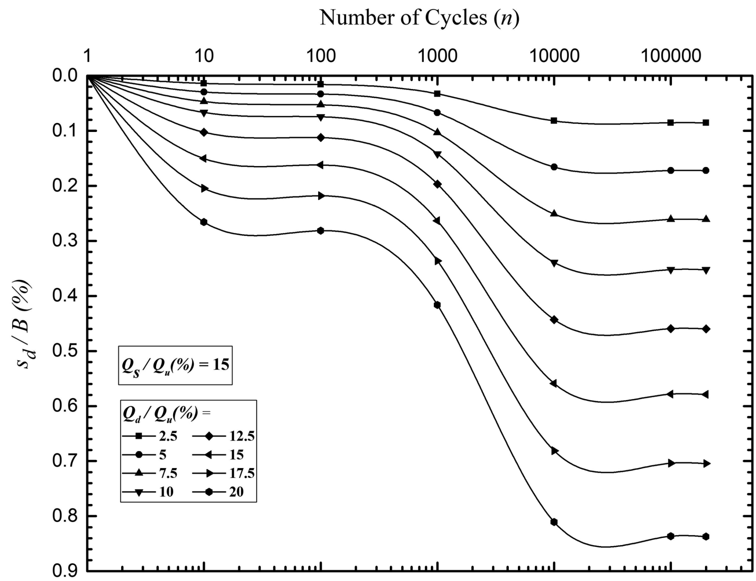


Fig. 5. Normalized settlement (s_d/B) due to only cyclic load with increasing load cycles (Q_s/Q_u = 15%)

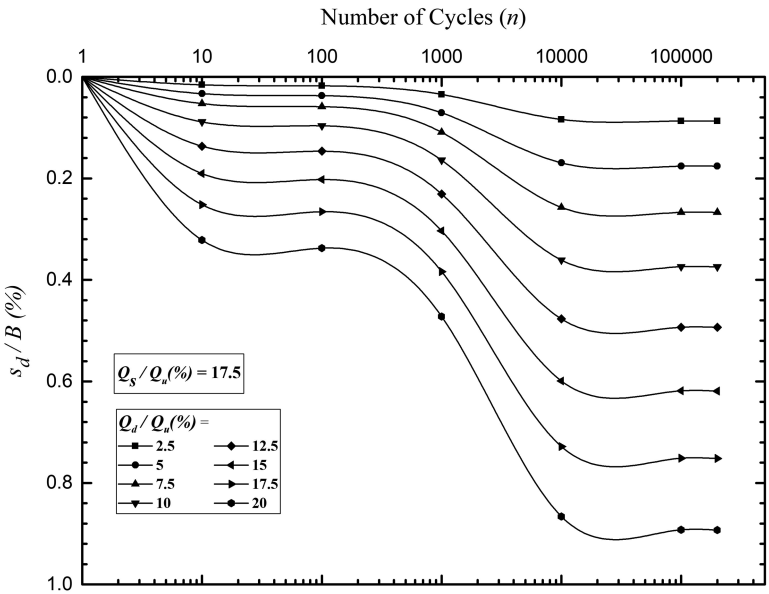


Fig. 6. Normalized settlement (s_d/B) due to only cyclic load with increasing load cycles (Q_s/Q_u = 17.5%)

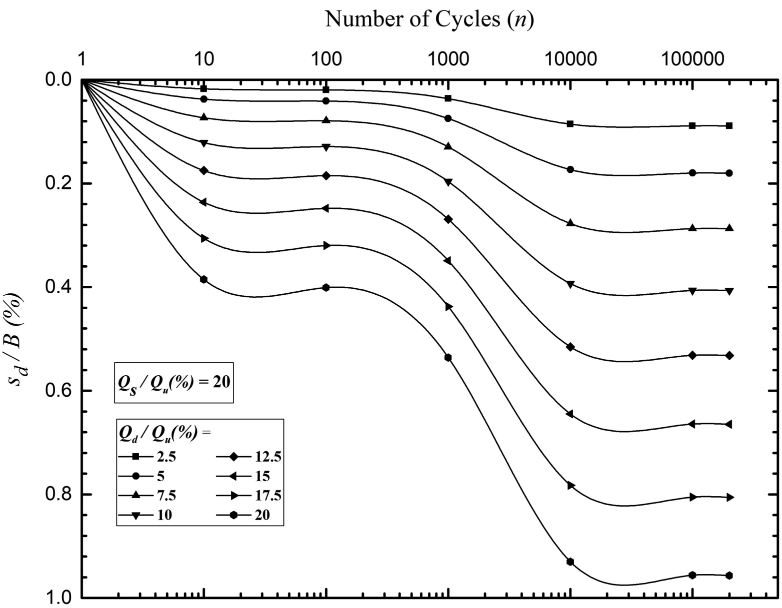


Fig. 7. Normalized settlement (s_d/B) due to only cyclic load with increasing load cycles (Q_s/Q_u = 20%)

