Geomechanics and Engineering, *Vol. 20, No. 4 (2020) 345-358*
DOI: https://doi.org/10.12989/gae.2020.20.4.345

Dynamic response and design of a skirted strip foundation subjected to vertical vibration

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(Received October 8, 2019, Revised January 9, 2020, Accepted January 30, 2020)

Abstract. Numerous studies have repeatedly demonstrated the efficiency of using skirts to increase the bearing capacity and to reduce settlement of shallow foundations subjected to static loads. However, no efforts have been made to study the efficiency of using these skirts to reduce settlement produced by machine vibration, although machines are very sensitive to settlement and the foundations of these machines should be designed properly to ensure that the settlement produced due to machine vibration is very small. This research has been conducted to investigate the efficiency of using skirts as a technique to reduce the settlement of a strip foundation subjected to machine vibration. A two-dimensional finite element model has been developed, validated, and employed to achieve the aim of the study. The results of the analyses showed that the use of skirts reduces the settlement produced due to machine vibration. However, the percentage decrease of the settlement is remarkably influenced by the density of the soil and the frequency of vibration, where it rises as the frequency of vibration increases and declines as the soil density rises. It was also found that increasing skirt length increases the percentage decrease of the settlement. Importantly, the results obtained from the analyses have been utilized to derive new dynamic impedance values that implicitly consider the presence of skirts. Finally, novel design equations of dynamic impedance that implicitly account to the effect of the skirts have been derived and validated utilizing a new intelligent data driven method. These new equations can be used in future designs of skirted strip foundations subjected to machine vibration.

Keywords: skirted foundation; machine foundation; dynamic impedance; finite element analysis; evolutionary polynomial regression analysis

1. Introduction

Machine foundations are the foundations that distribute the vibration induced due to machine working to the ground. The key design of these foundations is based on settlement limitation due to the sensitivity of the machines to large settlement, where the limitation of the settlement ranges between 0.001 mm to 1 mm based on the frequency of vibration of the machine (Das and Ramana 2011, Alzabeebee 2020).

The criteria of a very small settlement permitted for machine foundations made the subjected of the design of machine foundations of significant interest to past research projects, where previous studies proposed using soil reinforcement with geogrids (Samal *et al.* 2016, Venkateswarlu *et al.* 2018), soil reinforcement with geocell (Venkateswarlu *et al.* 2018, Ujjawal *et al.* 2019), soil replacement (Azzam 2015), soil stabilization with cement (Al-Wakel and Abdulrasool 2018) and soil stabilization with shredded tires (Rahil and Abd-Almuniem 2018) to reduce the settlement of machine foundations. However, these previous studies did not pay any attention to the possibility of using skirted foundation to reduce settlement induced by machine vibration. Skirted foundation is a shallow foundation with driven sheet piles attached to its edges; these sheet piles are usually referred to as structural skirts (Eid 2012). The concept of this foundation is based on using the structural skirts to confine the soil beneath the foundation; this confinement improves the bearing capacity and reduces settlement of foundations as has been noted by many studies in the literature (Bransby and Randolph 1998, Hu *et al.* 1999, Bienen *et al.* 2012, Al-Aghbari and Mohamedzein 2004a, b, 2006, Eid 2012, Khatri *et al.* 2017, Sajjad and Masoud 2017, Al-Aghbari and Mohamedzein 2018, Gnananandarao *et al.* 2018, Skau *et al.* 2018). However, these studies in the literature considered only static and cyclic loads, but these studies also provided good encouragement to investigate the efficiency of using this type of foundation for the case of machine vibration.

It is also worthy to mention that the available dynamic impedance, which is the key parameter in the design of machine foundations (Gazetas 1981), solutions were developed considering foundations without skirts (Gazetas 1980, 1981, Wolf 1998, Pradhan *et al.* 2004). Thus, skirted foundation cannot be easily used in practice due to lack of dynamic impedance design charts. Therefore, this research aims to advance the knowledge regarding skirted foundation by achieving the following objectives:

1-Developing and validating a finite element model that can correctly simulates the response of a strip foundation subjected to machine vibration.

2-Studying the efficiency of using structural skirts to

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http://www.techno-press.org/?journal=gae&subpage=7
ISSN: 2005-307X (Print), 2092-6219 (Online)

improvement of the performance of machine foundation.

3-Providing novel design equations of dynamic impedance of skirted strip foundation to enable suitable design of skirted foundation subjected to machine vibration.

2. Statement of the problem of the study

As mentioned in the introduction, this study aims to investigate the improvement of the performance of a machine foundation when reinforced with structural skirts. Hence, to achieve this aim, the cases of a non-skirted and skirted strip foundations have been considered in this research to compare the settlement produced for both types of foundations. Loose, medium, and dense sands have been considered in the analyses to understand the efficiency of the skirted foundation for all of the expected scenarios in practices and to provide design equations that can be used for different soil stiffnesses. In addition, three foundation widths have been modelled to understand the combined effect of the foundation width and structural skirts on the dynamic response of a machine foundation; these widths are 1.0 m, 2.0 m, and 3.0 m. Finally, the vibration of the machine has been modeled by applying a harmonic load on top of the strip foundation; this approach is very common to model the response of machine vibration and have been used in many previous studies (Fattah *et al.* 2014, Saikia 2014, Saikia and Das 2014, Fattah *et al.* 2015a, Majumder and Ghosh 2016, Majumder *et al.* 2017a, b). The applied harmonic load can be mathematically expressed using Eq. (10); again, this equation has also been used in previous studies in the literature (Fattah *et al.* 2014, Saikia 2014, Saikia and Das 2014, Fattah *et al.* 2015a, Majumder and Ghosh 2016, Majumder *et al.* 2017a, b).

$$Dynamic\ \ stress = P\sin(2\pi\omega t) \tag{1}$$

where, P is the maximum dynamic stress, ω is the frequency of machine vibration and t is the time.

The maximum dynamic stress has been considered equal to 10 kPa (Fattah *et al.* 2014). A frequency range of 0.50 Hz to 20 Hz has also been used; this range simulates the vibration of centrifugal pumps.

A two-dimensional finite element model has been developed, validated, and used to study the effect of skirts on the performance of machine foundation. The methodology of the finite element analysis is discussed in the next section.

3. Methodology of the finite element analysis

The finite element model of this study has been developed using PLAXIS 2D (Brinkgreve 2006). The left- and right-hand sides of the model have been allowed to deform only in the vertical direction to model the far ends of the finite element model. It is worthy to mention that this technique is robust and has been used in many validated numerical models in the literature (Baars 2017, Azzam and Basha 2018, Chavda and Dodagoudar 2018, Ouahab *et al.* 2018, El-Soud and Belal 2019, Haddad and Choobbasti 2019, Schweiger *et al.* 2019). Also, the bottom of the model has been fixed against the movement in both directions, to simulate the rigid rock layer; this technique is widely used in the literature to simulate the rigid rock layer (Ghosh 2012, Vivek and Ghosh 2012, Nguyen *et al.* 2016, Alzabeebee 2019a, b). Also, the Lysmer and Kuhlemeyer (1969) absorbent boundaries have been utilized in the dynamic analysis. These boundaries have been added to the sides and the bottom of the model to reduce the effect of wave reflection. This technique is very efficient and has been used by many other numerical modelling studies of dynamic soil-structure interaction problems (Alzabeebee 2014, 2017, 2019a, Alzabeebee *et al.* 2018a, Forcellini 2017, 2018, Fu and Wu 2019, Kampas *et al.* 2019, Liang *et al.* 2019, Mohasseb *et al.* 2019, Moghadam and Ashtari 2019, Manahiloh 2020). It is worthy to mention that the Lysmer and Kuhlmeyer (1969) absorbent boundaries are dampers formulated to absorb the shear and normal stresses developed at the left and right sides of the domain of the finite element model. These dampers are based on Eqs. (2) and (3) (Brinkgreve 2006).

$$\sigma_n = -C_1 \rho V_p \dot{u}_x \tag{2}$$

$$\tau = -C_2 \rho V_s \dot{u}_y \tag{3}$$

where, σ_n is the normal stress; C_1 and C_2 are relaxation coefficients considered in PLAXIS to enhance the robustness of the damper; ρ is the density of the soil; V_p is the pressure wave velocity; $\dot{u}_x$ is the velocity in the horizontal direction; τ is the shear stress; V_s is the shear wave velocity; and $\dot{u}_y$ is velocity in the vertical direction (Alzabeebee 2019b). The default values of C_1 and C_2 (1.0 and 0.25) are used in the analyses of this paper as these values are highly recommended in the manual of PLAXIS 2D (Brinkgreve, 2006).

