# Dynamic Interaction of Two Nearby Machine Foundations on Homogeneous Soil

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## ABSTRACT

This paper emphasizes on the dynamic interaction of two closely spaced embedded strip foundations under the action of machine vibration. One of the footings is excited with a known vibration source placed on the top of the footing, called the active footing. The objective is to study the effect of dynamic excitation of active footing on the nearby passive footing through a homogeneous c-ϕ soil medium. The analysis is performed numerically by using finite element software, PLAXIS 2D. The soil profile is assumed to obey the Mohr-Coulomb yield criteria. The analysis is performed under two different loading conditions; sinusoidal dynamic loading with constant and varying amplitude. Under the dynamic excitation, the settlement behavior of interacting footings is studied by varying the spacing between the footings. In addition, the variation of normal and shear stress developed below the passive footing is also explored. The response of the adjoining passive structure is found to be significant up to a spacing of 2B from the actual excited structure.

## INTRODUCTION

The phenomenon of foundation interference becomes an important aspect to be considered in closely built structures and the effect becomes further sensitive under dynamic condition caused by machine vibration operating at high frequency. Dynamic ground motions are in general, highly variable in space and time. The determination of dynamic response of nearby foundations under such ground motion can be a very important investigation as it may cause major catastrophe and therefore, should not be neglected. The analytical solution of dynamic interaction problem of nearby footings is generally found to be quite complex in nature, whereas few numerical solutions (Wong and Luco, 1986; Lin et al., 1987; Wang et al., 1991) are available for foundations resting on visco-elastic soil bed.

This paper presents a study on the dynamic response of two nearby strip footings in comparison with a single isolated footing in homogeneous soil deposit. Commercially available finite element software PLAXIS 2D (PLAXIS 2D V8, 2002) is used for the modeling purpose. Two different types of input excitation; sinusoidal dynamic loading with constant and varying amplitude are applied on the surface of one of the interacting footings called active footing. The present analysis deals with the effect of active footing on the neighboring passive footing through c-ϕ homogeneous soil medium. Both the footings have a constant embedment ratio (D/B) of 1.0, where B and D are width and depth of embedment of the footings, respectively. The analysis is carried out to determine the interference effect of closely placed foundations under dynamic condition in terms of various dynamic factors such as dynamic displacement factor ($\xi_{\delta m}$), dynamic shear ($\xi_{\tau mp}$) and normal ($\xi_{\sigma mp}$) stress factor for passive footing.

## DEFINITION OF PROBLEM

Two closely spaced embedded strip footings are placed on a dry homogeneous soil deposit with an embedment depth (*D*) of 1m from the ground surface as shown in Figure 1. Considering a high speed machine and the criteria to avoid resonance the active footing is subjected to sinusoidal loading with constant or varying amplitude. In addition, a dead load (*P)* of 300 kN is considered as the self weight of the machine, which causes uniform static load intensity on both active and passive footings. The footings are placed at different clear spacing (S). The objective is to study the interaction effect of the active footing on the nearby passive footing through a c-ϕ soil deposit.