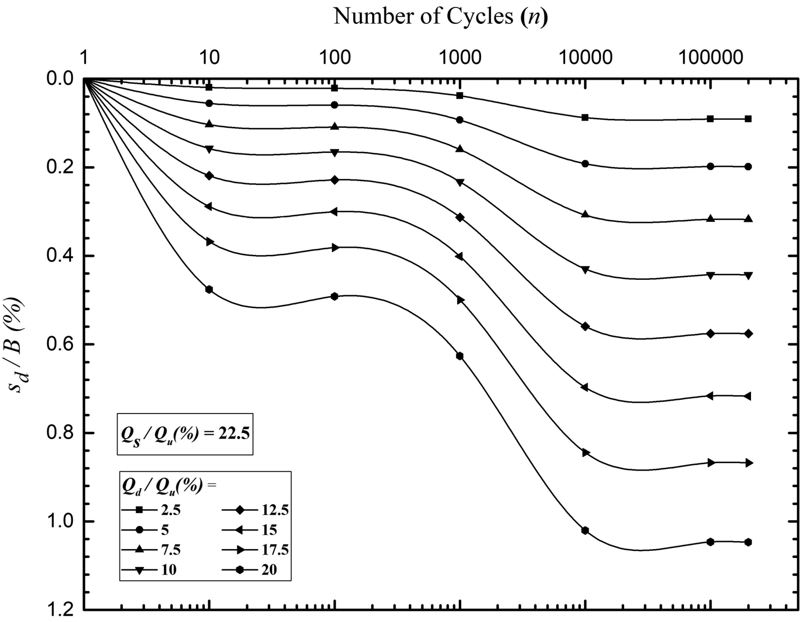


Fig. 8. Normalized settlement (s_d/B) due to only cyclic load with increasing load cycles (Q_s/Q_u = 22.5%)

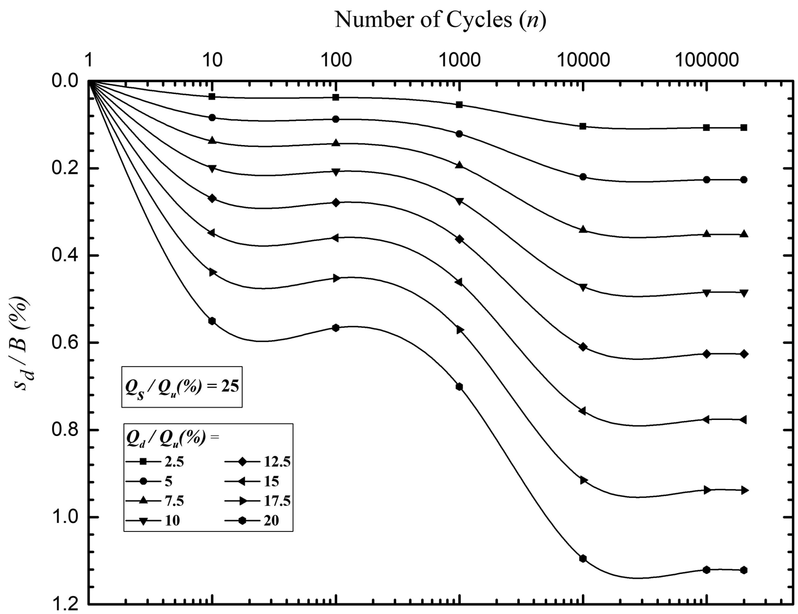


Fig. 9. Normalized settlement (s_d/B) due to only cyclic load with increasing load cycles (Q_s/Q_u = 25%)

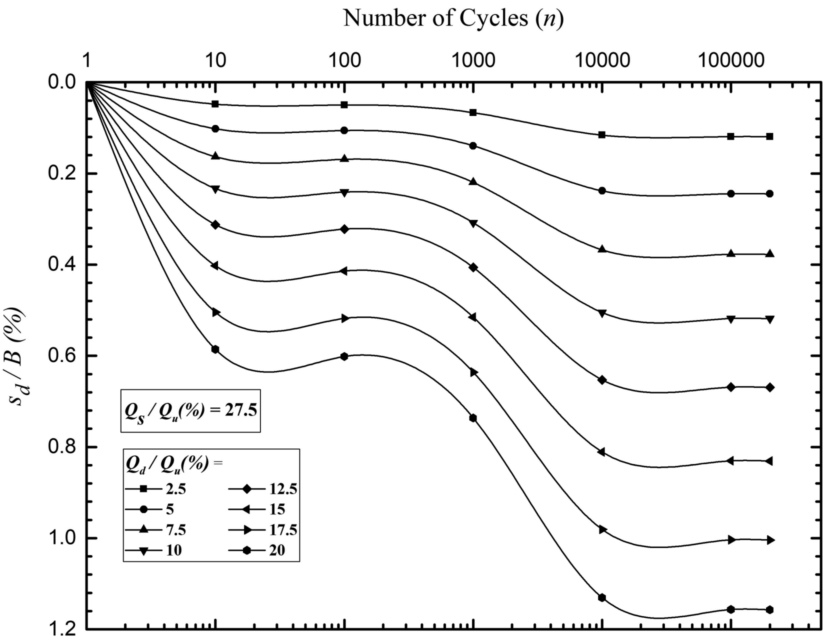


Fig. 10. Normalized settlement (s_d/B) due to only cyclic load with increasing load cycles (Q_s/Q_u = 27.5%)

