

## **EFFECT OF SOIL-STRUCTURE INTERACTION ON BASE-ISOLATED MACHINE FOUNDATIONS**

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### **ABSTRACT**

Machine foundations help in distribution of the machine loads and mitigation of vibrations developed due to the rotating machine parts. When vibration control devices are used, the design approaches of the machine foundations thereof are still in the development stage. Especially, the flexibility of underlying soil is ignored in the designs, which may influence the dynamic response significantly. In the present study, a numerical model is developed to investigate the effect of soil-structure interaction (SSI) on the dynamic response of base-isolated machine foundation founded on a homogenous elastic soil layer subjected to earthquake ground motions. Frequency-independent expressions for stiffness and damping coefficients are used to model the SSI. Parametric studies on dynamic response of the base-isolated framed-type machine foundation are conducted for various parameters such as fundamental time period of machine foundation, isolation time period, bearing yield strength, and yield displacement considering different soil types. This research concludes that the SSI decreases the natural frequencies of the entire system, which is significant in higher modes especially for rigid machine foundations resting on weak soil strata. Hence, the SSI activates the higher mode participation, resulting amplified responses in the base-isolated machine foundation.

### **NOMENCLATURE**

- $A$  Dimensionless parameter used in Wen's model
- $F_0$  Normalized yield strength of the base-isolator
- $F_b$  Restoring force of the base-isolator
- $F_y$  Bearing yield strength of the base-isolator
- $G$  Shear modulus of the soil
- $I_f$  Moment of inertia of the foundation raft
- $M$  Total mass of the base-isolated machine foundation
- $N$  Operating speed of rotary machine
- $T_b$  Time period of the base isolator
- $T_s$  Time period of the framed-foundation
- $W$  Total weight of the base-isolated machine foundation
- $Z$  Non-dimensional hysteretic displacement
- $a$  Equivalent radius of circular footing
- $c_b$  Damping of the base isolator in horizontal direction
- $c_h$  Damping of the soil in horizontal direction
- $c_s$  Damping of the frame in horizontal direction
- $c_\theta$  Damping of the soil in rocking direction
- $h$  Foundation to deck height
- $k_b$  Post-yield stiffness of the base isolator in horizontal direction
- $k_h$  Stiffness of the soil in horizontal direction
- $k_s$  Stiffness of the frame in horizontal direction
- $k_\theta$  Stiffness of the soil in rocking direction

- $m_b$  Lumped mass of the base raft including base isolator  
 $m_f$  Lumped mass of the foundation raft  
 $m_r$  Mass moment of inertia of the foundation raft  
 $m_s$  Lumped mass of the deck including machine  
 $n$  Integer constant controlling nonlinearity  
 $q$  Bearing yield displacement of the base isolator  
 $v_s$  Shear wave velocity of the soil  
 $x_b$  Lateral displacement at base isolator level  
 $x_f$  Lateral displacement at foundation level  
 $x_s$  Lateral displacement at deck level  
 $\alpha$  Ratio of post to pre-yielding stiffness  
 $\beta$  Dimensionless parameter used in Wen's model  
 $\xi_b$  Damping of isolation system  
 $\nu$  Poisson's ratio of the soil  
 $\rho$  Density of the soil  
 $\tau$  Dimensionless parameter used in Wen's model  
 $\omega_b$  Natural frequency of the base isolator  
 $\omega_m$  Operating frequency of the rotary machine  
 $\omega_n$  Natural frequency of the framed-foundation  
 $\ddot{x}_b$  Lateral acceleration at base isolator level  
 $\ddot{x}_f$  Lateral acceleration at foundation level  
 $\ddot{x}_s$  Lateral acceleration at deck level  
 $\ddot{\theta}_b$  Rotational acceleration at base isolator level  
 $\ddot{\theta}_f$  Rotational acceleration at foundation level  
 $\ddot{\theta}_s$  Rotational acceleration at deck level  
 $\dot{x}_b$  Lateral velocity at base isolator level  
 $\dot{x}_f$  Lateral velocity at foundation level  
 $\dot{x}_s$  Lateral velocity at deck level  
 $\dot{Z}$  Non-dimensional hysteretic velocity  
 $\Delta t$  Time interval of input acceleration

## INTRODUCTION

Machine foundations are inevitable components of any industrial infrastructure, which support heavy machines, transmit both static and dynamic loads. Framed-type machine foundations (also known as framed-foundation or table mounted foundation) are highly recommended to support high-speed rotary machines. Earthquake ground motions may induce significant seismic forces in machine foundation, cause excessive excitations in machine foundation, when the fundamental frequency is close to the dominant frequency content of the excitation. Such harmful effects are significant in framed-type machine foundations supporting high-speed rotary machines. Hence, it is necessary that the machine foundation is designed adequately for the dynamic loads to control the excessive vibration and avoid possible failures.