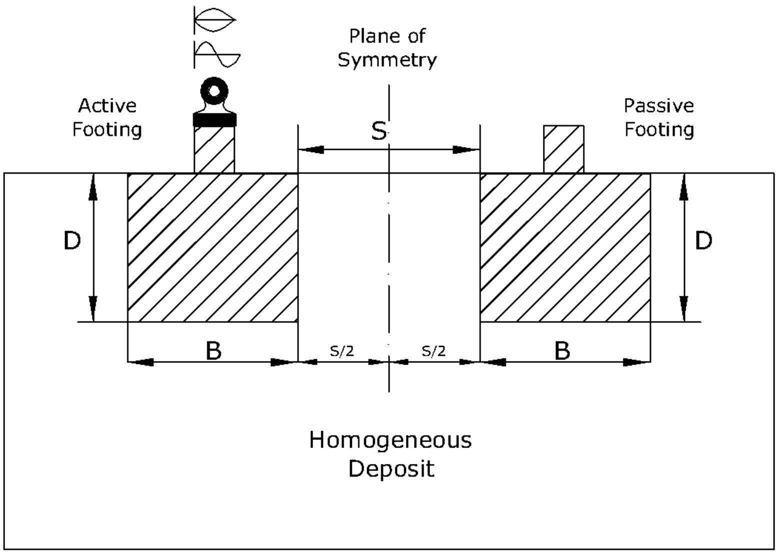


**Figure 1. Definition of the problem in homogeneous soil deposit.**

## PROPERTIES OF SOIL DEPOSIT AND FOUNDATION

To determine the dynamic interference effect between two nearby embedded strip footings in homogeneous bed, a single layer soil deposit (deposit-1) of 11.7 m depth is considered (Ghosh et al., 2011) in the present investigation. The properties of the foundation bed as obtained from Ghosh et al. (2011) are as follows: elastic modulus ($E_s$) = $2.06 \times 10^3$ kN/m$^2$, undrained cohesion ($c_u$) = 19.4 kN/m$^2$, unit weight (γ) =17 kN/m$^3$, angle of internal friction (ϕ) = $24.73^0$ and Poisson's ratio (ν) = 0.3. The water table is found to be at great depth, which is assumed to have no significant impact on the dynamic response analysis. The bulk and shear modulus of the embedded concrete foundations are considered as $1.39 \times 10^7$ kN/m$^2$ and $1.04 \times 10^7$ kN/m$^2$, respectively. The change in the stiffness of soil deposit under dynamic loading is determined by following the theory reported by Alpan (1970). The magnitude of dynamic stiffness ($E_d$) with respect to the static stiffness ($E_s$) determined from the empirical curves proposed by Alpan (1970) is found to be equal to $4.20 \times 10^4$ kN/m$^2$.

## SENSITIVITY ANALYSIS FOR OPTIMUM DOMAIN SIZE

The accuracy in finite element analysis mainly depends on the size of mesh and failure domain. A detailed sensitivity analysis is carried out to check the sensitivity of obtained results with the mesh and domain size. The optimum value of various parameters required to define the finite element mesh can be obtained from trial and error, such that beyond which there is no significant variation in the results. The depth of the soil deposit is fixed (11.7 m) from the available data; therefore the sensitivity analysis is conducted only for the width of the domain. The dynamic excitation along with the static working load is applied on the surface of an isolated footing for a fixed period (Liang, 1974). The same procedure is repeated for different domain size until the total displacement below the footing almost becomes constant. Similar studies are performed to determine the size of the mesh. In Figure 2, it can be seen that no significant variation in the displacement response is observed beyond the domain width of 250B and hence the domain width of 250B is considered in the present analysis. Similarly, the sensitivity analysis reveals that an average element size (Δh) of 0.286m is found to be perfect for the present study.