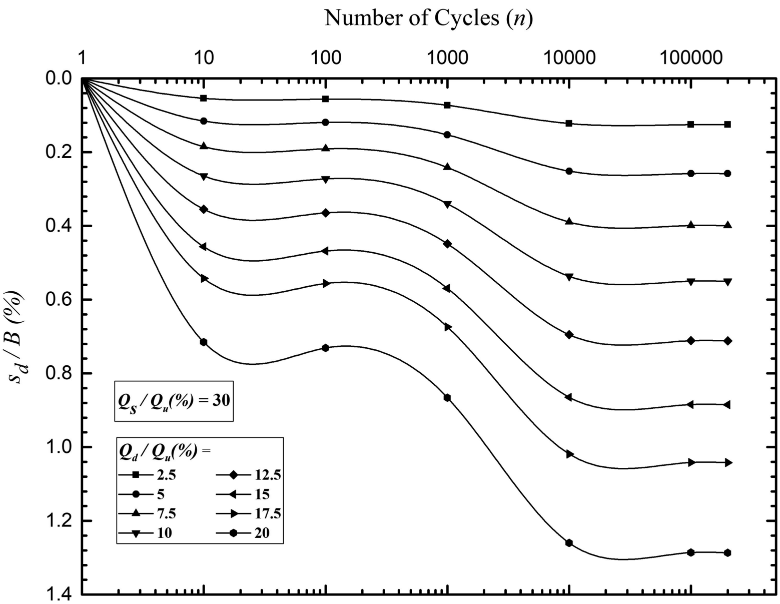


Fig. 11. Normalized settlement (s_d/B) due to only cyclic load with increasing load cycles (Q_s/Q_u = 30%)

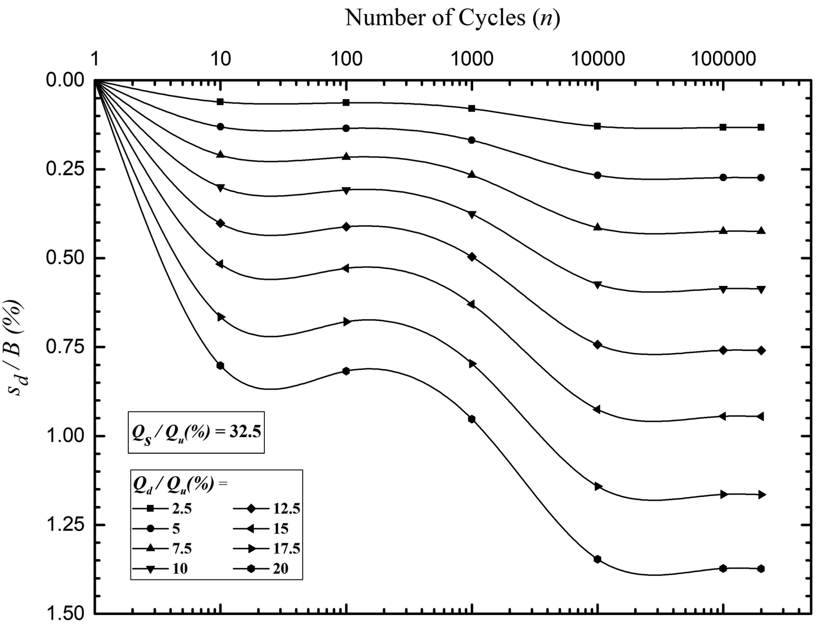


Fig. 12. Normalized settlement (s_d/B) due to only cyclic load with increasing load cycles (Q_s/Q_u = 32.5%)

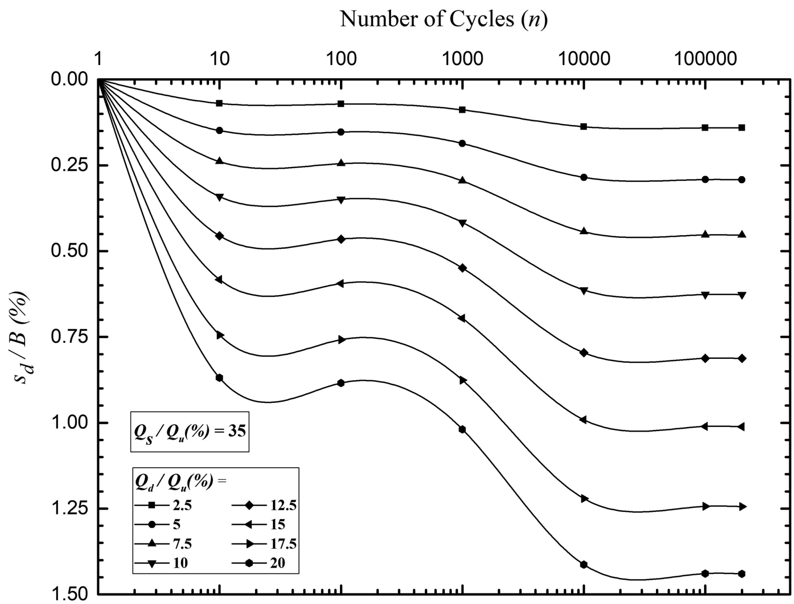


Fig. 13. Normalized settlement (s_d/B) due to only cyclic load with increasing load cycles (Q_s/Q_u = 35%)