Fifteen-node elements have been used to model the soil and the foundation and five-node beam elements have been used to model the structural skirts; similar approach has been used by Eid (2012). Rough interface has been considered between the soil and the skirts; this modelling approach has been considered because the settlement for the case of machine foundations is very small (the maximum settlement in this research is less than 4.0 mm) and hence, the slippage between the soil the and the skirts is very small and does not affect the accuracy of the modelling. This assumption has also been checked by comparing the results of the dynamic settlement produced using two models one with rough interaction between the soil and the skirts, and the other one with a friction coefficient of 0.65 (Skau *et al.* 2018). The results from this comparison showed very minor effect for the interaction coefficient, where the difference between both models was less than 1%, confirming the robustness of the approach considered in this study. It is also worthy to state that Eid (2012) has also considered a rough interface between the skirts and the soil.

The linear elastic model has been utilized to model the response of the soil, the concrete foundation, and the structural steel skirts. The linear elastic soil model is deemed appropriate to model the soil because machines usually apply very small stress (10 kPa for the case of this study) on the foundation and hence, produces very small settlement (the maximum settlement in this research is less than 4.0 mm). This assumption has also been checked by comparing the results of the linear elastic model and the Mohr-Coulomb elastic-perfectly-plastic model. The results from these comparisons showed insignificant difference between the two model (less than 0.5%). This behaviour is because the strain inducted due to machine vibration is very small; therefore, the soil stays in the elastic range due to the application of the vibration (Ali *et al.* 2017, Bose *et al.* 2018, Kumar and Ghosh 2020). Therefore, the use of the linear elastic soil model is robust. This model has also been used in many previous studies to model the soil in problems related to soil-machine foundation interaction (Yang *et al.* 2013, Saikia 2014, Saikia and Das 2014, Fattah *et al.* 2015b, Ali *et al.* 2017, Bose *et al.* 2018, Kumar and Ghosh 2020). A numerical damping (using Rayleigh damping parameters α and β) has been considered in the analyses as the linear-elastic model does not implicitly account to the influence of the hysteretic soil damping (Kontoe *et al.* 2011, Sun *et al.* 2019). It is important to mention that this approach is acceptable in the area of the numerical modelling of machine foundations and has also been used in many previous studies (Saikia 2014, Saikia and Das 2014, Vivek and Ghosh 2012, Ghosh 2012, Fattah *et al.* 2015a, Majumder and Ghosh 2016, Majumder *et al.* 2017a, b, Bose *et al.* 2018, Kumar and Ghosh 2020). The numerical damping also improves the stability of the numerical analysis (Forcellini 2019). In addition, the use of the linear elastic model to simulate both the concrete foundation and the steel skirts is justifiable because the stress applied due to machine vibration is very small and is less than the yield stress of the concrete and the steel. The governing equation of the finite element analysis considering the damping is shown in Eq. (4) (Vivek 2011).

$$M\ddot{u} + C\,\dot{u} + Ku = F \tag{4}$$

$$C = \alpha\, M + \beta K \tag{5}$$

where, M is the mass matrix, $\ddot{u}$ is the acceleration, $\ddot{u}$ is the acceleration, $\dot{u}$ is the velocity, u is the displacement, C is the damping matrix, K is the stiffness matrix, and F is the load vector.

The finite element analysis has been done using three stages;

-Stage a: the *in-situ* stress has been obtained in this stage. The at rest lateral earth pressure has been calculated using the equation proposed by Jackey (Brinkgreve 2006); this equation is recommended by PLAXIS developers (Brinkgreve 2006).

-Stage b: the static load produced by the machine weight and the foundation has been applied in this stage utilizing a static analysis.

-Stage c: the vibration of the machine has been applied in this stage utilizing a time-history finite element analysis. A total analysis time of 5 seconds is considered in the analysis of this stage; this time is enough to capture the maximum amplitude of the dynamic settlement. In addition, a time step of 0.004 sec has been utilized in this analysis; this time step has been calculated based on the developed finite element mesh (i.e., the smallest element size) to ensure a stable analysis.

Table 1 The parameters of the soils

Parameter	Loose sand	Medium sand	Dense sand
γ (kN/m^3)	16.00	18.50	20.00
E (kPa)	18,000	35,000	65,000
υ	0.30	0.32	0.34
α	0.0065	0.0070	0.0104
β	0.0075	0.0058	0.0045

Table 2 The parameters of the concrete foundation and the steel skirts

Parameter	Concrete foundation	Steel skirts
γ (kN/m^3)	24.00	78.00
E (kPa)	20,000,000	200,000,000
υ	0.20	0.20

Table 1 shows the properties of the soils used in the analyses. These properties have been taken from Fattah *et al.* (2015a). Table 2 shows the properties of the concrete foundation and the steel skirts; these properties have been taken from Eid (2012). Finally, it is worthy to mention that a skirt thickness of 5 cm is used in the analyses; this thickness simulates the sheet piles available in the markets, which are usually used to support shallow foundations (Eid 2012).

4. Calibration of the finite element model

This section disuses the choices made for the dimensions of the finite element model and the mesh size to demonstrate the development of a calibrated and robust finite element model.

First, the depth of the model has been assumed to extend to the location of the rigid rock layer, which is usually located at a depth of 25 m from the natural ground in Baghdad. The width of the model has been selected after many trials with different widths conducted using the largest foundation width (which is 3.0 m). Fig. 1 shows the results of these trials; these results are for the case of a frequency of vibration of 0.5 Hz and dense sand as this case represents the largest wavelength. As it is obvious from the figure, the trials started with a model width of 10 m and then the width increased to understand the influence of the finite element model extend. The results of the figure clearly show that as the model width increases the obtained dynamic settlement decreases with significant decrease occurs as the width rises from 10 m to 20 m, and from 20 m to 30 m. Importantly, it is obvious from the figure that there is no significant change of the dynamic settlement as the model width increases from 50 m to 60 m; this means that the effect of the finite element model width can be eliminated when the model width is equal to or greater than 50 m. Thus, a finite element model width of 50 m has been selected for this study.