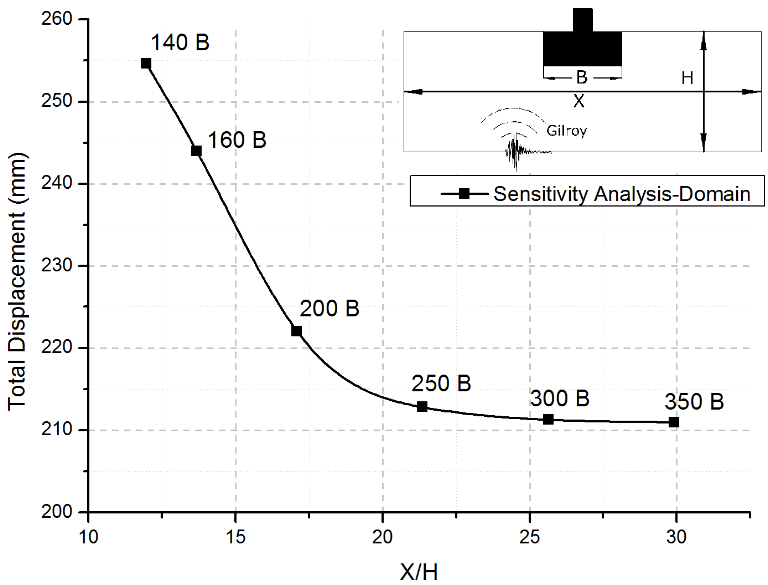


**Figure 2. Sensitivity analysis for domain size.**

## ANALYSIS

In the current study six noded triangular elements are used to discretize the soil medium under the plane strain condition. In order to obtain the integral over a line or area, gauss integration scheme is employed in the analysis. Since the medium is dry, the initial effective stress due to gravity can be determined using Jaky's formula ($K_o = 1 - \sin\phi$). The boundary conditions and other modeling details considered for single isolated footing are shown in Figure 3. Total fixities ($U_x = U_y = 0$) are applied at the base of the model (BC) and horizontal fixities ($U_x = 0$) are applied at the extreme vertical boundaries (AB and CD) restraining the motion along the horizontal direction. Under dynamic condition, the boundaries are generally kept far away from the footings to minimize the boundary effect. However, in the present analysis absorbent boundaries are applied along AB, BC and CD to avoid the reflection of stress waves back to the failure domain.

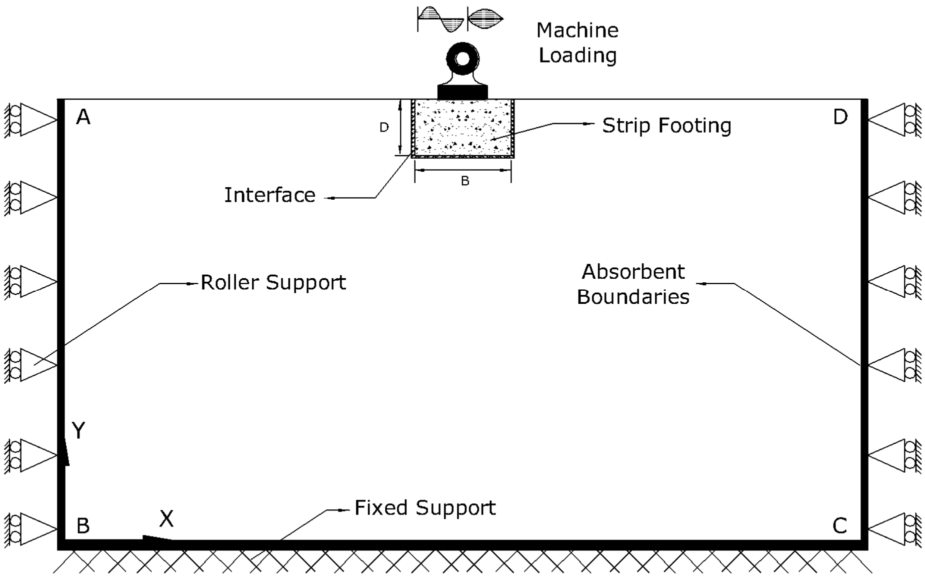


**Figure 3. Schematic diagram of failure domain for single isolated footing.**

The soil deposit is assumed to follow the Mohr-Coulomb failure criterion. However, the effect of dilatancy is ignored in the present study. The interface elements are used to define the interface between the footing and soil. The interface elements are modeled using bi-linear Mohr-Coulomb model. The interface is generally found to be weaker and more flexible than the associated soil layer to approximate the physical soil-structure interaction. Therefore, throughout the analysis the strength reduction factor ($R_{inter}$) is taken to be 2/3 for the interface. The dynamic analysis is performed in the time domain with a constant damping ratio of 2% (Vivek, 2011). The Rayleigh damping coefficients (α and β) are determined for 2% damping ratio and are given in Table 1.