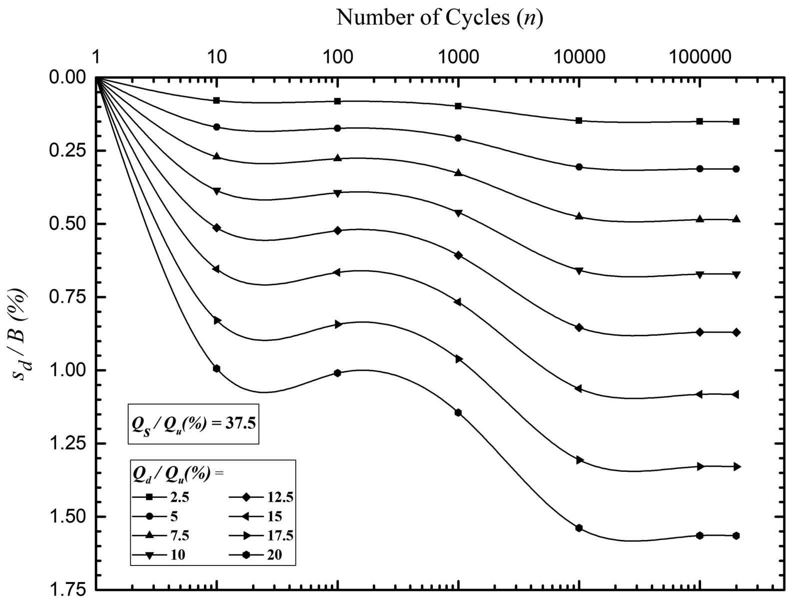


Fig. 14. Normalized settlement (s_d/B) due to only cyclic load with increasing load cycles (Q_s/Q_u = 37.5%)

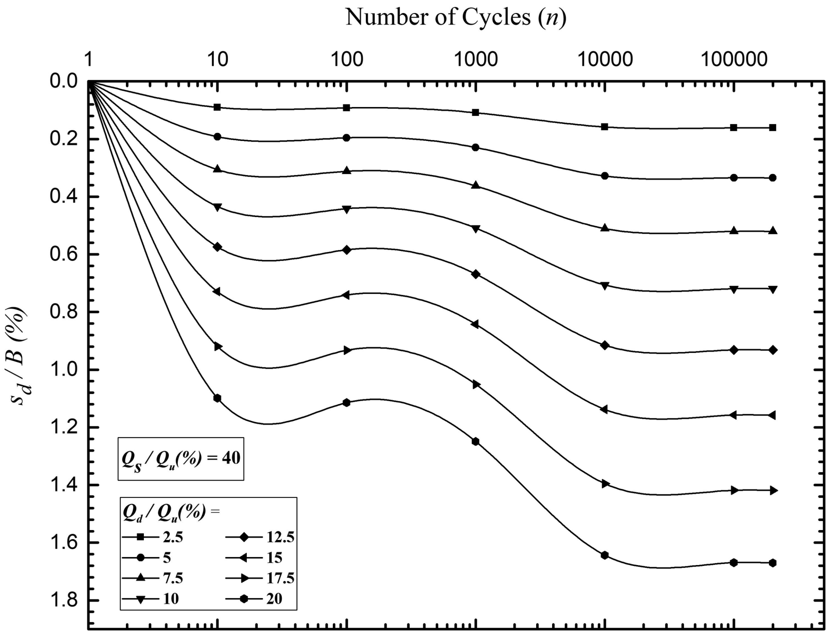


Fig. 15. Normalized settlement (s_d/B) due to only cyclic load with increasing load cycles (Q_s/Q_u = 40%)