The effect of the mesh size has been investigated by developing finite element models with fine mesh (total

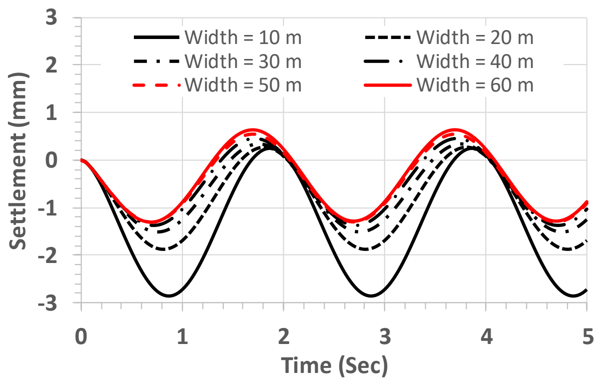


Fig. 1 Effect of the finite element model width on the response of the foundation

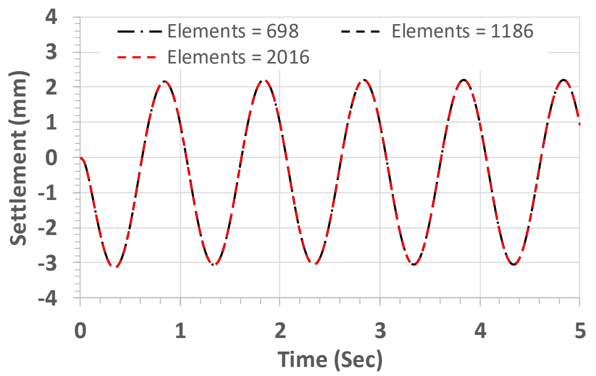


Fig. 2 Effect of the mesh density on the results of the finite element modelling

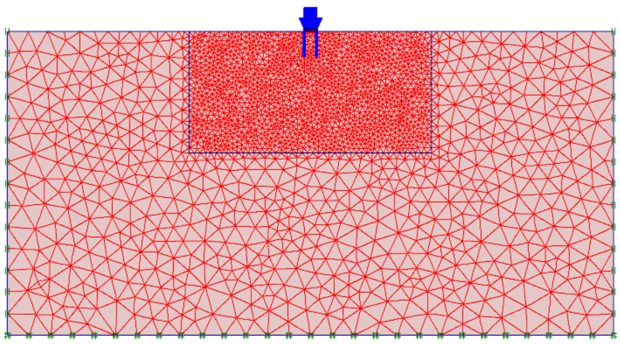


Fig. 3 The finite element model of the skirted foundation

number of elements = 986), very fine mesh (total number of elements = 1186), and extremely fine mesh (total number of elements = 2016) for the case of a foundation width of 3.0 m. The extremely fine mesh has been developed by dividing the finite element model into two regions; the region away from the foundation has been meshed using very fine mesh and the region near the zone of interest (i.e., the foundation) has been discretized using very fine mesh with extra local refinement. Fig. 2 presents the dynamic settlement-time response for the three mesh configurations; this figure has been produced considering a vibration frequency of 1.0 Hz and dense sand. It is clear from the figure that the mesh has a very minor effect on the results and all of the mesh sizes produced the same trend and approximately same magnitude of the dynamic settlement. The fine mesh produced a maximum dynamic settlement of 3.12 mm, while the very fine and extremely fine mesh produced a settlement of 3.14 mm. However, an extremely fine mesh (total number of elements = 2016) has been used in the analyses as this mesh produces excellent contour plots, which aids the understanding of the influence of the skirts as will be discussed later in this paper. Finally, the considered finite element model (i.e., with width of 50 m and depth of 25 m), is shown in Fig. 3.

5. Validation of the methodology of the analysis

The validation has been achieved by comparing the results of the finite element model with the results of the cone model. Cone model is a closed form solution developed to estimate the dynamic impedance of a circular foundation subjected to machine vibration. Eqs. (6)-(17) show the procedure to calculate the dynamic impedance (K_d) according to the cone model (Wolf 1998).

$$K_d = K_{static}(K(a_o) + ia_o + c(a_o) - Ba_o^2) \tag{6}$$

$$K_{static} = \frac{4GR}{1-\upsilon} \tag{7}$$

$$K(a_o) = 1 - \frac{\mu}{\pi}\frac{Z_o}{r_o}\frac{V_s^2}{c^2}{a_o}^2 \tag{8}$$

$$\mu = 0 \quad \text{for } \upsilon \leq \tfrac{1}{3} \tag{9}$$

$$\mu = 2.4\pi(\upsilon - \tfrac{1}{3}) \quad \text{for } \tfrac{1}{3} < \upsilon \leq \tfrac{1}{2} \tag{10}$$

$$\frac{Z_o}{r_o} = \frac{\pi}{4}(1-\upsilon)\left(\frac{c}{V_s}\right)^2 \tag{11}$$

$$c = V_s\sqrt{\tfrac{2(1-\upsilon)}{(1-2\upsilon)}} \quad \text{for } \upsilon \leq \tfrac{1}{3} \tag{12}$$

$$c = 2V_s \quad \text{for } \tfrac{1}{3} < \upsilon \leq \tfrac{1}{2} \tag{13}$$

$$a_o = \frac{fR}{V_s} \tag{14}$$

$$c(a_o) = \tfrac{Z_o}{r_o}\tfrac{V_s}{c} \tag{15}$$

$$B = 0.25b_o(1-\upsilon) \tag{16}$$

$$b_o = \frac{m}{\rho R^3} \tag{17}$$

where, K_{static} is the spring stiffness of the soil for the case of static load, G is the soil shear modulus, R is the foundation radius, $K(a_o)$ is the normalized spring coefficient, μ is a coefficient used to employ the trapped mass contribution, Z_o/r_o is the aspect ratio, c is the appropriate wave velocity, a_o is the dimensionless frequency, $c(a_o)$ is the normalized damping coefficient, B

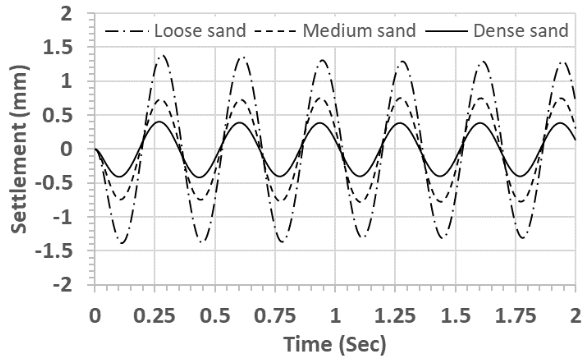


Fig. 4 The results of the finite element analysis of the dynamic settlement of a circular foundation resting on loose, medium, and dense sands

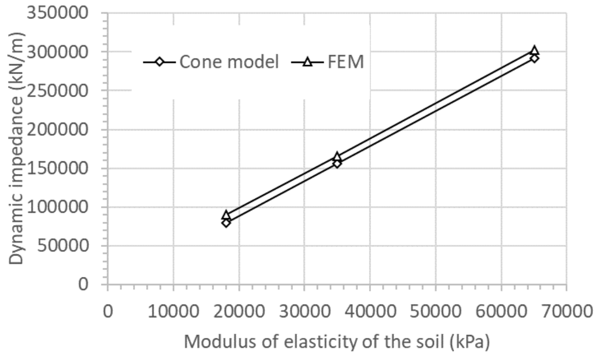


Fig. 5 Comparisons of the calculated and obtained dynamic impedance

is the modified mass ratio, b_o is the mass ratio, u is the maximum settlement due to machine vibration, and DS_{max} is the maximum vertical dynamic stress applied on the foundation.

An axisymmetric model has been developed using PLAXIS 2D to simulate the case of a circular foundation with a radius of 2.0 m and subjected to a vertical harmonic vibration so that the results would be easily compared with the cone model as the cone model is developed for the case of a circular foundation. The frequency of vibration is assumed to be equal to 3.0 Hz and the maximum dynamic stress is assumed to be equal to 10 kPa. Loose, medium, and dense sands have been considered in the validation analyses. The analysis methodology was similar to the methodology discussed in previous section. Also, the material properties shown in Table 1 (for the soils) and Table 2 (for the concrete foundation) have been used in the validation analyses. Fig. 4 shows the obtained relationship of the dynamic settlement with time for loose, medium, and dense sands. The dynamic impedance has been obtained by dividing the maximum applied dynamic force by the maximum settlement obtained from the finite element analysis (Fig. 4). Furthermore, the same problem analysed using the cone model utilizing Eqs. (6)-(17) to obtain the dynamic impedance. Fig. 5 compares the dynamic impedance obtained from the cone model and the finite element analysis (FEM). It is clear from the figure that the percentage difference between the cone model and the finite element analysis is very small as it ranges from 1% to 3%; hence, it can be concluded that the finite element methodology utilized in this research is robust and produces trusted results.