**Table 1. Rayleigh damping coefficients (α and β)**

| | A | β |
|---|---|---|
| Deposit-1 | 0.388 | 0.0007718 |

As mentioned earlier, two different sinusoidal dynamic loading with constant and varying amplitudes are applied on the active footing. However, the dynamic loading is so chosen that the possible condition of resonance can be avoided. For high speed machine in which the operating frequency is higher than 17 cps, the resonant frequency of the soil-foundation system should be less than half of the operating frequency (Valliappan and Hakam, 2001). The natural frequency of the present soil-foundation system is determined as 2.77 Hz by using various formulae and charts available for obtaining impedance of surface and embedded foundation (Gazetas, 1983). Considering a high speed machine and the criteria to avoid resonance, the maximum loading amplitude of 200 kN with an operating frequency of 1000 cpm (16.67 Hz) is considered in the present study. In addition, a dead load of 300 kN is considered on both active and passive footings as the self weight of the machine. Figure 4 shows the sinusoidal loading with constant amplitude (loading-1) which operates for a period of 5 sec with 83 cycles. For obtaining the sinusoidal wave with varying amplitude, an envelope function ($[1-\cos \omega' t]/2$) of duration 5 sec is multiplied with the input wave, to provide a gradual build-up and decay of the wave, where $\omega' = 2\pi/5$. Figure 5 shows the sinusoidal loading with varying amplitude (loading-2) achieving the peak at 2.5 sec and gradually decreasing to zero at the end of 5 sec. It is worth mentioning here that increase in excitation time considerably increases the computational effort and hence, in the present study the time of the excitation is limited to 5 sec though much higher time range can be expected in real situation.

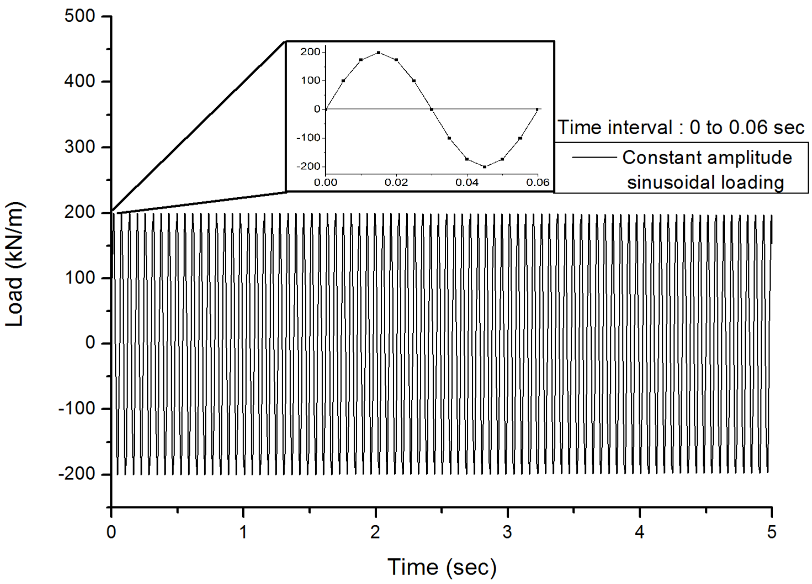


**Figure 4. Sinusoidal dynamic loading with constant amplitude (loading-1).**

## RESULTS AND DISCUSSION

A sinusoidal wave loading with constant or varying amplitude is applied on the top of the active footing for a period of 5 sec and the corresponding displacements are monitored at the nodes below both active and passive footings. The magnitude of displacement at the base of the footing is found to increase gradually with time and the displacement at the end of 5 sec is recorded. Figure 6 shows a typical time-displacement curve for interacting footings at S/B = 1 with active footings being subjected to loading-1 and loading-2.

To determine the dynamic interference effect of two nearby strip footings in terms of displacement, the dynamic displacement factor ($\xi_{\delta m}$) is determined, which can be defined as the ratio of displacement of active (AF) or passive (PF) footing at the end of excitation in presence of passive (PF) or active (AF) footing to that of single isolated active footing (AF) at the end of excitation. Therefore, the dynamic displacement factor for active footing ($\xi_{\delta ma}$) can be expressed as

$$\xi_{\delta ma} = \frac{\text{Displacement of AF at the end of excitation in presence of PF}}{\text{Displacement of isolated AF at the end of excitation}}$$

Similarly, the dynamic displacement factor for passive footing ($\xi_{\delta mp}$) can be expressed as

$$\xi_{\delta mp} = \frac{\text{Displacement of PF at the end of excitation in presence of AF}}{\text{Displacement of isolated AF at the end of excitation}}$$