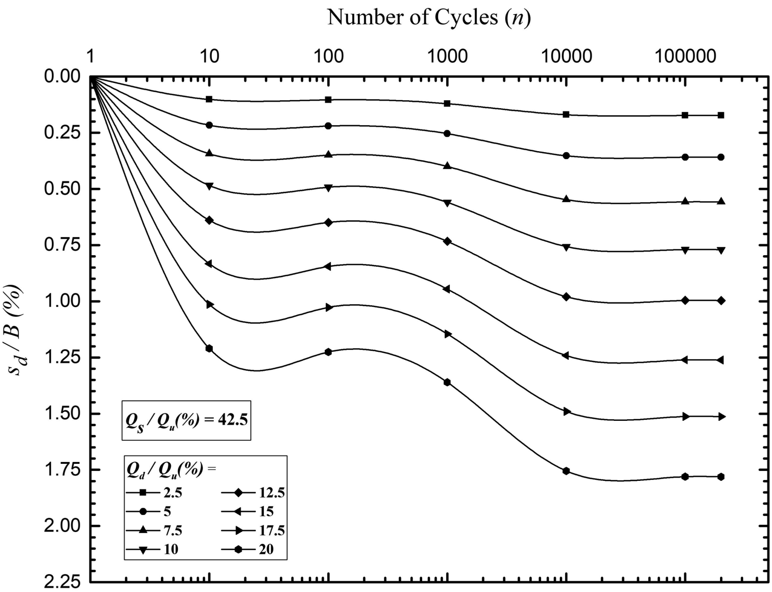


Fig. 16. Normalized settlement (s_d/B) due to only cyclic load with increasing load cycles (Q_s/Q_u = 42.5%)

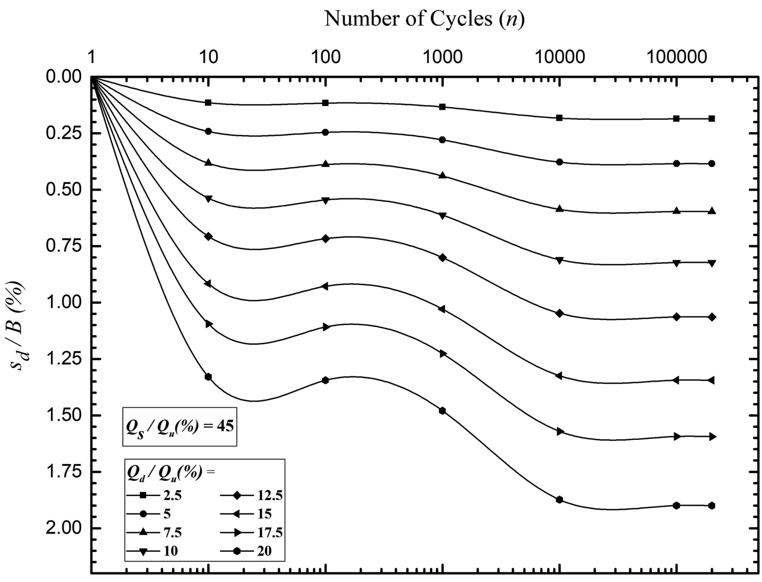


Fig. 17. Normalized settlement (s_d/B) due to only cyclic load with increasing load cycles (Q_s/Q_u = 45%)

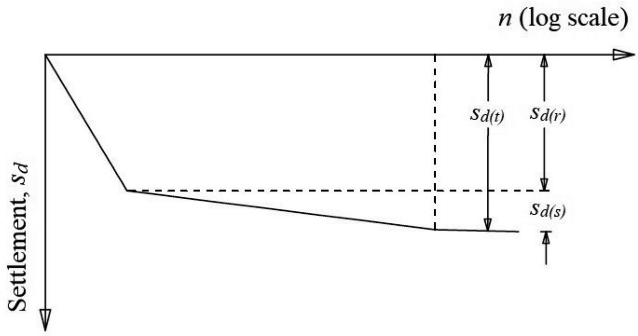


Fig. 18. Nature of variation of dynamic settlement (s_d) versus number of load cycles (n) (Das and Shin 1996)

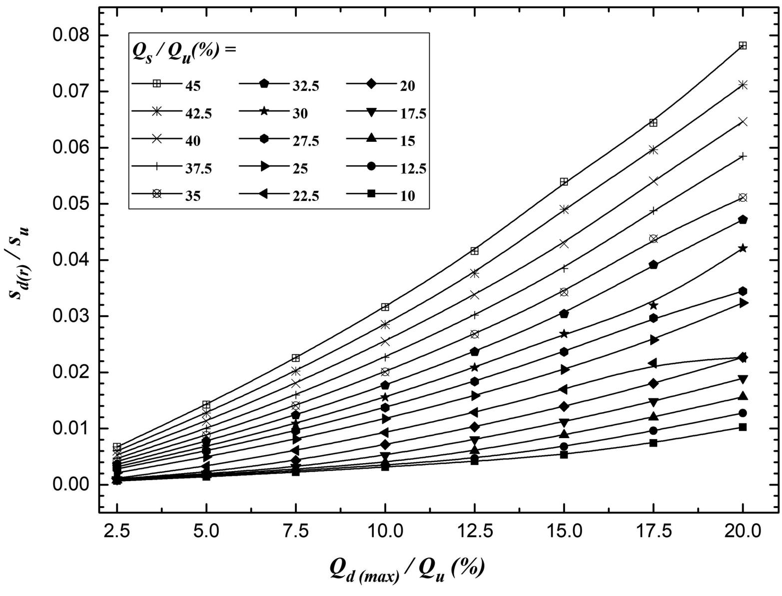


Fig. 19. Variation of ratio of primary rapid settlement to ultimate settlement ($s_{d(r)}/s_{u}$) with respect to ratio of dynamic to ultimate static load ($Q_{d(max)}/Q_u$)