6. Analysis of foundation without skirts

The effect of the soil stiffness and frequency of vibration for the case of foundation without skirts have been studied in this section to provide useful reference cases for the analyses of the effect of skirts. The analyses in this section have been conducted for a foundation width of 1.0 m, 2.0 m, and 3.0 m and for a frequency range of 0.5 Hz to 20.0 Hz. The maximum dynamic settlement has been recorded for each case and the obtained values are presented in Figs. 6, 7, and 8, for the case of foundation width of 1.0 m, 2.0 m, and 3.0 m, respectively. It is evident from the figures that the maximum dynamic settlement decreases as the soil stiffness increases. It is also clear that the natural frequency of the system is very low and is less than 0.5 Hz as the settlement continually decreases as the frequency of vibration increases.

Comparing the results of Figs. 6, 7, and 8 clearly shows that the maximum dynamic settlement rises as the foundation width increases. This behaviour is due to the change of failure mechanism from general to progressive failure as the width of the foundation increases, which

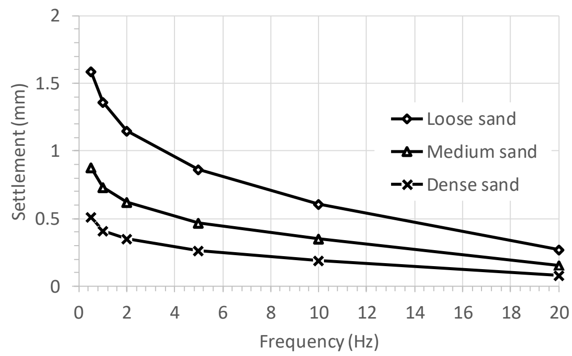


Fig. 6 Maximum dynamic settlement of a strip foundation without skirts for the case of a foundation width of 1.0 m

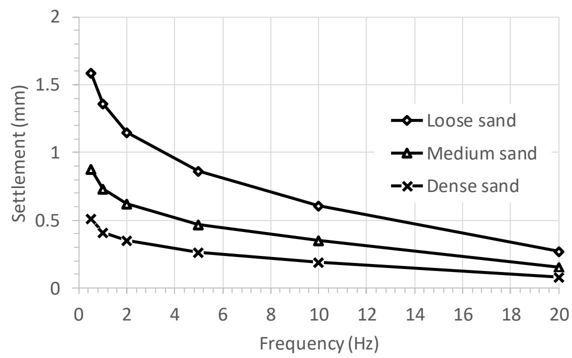


Fig. 7 Maximum dynamic settlement of a strip foundation without skirts for the case of a foundation width of 2.0 m

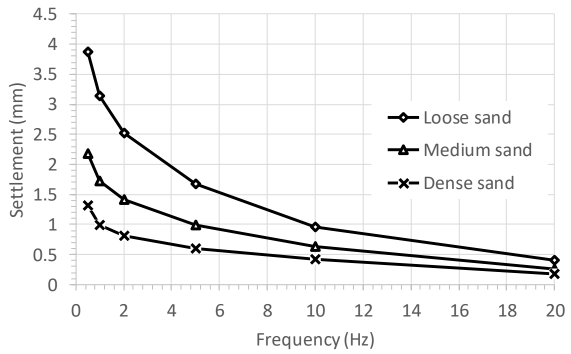


Fig. 8 Maximum dynamic settlement of a strip foundation without skirts for the case of a foundation width of 3.0 m

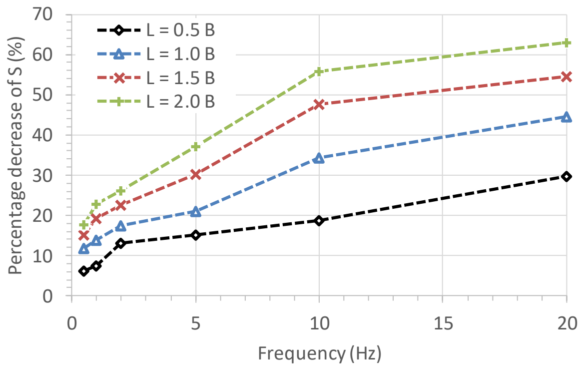


Fig. 9 Percentage decrease of the dynamic settlement (S) due to the presence of skirts for a strip foundation with a width of 1.0 m and resting on loose sand

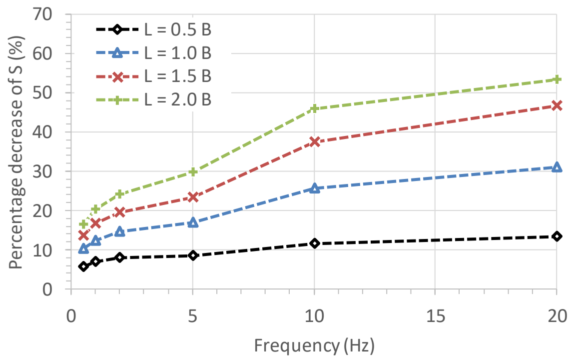


Fig. 10 Percentage decrease of the dynamic settlement (S) due to the presence of skirts for a strip foundation with a width of 1.0 m and resting on medium sand

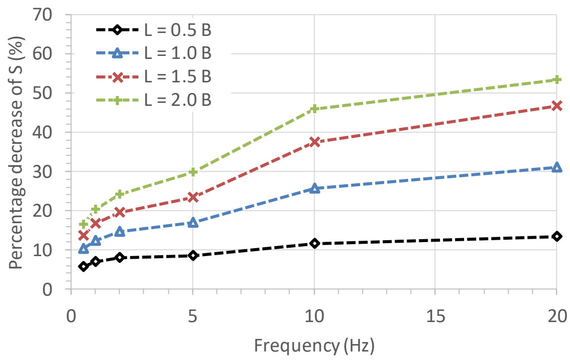


Fig. 11 Percentage decrease of the dynamic settlement (S) due to the presence of skirts for a strip foundation with a width of 1.0 m and resting on dense sand

ultimately changes the distribution of the stress beneath the foundation (Clark 1998). It is also worthy to state that similar effect for the foundation width has also been noted in previous studies for the cases of foundations subjected to static load (Cerato and Lutenegger 2007, Rezania and Javadi 2007, Shahnazari *et al.* 2014).