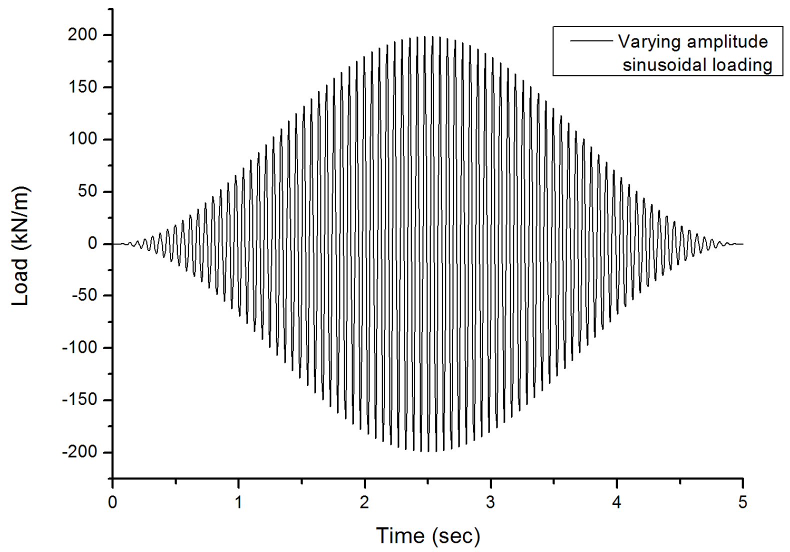


**Figure 5. Sinusoidal dynamic loading with varying amplitude (loading-2).**

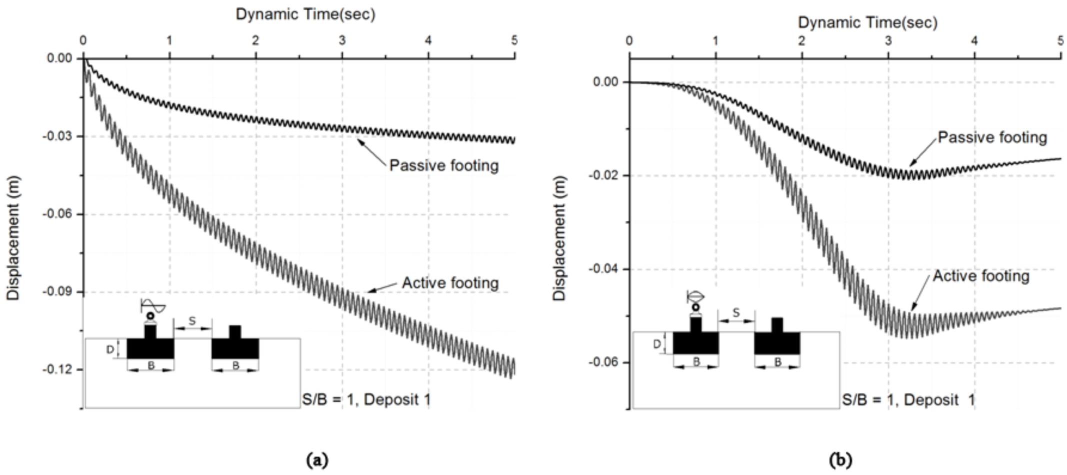


**Figure 6. Time-displacement curve for interacting footings at S/B=1 under (a) loading-1 (b) loading-2.**

The variations of $\xi_{\delta ma}$ and $\xi_{\delta mp}$ with different magnitude of S/B under sinusoidal loading with constant (loading-1) and varying (loading-2) amplitude are shown in Figures 7 and 8, respectively. It can be seen that the settlement of active footing subjected to either loading-1 or loading-2, in presence of the passive footing, reaches the minimum value at a spacing of 2B. As the spacing between the active and passive footings increases beyond 2B, the vertical displacement of the active footing gradually increases and tends to reach a value corresponding to that of single isolated active footing, whereas the vertical displacement below the passive footing is found to continuously decrease with increase in S/B ratio. It is worth noting here that the negative value of $\xi_{\delta mp}$ indicates the uplift of passive footing.