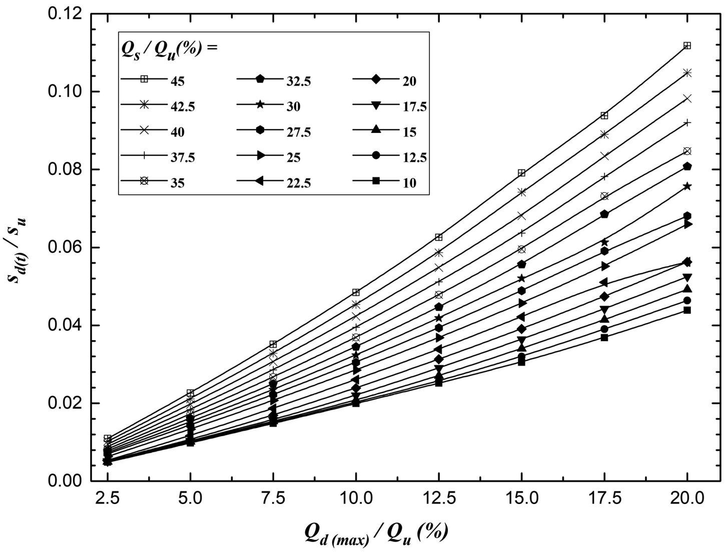


Fig. 20. Variation of ratio of total dynamic settlement to ultimate settlement ($s_{d(t)}/s_u$) with respect to ratio of dynamic to ultimate static load ($Q_{d(max)}/Q_u$)

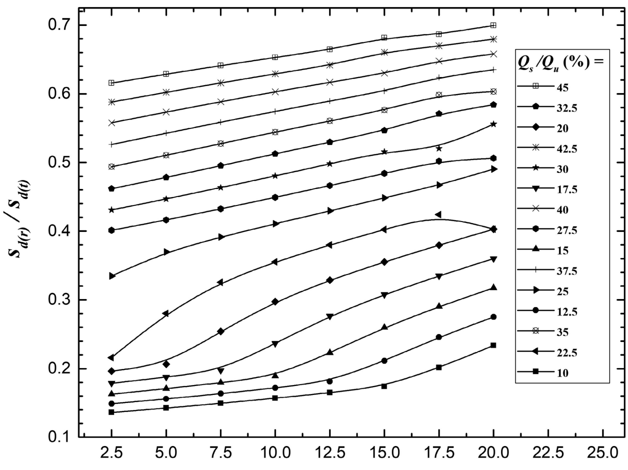


Fig. 21. Plot of ratio of primary rapid settlement to total dynamic settlement ($s_{d(r)}/s_{d(t)}$) versus ratio of dynamic to ultimate static load ($Q_{d(max)}/Q_u$)

4 Effect of Frequency of Loading

The effect of change in frequency on the settlement of footing is studied by considering three different frequencies. Figures 22, 23, 24, 25, 26 and 27 demonstrate the plots of the normalized dynamic settlement $(s_d/B)\%$ versus the number of cycles of load (n) for Q_s/Q_u = 10, 17.5, 25, 32.5, 40 and 45%, and Q_d/Q_u = 2.5 and 20%, where each cyclic load is applied at three different frequencies i.e. 0.5 Hz, 1 Hz and 2 Hz. It is observed that there is no significant effect of change in frequency of loading on both the primary rapid settlement and total dynamic settlement. But with the increase in the frequency of loading, the critical number of load cycles (n_{cr}) decreases i.e. the increase in loading frequency leads to the earlier occurrence of total permanent settlement. The total settlement of the footing after 2×10^5 cycles is approximately same irrespective of the frequency of loading, which is attributed to the fact that there occurs hardly any settlement once n_{cr} is reached.

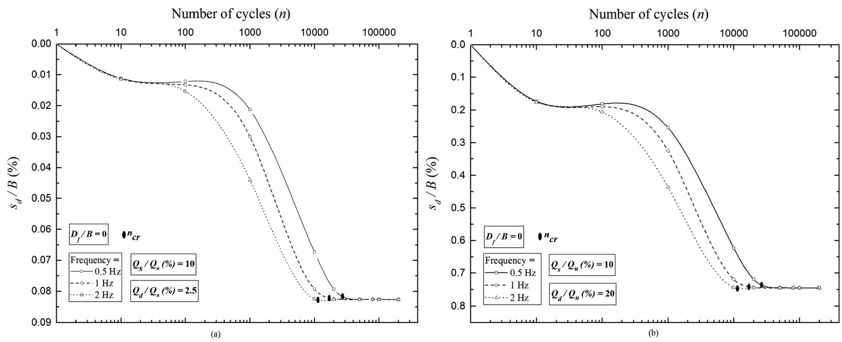


Fig. 22. Normalized settlement (s_d/B) due to only cyclic load with increasing load cycles [Q_s/Q_u = 10% and Q_d/Q_u = (a) 2.5%, (b) 20%] for different frequency