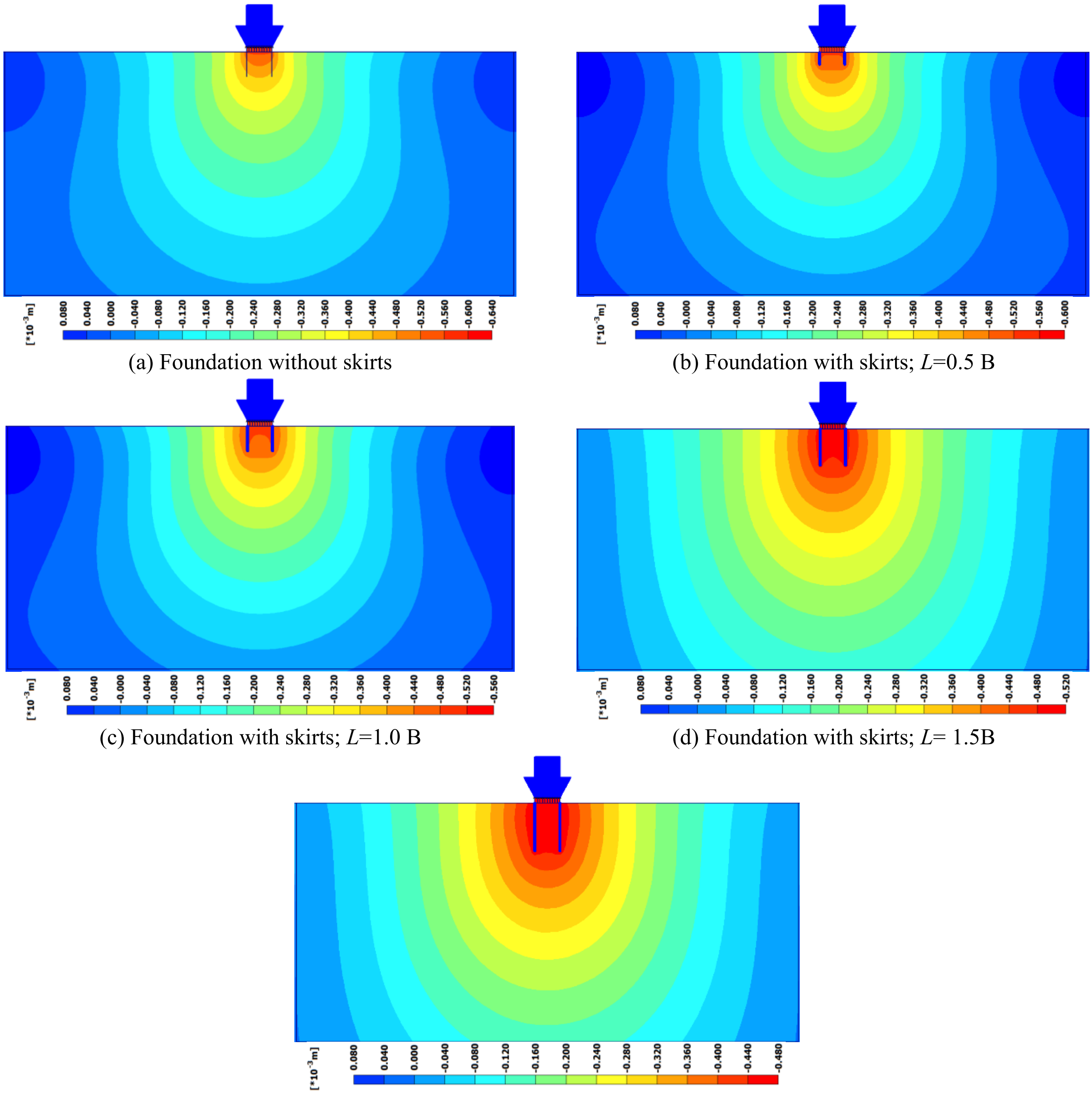
7. Analysis of foundation with skirts

Finite element models have been developed for foundations reinforced with structural skirts. Different lengths of structural skirts have been simulated to allow insight into the influence of the skirt length for foundations with different widths and vibrating with different frequencies. The range of the length of skirts (L) considered in this research is 0.5 B to 2.0 B, where B is the foundation width. The maximum dynamic settlement has been obtained for each case and the percentage decrease of the dynamic settlement has been calculated for each case using Eq. (18), to enable direct understating of the effect of the length of skirts.

$$Percentage\ decrease = \frac{S_{ns} - S_{ws}}{S_{ns}} \times 100\% \qquad (18)$$

where, S_{ns} is the dynamic settlement of the foundation with no skirts and S_{ws} is the dynamic settlement with skirts.

Figs. 9, 10, and 11 show the obtained percentage decrease of the dynamic settlement (S) for the case of foundation width of 1.0 m and resting on loose, medium, and dense sand, respectively. Fig. 9 shows that the presence of skirts reduces the dynamic settlement for the case of loose sand. It is also clear from Fig. 9 that the percentage decrease of the dynamic settlement is remarkably influenced by the frequency of vibration as it is very clear that the percentage decrease rises as the frequency of vibration increases; however, the rate of increase is not constant. For the case of skirts length (L) of 0.5 B, the percentage decrease is equal to 6%, 7 %, 13 %, 15%, 19%, and 30% for a vibration frequency of 0.5 Hz, 1.0 Hz, 2.0 Hz, 5.0 Hz, 10 Hz, and 20 Hz, respectively. Fig. 9 also shows that the percentage decrease of the settlement surges as the length of skirts increases. Also, the trend of the relationship between the percentage decrease of settlement and the frequency of vibration is approximately similar for all of the cases of skirts length. However, It is also clear from Fig. 9 that the degree of improvement obtained from increasing the length of skirts is remarkably dependent on the frequency of vibration; for example, increasing length of skirts from 0.5 B to 2.0 B rises the percentage decrease by 12% (from 6% to 18%) for the case of a vibration frequency of 0.5 Hz and 33% (from 30% to 63%) for the case of a vibration frequency of 20 Hz. Figs. 10 and 11 show similar trend to Fig. 9, where the percentage decrease



(a) Foundation without skirts

(b) Foundation with skirts; L=0.5 B

(c) Foundation with skirts; L=1.0 B

(d) Foundation with skirts; L= 1.5B

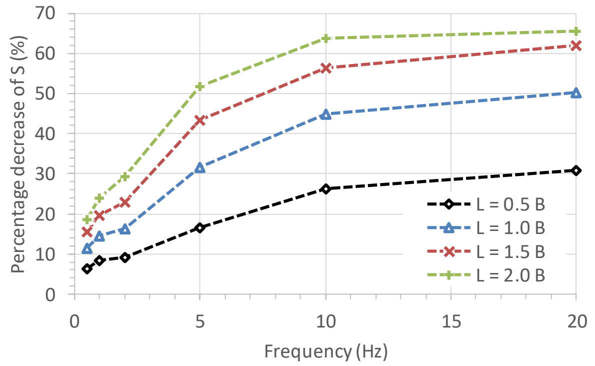
(e) Foundation with skirts; L= 2B

Fig. 12 Contour lines of the vertical settlement at the maximum dynamic load for the case of a vibration frequency of 1.0 Hz

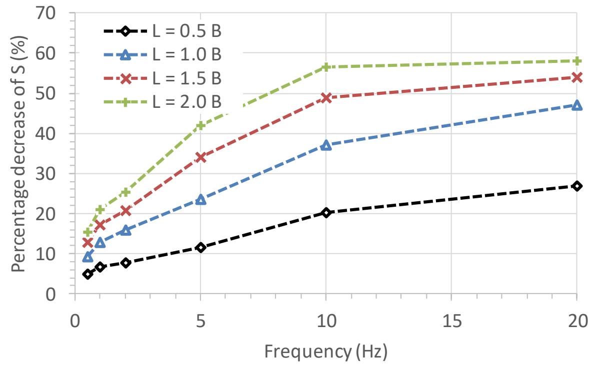
of settlement rises as the length of skirts increases and the figures also show the nonlinear trend of the relationship of the percentage decrease of settlement and the frequency of vibration.

It can also be noticed by comparing results of Figs. 9, 10, and 11 that the efficiency of using skirts in reducing the dynamic settlement decreases as the stiffness of soil increases. For example, for the case of length of skirts of 1.0 B and vibration frequency of 2.0 Hz, the percentage decrease of settlement is equal to 17%, 15%, 14% for loose, medium, and dense sand, respectively. This observation of the decrease of the efficiency of skirts as the soil stiffness increases is also noticed in the literature for the case of foundation subjected to static loads by Eid (2012), Khatri *et al.* (2017), and Sajjad and Masoud (2018).