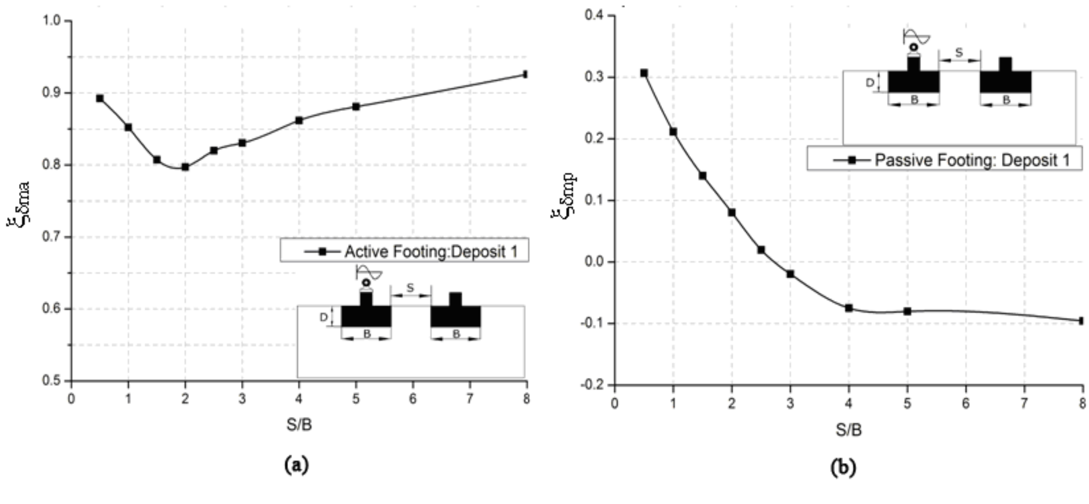


**Figure 7. Variation of dynamic displacement factors with S/B for (a) active footing and (b) passive footing subjected to loading-1.**

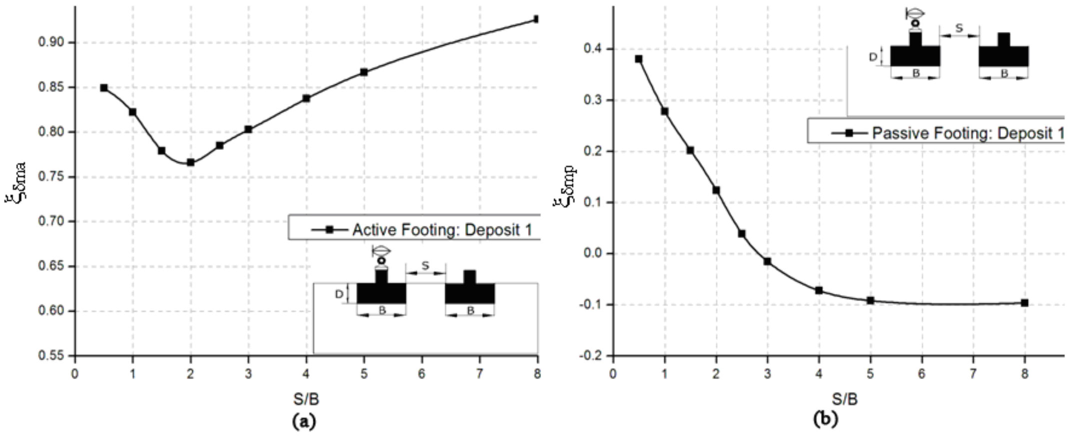


**Figure 8. Variation of dynamic displacement factors with S/B for (a) active footing and (b) passive footing subjected to loading-2**

The interference effect on the peak shear stress and peak equivalent normal stress developed on the plane considered at the base of the passive footing (PF) can be expressed in terms of dynamic shear stress ($\xi_{\tau mp}$) and normal stress ($\xi_{\sigma mp}$) factors, which can be defined as

$$\xi_{\tau mp} = \frac{\text{Peak shear stress developed below PF in presence of AF}}{\text{Peak shear stress developed below single isolated AF}}$$

$$\xi_{\sigma mp} = \frac{\text{Equivalent peak normal stress developed below PF in presence of AF}}{\text{Equivalent peak normal stress developed below single isolated AF}}$$

The variation of dynamic shear stress ($\xi_{\tau mp}$) and normal stress ($\xi_{\sigma mp}$) factors with S/B ratio under loading-1 and loading-2 is shown in Figures 9 and 10, respectively. It can be observed that the stresses below the passive footing gradually decrease with increase in S/B ratio.