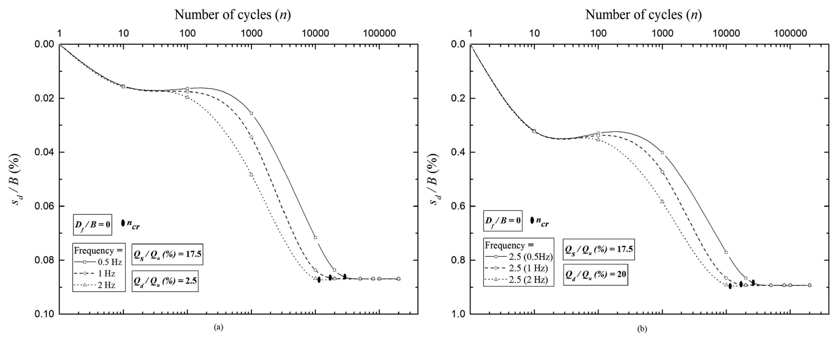


Fig. 23. Normalized settlement (s_d/B) due to only cyclic load with increasing load cycles [Q_s/Q_u = 17.5% and Q_d/Q_u = (a) 2.5%, (b) 20%] for different frequency

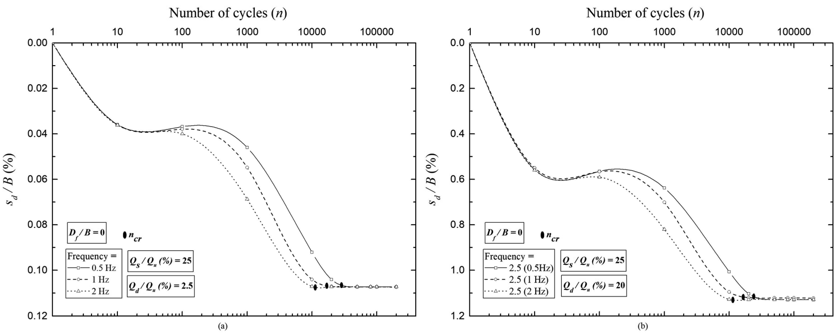


Fig. 24. Normalized settlement (s_d/B) due to only cyclic load with increasing load cycles [Q_s/Q_u = 25% and Q_d/Q_u = (a) 2.5%, (b) 20%] for different frequency

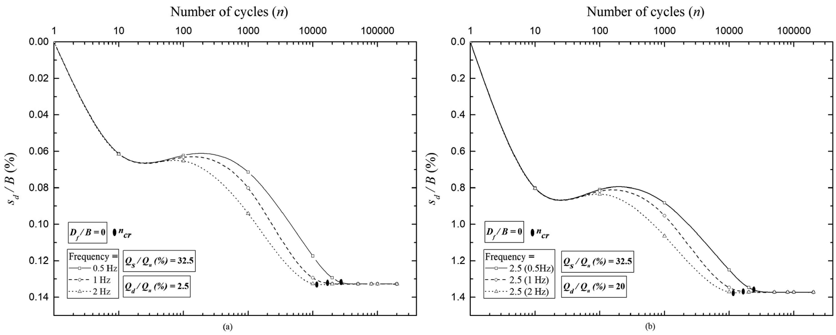


Fig. 25. Normalized settlement (s_d/B) due to only cyclic load with increasing load cycles [Q_s/Q_u = 32.5% and Q_d/Q_u = (a) 2.5%, (b) 20%] for different frequency

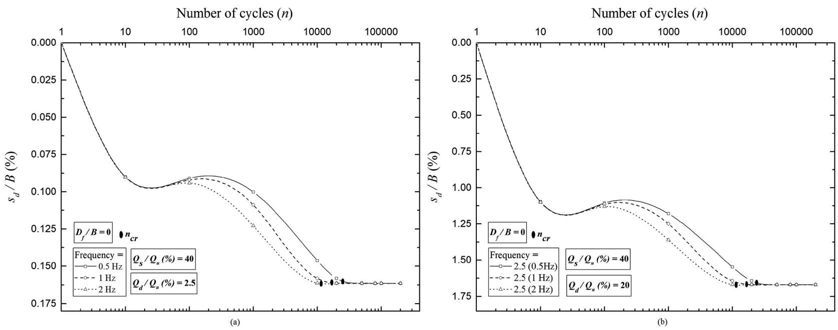


Fig. 26. Normalized settlement (s_d/B) due to only cyclic load with increasing load cycles [Q_s/Q_u = 40% and Q_d/Q_u = (a) 2.5%, (b) 20%] for different frequency

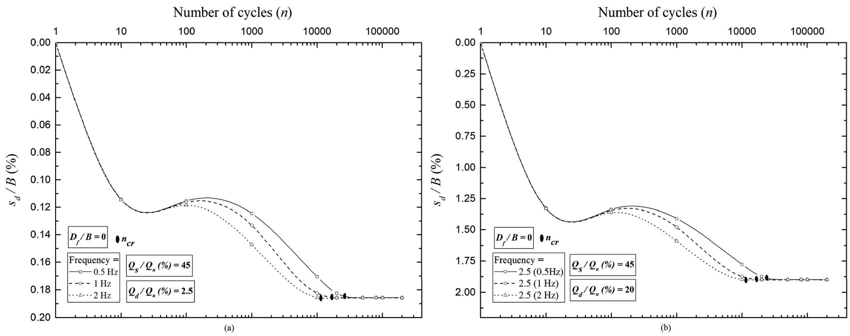


Fig. 27. Normalized settlement (s_d/B) due to only cyclic load with increasing load cycles [Q_s/Q_u = 45% and Q_d/Q_u = (a) 2.5%, (b) 20%] for different frequency