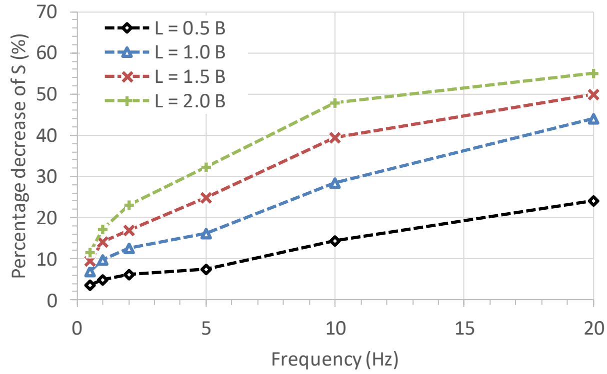
It is worthy to state that the decrease of the settlement as the length of the skirts increases is because the skirts help in distributing the load to a greater depth, which enables the skirted foundation system to behave in a manner similar to piers as noted by Eid (2012). In other words, this means that the confined soil below the foundation becomes part of the foundation and hence the load applied by the foundation will be distributed more uniformly at a greater depth; this can be clearly seen in the contour lines of the maximum dynamic settlement presented in Figs. 12(a)-12(e), which is for the case of a frequency of vibration of 1.0 Hz. Figs. 12(a)-12(e) compare the contour lines of the maximum dynamic settlement for the case of no skirts (Fig. 12(a)), skirts length of 0.5 B (Fig. 12(b)), skirts length of 1.0 B (Fig. 12(c)), skirts length of 1.5 B (Fig. 12(d)), and skirts



(a) Loose sand

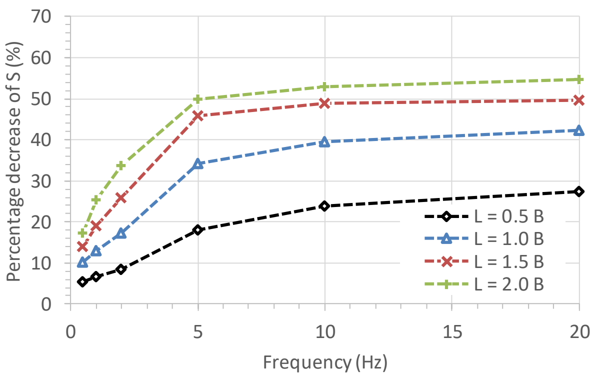


(b) Medium sand

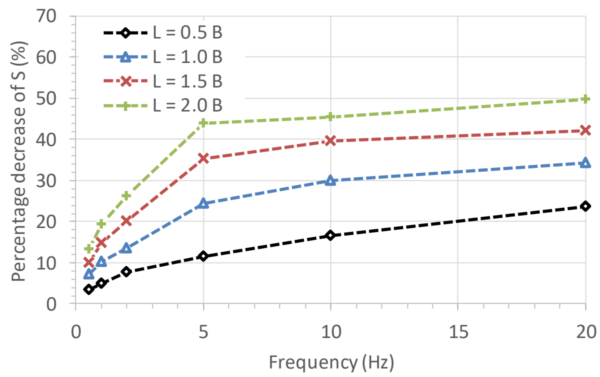


(c) Dense sand

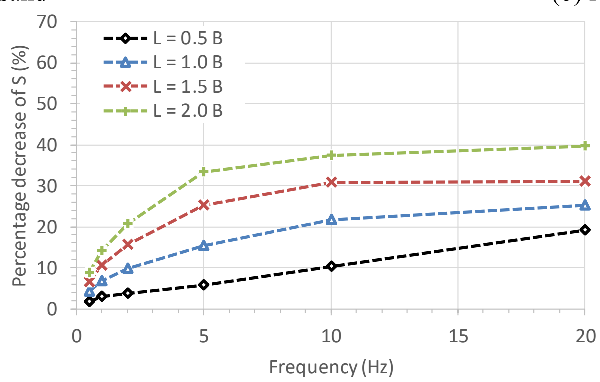
Fig. 13 Percentage decrease of the dynamic settlement due to the presence of skirts for a strip foundation with a width of 2.0 m



(a) Loose sand



(b) Medium sand



(c) Dense sand

Fig. 14 Percentage decrease of the dynamic settlement due to the presence of skirts for a strip foundation with a width of 3.0 m length of 2.0 B (Fig. 12(e)). The figures evidently show that the distribution of the settlement remarkably changes when the skirts are included in the analysis and also the figures clearly show that the zone of the uniform settlement below the foundation increases as the length of the skirts increases.

Finally, Figs. 13 and 14 show the percentage decreases of settlement for the case of foundation width of 2.0 m and 3.0 m, respectively. It is very clear from these figures that the relationship of the percentage decrease of settlement and frequency of vibration follows the same trend already discussed in Figs. 9-11, where increasing the vibration frequency and length of skirts rise the percentage decrease of the settlement, and increasing the soil stiffness decreases the efficiency of the skirts in reducing the settlement.

8. Dynamic impedance

Designers of machine foundations usually utilize the dynamic impedance to calculate the amplitude of settlement produced due to machine vibration. However, no equations or design charts are available in the literature to calculate the dynamic impedance for the case of skirted foundation as discussed earlier in this research. Thus, the results obtained from the numerical analyses have been used to derive novel dynamic impedance values for skirted foundation to enable useful outcome from this research to practitioners. The dynamic impedance has been obtained by diving the maximum dynamic stress (i.e., 10 kPa) by the maximum amplitude of settlement. The reason to divide the stress by the amplitude of settlement and not the force by the amplitude of settlement is because this study considered a strip foundation with unlimited length as the study utilized the plane strain analysis and hence, the length of the foundation is not available. However, by utilizing the maximum dynamic stress it is possible to obtain dynamic impedance values that works for strip foundations and can be used in future designs. Thus, the units of the derived dynamic impedance values will by kN/m^3 and not kN/m.

Figs. 15, 16, and 17 show an example of the obtained dynamic impedance, which is for the case of a foundation width of 1.0 m and resting on loose, medium, and dense sand, respectively. It is clear from the figures that the dynamic impedance increases as the frequency of vibration, length of skirts, and soil stiffness increase; this is because the dynamic impedance inversely proportional to the amplitude of settlement. In other words, less settlement means higher dynamic impedance. Furthermore, and as has been discussed earlier, the settlement increases as the foundation width increases; this means that the dynamic impedance also changes as the foundation width changes, but the results for other foundation widths have not been presented in this section for sake of briefing. However, all the results of the dynamic impedance have been used in the development of novel dynamic impedance design equations utilizing a robust data driven method called the evolutionary polynomial regression analysis. This approach has been followed to enable better use of the results of this study and to provide useful design equations. The next section discusses the use of the EPR method in the development of the new design equations.