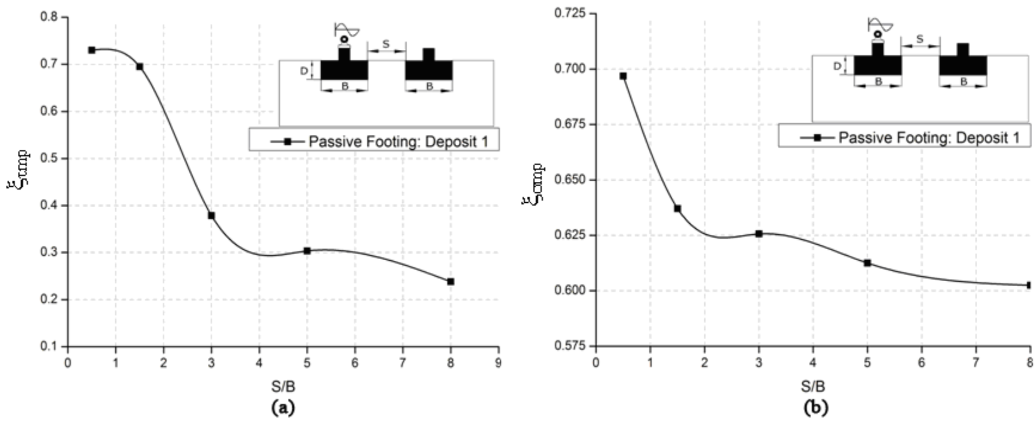


**Figure 9. Variation of dynamic stress factors with S/B under loading-1 (a) $\xi_{\tau mp}$, (b) $\xi_{\sigma mp}$.**

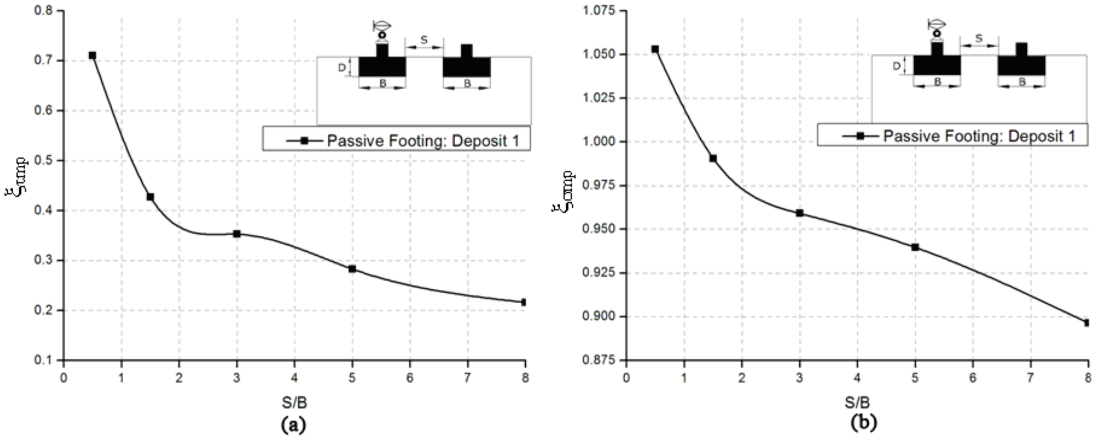


**Figure 10. Variation of dynamic stress factors with S/B under loading-2 (a) $\xi_{\tau mp}$, (b) $\xi_{\sigma mp}$.**

## CONCLUSIONS

In this paper, the interaction of two nearby strip footings under dynamic condition is explored. The vertical displacement and stresses developed at the base of active and passive footings at the end of the dynamic excitation are presented in terms of various normalized factors. It can be observed that the vertical displacement of active footing subjected to either loading-1 or loading-2, in presence of the passive footing, reaches the minimum value at a spacing of 2B. As the spacing between the active and passive footings increases beyond 2B, the vertical displacement of the active footing gradually increases and tends to reach a value corresponding to that of single isolated active footing. The response of the adjoining passive structure is found to be significantly affected by the actual excited structure. Under both loading-1 and loading-2, the vertical displacement of passive footing is observed to decrease with increase in spacing. The peak shear and peak equivalent normal stress developed at the base of the passive footing in presence of the active footing are found to decrease gradually with the increase in spacing between the active and passive footings.

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