5 Conclusions

The present paper emphasizes on observing the settlement of a shallow strip foundation resting on soft clay subjected to vertical cyclic (rectangular pulse) load. The foundation is modeled numerically using *OpenSees*, based on Beam-on-Nonlinear-Winkler foundation model. The foundation is analyzed for both static and dynamic loading case. In the static analysis, the foundation is subjected to a gradual static load of magnitude equal to the ultimate load capacity of the foundation (as per Meyerhof 1963) and the settlement is noted. The ultimate bearing capacity of the foundation and the ultimate settlement are determined. The dynamic analysis has been done by applying a safe static load depending on the factor of safety and a superimposed low frequency (1 Hz) vertical cyclic load. For various combinations of Q_s/Q_u (10 to 45% @ 2.5%) and Q_d/Q_u (2.5 to 20% @ 2.5%), the settlement with number of cycles are noted. The followings are the important outcomes concluded from the study.

- The load per unit area (q) versus the normalized settlement (s/B) response obtained in this study, has good agreements with the same obtained by Das and Shin (1996) and that using PLAXIS 2D.
- The total settlement due to only cyclic load is composed of two parts. Primary rapid settlement and secondary slower settlement.
- The primary rapid settlement is the response of the foundation for the first 10 to 20 load cycles. The secondary slower settlement takes place up to the arrival of the critical number of load cycle (n_{cr}), after which the settlement becomes negligible.
- Irrespective of the intensity of static and cyclic loading the critical number of load cycle (n_{cr}) takes a value in between 15000 to 20000.
- $s_{d(r)}/s_u$ and $s_{d(t)}/s_u$ bear a non-linear relationship with Q_d/Q_u, whereas $s_{d(r)}/s_{d(t)}$ bears almost linear relationship with Q_d/Q_u.
- Frequency does not affect the rapid and total settlement significantly. However, for a given intensity of static and cyclic loading, the critical number of load cycle (n_{cr}) decreases with the increasing frequency of dynamic loading.

References

Allotey, N., El Naggar, M.H.: An investigation into the Winkler modeling of the cyclic response of rigid footings. Soil Dyn. Earthq. Eng. **28**(1), 44–57 (2008a)

Allotey, N., El Naggar, M.H.: Generalized dynamic Winkler model for nonlinear soil-structure interaction analysis. Can. Geotech. J. **45**(4), 560–573 (2008b)

Boulanger, R.W.: The PySimple1, QzSimple1, and TzSimple1 material documentation. Documentation for the OpenSees platform (2000). http://opensees.berkeley.edu/

Das, B.M., Shin, E.C.: Laboratory model tests for cyclic load-induced settlement of a strip foundation on a clayey soil. Geotech. Geol. Eng. **14**(3), 213–225 (1996)

EPRI: Manual on Estimating Soil Properties for Foundation Design. Electric Power Research Institute, Palo Alto (1990)

Federal Emergency Management Agency (FEMA): Prestandard and Commentary for the Seismic Rehabilitation of Buildings, FEMA (Series) 356, Washington, D.C. (2000)

Gajan, S., Hutchinson, T.C., Kutter, B., Raychowdhury, P., Ugalde, J.A., Stewart, J.P.: Numerical models for the analysis and performance-based design of shallow foundations subjected to seismic loading. Rep. No. 2007/04, Pacific Earthquake Engineering Research Center (PEER), Berkeley, CA (2008)

Gazetas, G.: Formulas and charts for impedances of surface and embedded foundations. J. Geotech. Eng. ASCE **117**(9), 1363–1381 (1991)

Harden, C., Hutchinson, T., Martin, G.R., Kutter, B.L.: Numerical modeling of the nonlinear cyclic response of shallow foundations. Rep. No. 2005/04, Pacific Earthquake Engineering Research Center (PEER), Berkeley, CA (2005)

Meyerhof, G.G.: Some recent research on the bearing capacity of foundations. Can. Geotech. J. **1** (1), 16–26 (1963)

OpenSees (Computer Software): Open system for earthquake engineering simulation, Pacific Earthquake Engineering Research Center (PEER), University of California, Berkeley. http://OpenSees.berkeley.edu/

Raychowdhury, P.: Nonlinear Winkler-based shallow foundation model for performance assessment of seismically loaded structures. Ph.D. dissertation, University of California, San Diego (2008)

Raymond, G.P., Komos, F.E.: Repeated load testing of a model plane strain footing. Can. Geotech. J. **15**(2), 190–201 (1978)