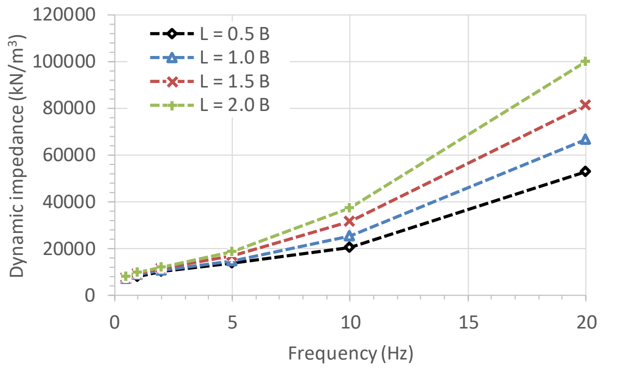


Fig. 15 Dynamic impedance for the case of a strip foundation with a width of 1.0 m and resting on loose sand

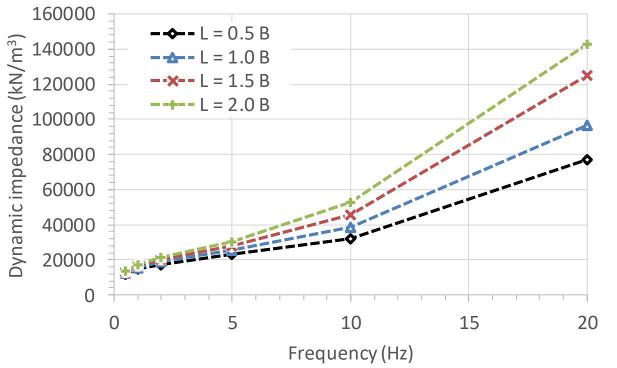


Fig. 16 Dynamic impedance for the case of a strip foundation with a width of 1.0 m and resting on medium sand

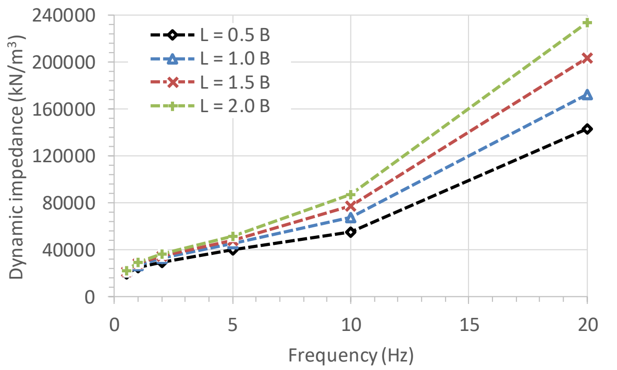
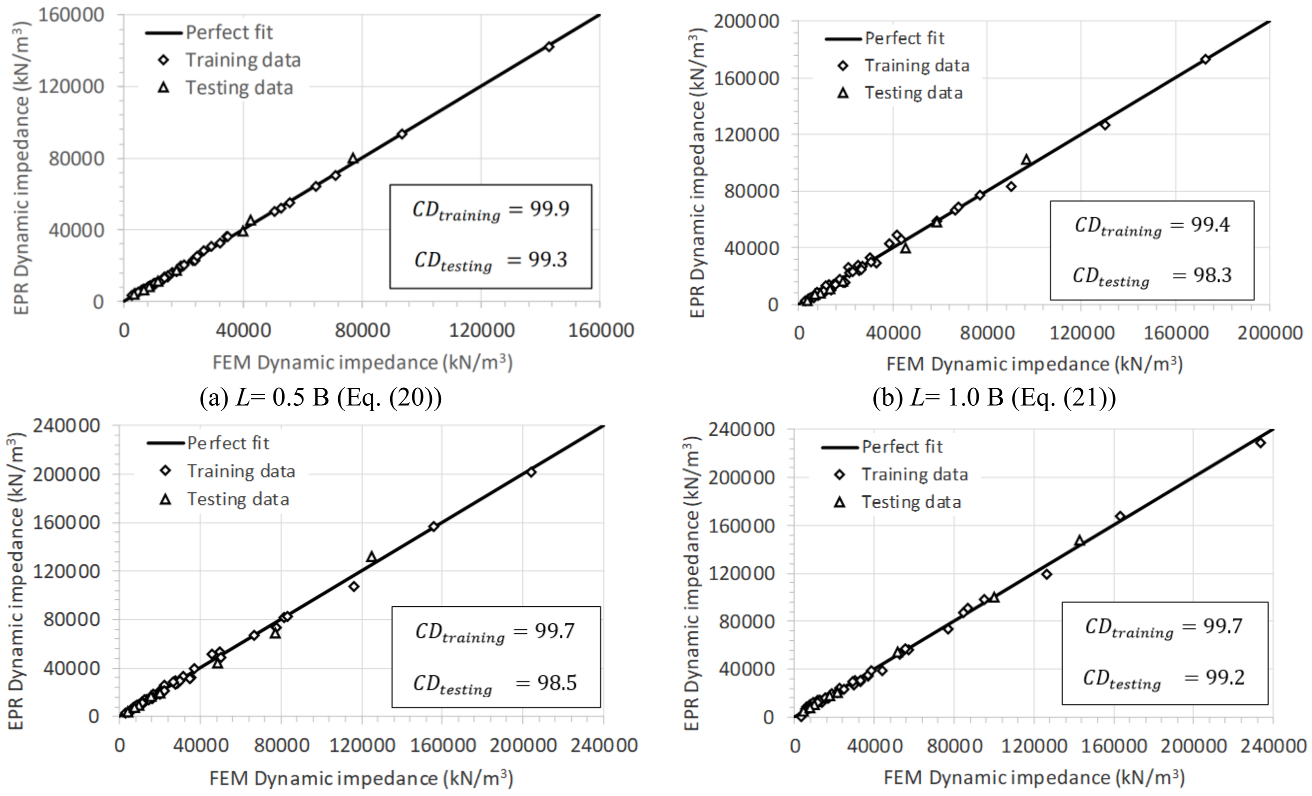


Fig. 17 Dynamic impedance for the case of a strip foundation with a width of 1.0 m and resting on dense sand

9. Development of new equations of the dynamic impedance

The evolutionary polynomial regression analysis (EPR) has been utilized in the development of the new equations. This method has been used because it proved its powerful capabilities in providing robust and accurate design equations for many applications in the area of geotechnical engineering (Alzabeebee *et al.* 2018b, 2019, Alzabeebee 2019a). The EPR is a data driven method based on



(a) L= 0.5 B (Eq. (20)) (b) L= 1.0 B (Eq. (21))

(c) L = 1.5 B (Eq. (22)) (d) L = 2.0 B (Eq. (23))

Fig. 18 Comparison of the dynamic impedance obtained using Eqs. (20), (21), (22), and (23), and the dynamic impedance derived from the results of the finite element analysis

regression analysis and artificial intelligence. This method has been developed by Giustolisi and Savic (2006) and improved further by the same researchers in 2009 (Giustolisi and Savic 2009). Giustolisi and Savic (2006) also introduced a coefficient called the coefficient of determination (CD); this coefficient is used in the EPR method to judge the accuracy of the developed mathematical model. The CD can be calculated using Eq. (19); it ranges from 0 to 100%, where 100% represents a perfect fit equation. This coefficient will also be used in this section to judge the accuracy of the developed equations. For sake of briefing, the methodology of the EPR analysis has not been discussed in this section; however, further information on the methodology can be found in Giustolisi and Savic (2006), Giustolisi and Savic (2009), and Alzabeebee (2017).

$$CD = 1 - \frac{\sum_N \left(Kd_{(m)} - Kd_{(p)}\right)^2}{\sum_N \left(Kd_{(m)} - \frac{1}{N}\sum_N Kd_{(p)}\right)^2} \tag{19}$$

where, $Kd_{(m)}$ is the input dynamic impedance (i.e., the dynamic impedance calculated based on the finite element analysis), $Kd_{(p)}$ is the dynamic impedance predicted using the EPR, and N is the total number of points, which have been used in the EPR to develop the mathematical equation. The EPR analysis is based on dividing the data into training and testing, where the training data are used to develop the mathematical equation and the testing data is used to test the mathematical equation. The accuracy of the developed equation is judged by calculating the CD for both training and testing data to ensure that the mathematical equation can predict the results of the data used in the development of the equation and the data which has not been used in the development of the equation. This approach has also been used by all the studies which have utilized by the EPR analysis (Alzabeebee *et al.* 2018b, 2019, Alzabeebee 2019a).

As a first step to conduct the EPR analysis, the data obtained from the numerical modelling has been arranged as dependent variable (the dynamic impedance) and the associated independent variables (the modulus of elasticity of the soil, the frequency of vibration, and the width of the foundation). It is worthy to state that it is not possible to use normalized results in the EPR analysis. Thus, an equation for each length of skirts has been developed; this means that a total number of 54 records were prepared for each length of skirts. The data then divided into training and testing, where 80% of the data used in the training and 20% of the data used in the testing. The statistical measures of the training and testing data have been calculated to ensure that the testing data are within the range of the training data; this technique has been used to avoid model extrapolation (Alzabeebee *et al.* 2018b, 2019a). Table 3 shows the maximum (Max), minimum (Min), and average (Avg) values of the testing and training data, where it is clear from the results of the table that the testing data range is within the range of the training data. These data were then used in the EPR analysis, where different forms of equations have been tested by calculating the CD values and by also

Table 3 Maximum, minimum and average values of the data used in the EPR analysis

		L = 0.5 B				L = 1.0 B			
		K_d	f	E	B	K_d	f	E	B
Training data	Max	2732.2	0.5	18000.0	1.0	2876.0	0.5	18000.0	1.0
	Min	142857.1	20.0	65000.0	3.0	172771.3	20.0	65000.0	3.0
	Avg	24170.5	6.3	40173.9	2.0	28843.4	6.3	40173.9	2.0
Testing data	Max	3413.0	0.5	18000.0	1.0	3663.0	0.5	18000.0	1.0
	Min	76923.1	20.0	65000.0	3.0	96525.1	20.0	65000.0	3.0
	Avg	25860.0	6.8	34500.0	1.9	31595.1	6.8	34500.0	1.9

		L = 0.5 B				L = 1.0 B			
		K_d	f	E	B	K_d	f	E	B
Training data	Max	2732.2	0.5	18000.0	1.0	2876.0	0.5	18000.0	1.0
	Min	142857.1	20.0	65000.0	3.0	172771.3	20.0	65000.0	3.0
	Avg	24170.5	6.3	40173.9	2.0	28843.4	6.3	40173.9	2.0
Testing data	Max	3413.0	0.5	18000.0	1.0	3663.0	0.5	18000.0	1.0
	Min	76923.1	20.0	65000.0	3.0	96525.1	20.0	65000.0	3.0
	Avg	25860.0	6.8	34500.0	1.9	31595.1	6.8	34500.0	1.9

checking if the developed equations are capable of predicting the trend of the relationship of the dynamic impedance. The percentage error of each data point is also checked. Eqs. (20), (21), (22), and (23) present the best mathematical equations obtained from the EPR analysis for predicting the dynamic impedance for the case of length of skirts of 0.5 B, 1.0 B, 1.5 B, and 2.0 B, respectively.

$$K_d = 0.484\frac{E\sqrt{f}}{B} - 0.127\frac{Ef}{B} + 1.001f^2\sqrt{E} - 0.008f^{2.5}B\sqrt{E} + 8.8\times10^{-9}\frac{f^{2.5}E^2}{B^2} + 1737.38 \tag{20}$$

$$K_d = 0.395\frac{E}{B} + 4.868f^{1.5}\sqrt{E} - 0.00035Ef^{1.5}B^3 + 4.5\times10^{-12}\frac{f^3E^{2.5}}{B} \tag{21}$$

$$K_d = 0.388\frac{E}{B} - 398671\frac{f}{\sqrt{E}} + 5332f - 0.00027Ef^2B^{2.5} + 0.00021Ef^3 - 1253 \tag{22}$$

$$K_d = -782568\frac{\sqrt{B}}{\sqrt{f}\sqrt{E}} + 0.00098\frac{E^{1.5}\sqrt{f}}{B^{1.5}} + 205.5fB - 4.07\frac{f^{2.5}\sqrt{E}}{B^3} + 4.374\frac{f^{2.5}\sqrt{E}}{B^{2.5}} + 13896 \tag{23}$$

Figs. 18(a), 18(b), 18(c), and 18(d) present the relationship between the values of the dynamic impedance used in the development of the equations (FEM Dynamic impedance) and the corresponding dynamic impedance values obtained from the EPR analysis (EPR Dynamic impedance) using Eqs. (20), (21), (22), and (23) for the case of length of skirts of 0.5 B, 1.0 B, 1.5 B, and 2.0 B, respectively. Also, the CD values of the training and testing data are presented in the figures for each case. The figures obviously show that the developed mathematical equations are robust as most of the data are on the perfect fit line, which represents the line of no-error in the predication. Figs. 18(a)-18(d) also show that the developed mathematical equations achieved very high CD values for both training data and testing data. These excellent CD values add additional support to the high quality of the developed equations and enable a confidence in the use of these equations in future designs.

Finally, it is useful to state that the developed equations can be easily used by designers to calculate the maximum settlement by simply diving the maximum dynamic stress due to machine vibration by the dynamic impedance calculated from Eqs. (20)-(23). The designer can then check which length of skirts should be used to ensure that the settlement does not exceed the design limitation. It must also be noted that these data driven design equations have been developed utilizing data with ranges as listed in Table 3; hence, these equations should be used for designs within this range (foundation width, modulus of elasticity of soil, and frequency of vibration) to ensure robust and accurate design. Therefore, new finite element models are required for cases outside the ranges listed in Table 3.

10. Conclusions

A robust plane-strain two-dimensional finite element model has been developed and validated to study the efficiency of using structural skirts to reduce settlement of foundation subjected to machine vibration. A total number of 270 finite element models have been built to provide a comprehensive understanding of the influence of skirts on the settlement of machine foundation. Furthermore, the obtained results from the finite element analyses have been employed to produce practical design solutions by calculating the dynamic impedance and using a robust data driven method to obtain accurate design equations of the dynamic impedance that can help with future designs. The main findings from this research can be briefly stated in the followings:

- Using skirted foundation reduces the settlement induced due to machine vibration compared with the case of foundation without skirts. The percentage decrease of the settlement is remarkably influenced by the length of skirts, frequency of vibration, and soil stiffness.

- Increasing the frequency of vibration rises the efficiency of the skirts in reducing the dynamic settlement. The percentage decrease of the settlement for the case of a vibration frequency of 0.5 Hz ranges between 2% to 5% depending on the foundation width, skirts length, and soil stiffness, while it ranges from 40% to 70% for the case of a vibration frequency of 20 Hz.

- Increasing the soil stiffness decreases the efficiency of the skirts in reducing the dynamic settlement. Based on all the obtained results, the percentage decrease of the settlement ranges between 2% to 70% for the case of loose sand, while it decreases to 1% to 68% for the case of medium sand, and 0.5% to 67% for the case of dense sand.

- As expected, increasing the length of skirts increases the percentage decrease of the settlement. Also, the effect of the length of skirts becomes more pronounced as the frequency of vibration increases. For example, increasing length of skirts from 0.5 B to 2.0 B rises the percentage decrease by 12% (from 6% to 18%) for the case of a vibration frequency of 0.5 Hz and 33% (from 30% to 63%) for the case of a vibration frequency of 20 Hz

- Novel dynamic impedance values have been obtained based on the results of the numerical modelling. These values were used to develop novel design equations utilizing an intelligent data driven method called the evolutionary polynomial regression analysis. The accuracy of the developed equations was illustrated, and these equations can be recommended to be utilized in future designs. These equations also enable the implication of the skirted foundation principle in the routine design of machine foundations.

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