### 1. Studies on Soil-Structure Interaction

Though, the soil-structure interaction (SSI) effect was studied over several decades, its importance on structures was paid attention only after the damage in the nuclear plant structure in California during 1971

San Fernando earthquake. Mayerhof (1953) recognized the importance of superstructure-foundation-soil interaction in the design of machine foundation and elaborated the SSI phenomena. Tsai et al. (1974) evaluated the validity of approximating frequency-independent foundation impedance functions by constant parameters. Danisch and Labes (1976) explained the improvement measures on aseismic design of turbine houses for nuclear power plants under earthquakes of various intensity. For supporting medium-speed rotary machines (i.e.  $1500 < N < 3000$  rpm), spring elements were introduced to replace the reinforced concrete columns. Arya et al. (1979) explained the various analytical methods prevailed for analysis of framed-type machine foundation. Gazetas (1984) discussed the dynamic response of shallow and deep foundations subjected to the machine type loadings. In addition, crucial parameters related to the soil profile, foundation geometry, and their effects were discussed. The study reported by Wolf (1997) explained the mass-spring-dashpot models for dynamic analysis of various foundations. Wu (1997) proposed an equivalent fixed-base model to represent the SSI. Kumar and Reddy (2006) observed that employing cushion (having stiffness much lesser than that of soil strata) between the machine base and footing leads to significant reduction in the resonant frequency of the machine structure. Prakash and Puri (2006) modeled the machine basement by idealizing the foundation-soil system using equivalent spring-dashpot model having one or two degrees of freedom to duly represent their behavior. Chandrakaran et al. (2007) and Simoes et al. (2007) presented a simple way to predict the effects of vibration due to the machine operations on its surroundings by considering the foundation as a vibration source on the surface of an elastic medium. Bhatia (2008) explained the dynamic interaction between the machine, foundation, and soil during earthquake ground motions and proposed some recommendations for the dynamic design of industrial constructions. Fleischer and Trombik (2008) observed that the substructure of machine foundation should be stiff enough to avoid the interaction of frequencies of machine foundation and substructure. Padron et al. (2009) studied the dynamic soil-structure interaction for the pile-supported structures in a viscoelastic half-space under Rayleigh waves. Subsequently, many soil models were proposed by researchers that model the soil-structure interaction (Jeremic et al., 2009; Soong et al., 2009). Auersch (2010) studied the building response due to ground vibrations by modeling the soil medium with springs and viscous damper. Rajkumar et al. (2015) improved the amplitude method by adding an additional degree of freedom (to represent foundation-soil system) and studied the effects of the SSI in machine foundation under vertical mode of vibration. They concluded that, ignoring SSI in dynamic analysis of machine foundation leads to under-estimate the actual response especially in high-tuned condition due to shift in natural frequencies.

## 2. Studies on Base-Isolated Structures

For protecting structures from the damaging effects of vibrations, base isolation is one of the most ingenious ways. When used to protect structures from earthquakes using the base isolation technique, the machine foundation is isolated from the shaking ground by insertion of flexible layer, which is formed by elastomeric and/or sliding bearings. The term isolation refers to such reduced interaction between the structure and the ground. Moreover, the bearings provide additional means of energy dissipation through high damping. For the past few decades many research works have been reported on the significant use of base isolators in conventional buildings and bridges. Kelly (1982; 1986) presented reports about the various base isolation systems and their characteristics, limitations, and range of applicability. Pantelides (1991) presented active tendon, active mass damper, and active base control systems for active control of machine foundations in seismic regions for reducing their dynamic response. An article presented by Bomhard and Stempniewski (1993) examined experimentally the performance of laminated elastomeric bearings in liquefied natural gas (LNG) storage tanks under seismically highly affected sites such as Revythousa LNG Terminal, Greece and Incheon LNG Terminal, Korea. Jangid and Datta (1995) presented a review of behavior of base-isolated buildings under earthquake ground motions and discussed some theoretical aspects of earthquake base isolation. Stammers and Sireteanu (1998) proposed the use of semi-active dry-friction damping for vibration control of machines. Su et al. (2000) used resilient-friction base isolator (R-FBI) in structures to mitigate vibrations due to machines. They concluded that the R-FBI helped in reducing the seismic response of rotating components to the potentially damaging ground excitations. Chaudhary et al. (2001) as well as Spyrakos and Vlassis (2002) discussed effects of the SSI on seismically isolated bridges. Matsagar and Jangid (2004) discussed the seismic response of base-isolated structures explaining the mathematical modeling of isolators and the influence of isolator force-deformation loop on the response of isolated structure. Jangid (2007) presented a report to identify the optimum bearing yield strength parameter for buildings and bridges under near-fault earthquakes.

Spyrakos et al. (2009) studied the seismic response of base-isolated buildings considering the SSI effect. It was concluded that the SSI affects the modal properties of the system, but has little effect on damping which is dominated by isolation damping. Recently, Vijayan et al. (2014) adopted the passive vibration isolation technique by compliant mechanism and Bai et al. (2017) implemented the magneto-rheological energy absorber for controlling the vibration. From the above reviews, it can be inferred that very few studies have reported the SSI effects on base-isolated machine foundation. Therefore, it will be interesting to study the dynamic behavior of base-isolated machine foundation supporting medium to high-speed rotary machines while duly considering the SSI effects.

In this paper, the seismic response of base-isolated framed-type machine foundation is investigated under earthquake ground motion. The specific objectives of the present study are, (i) to mathematically model and numerically solve the governing equations of motion for the framed-type machine foundation; (ii) to investigate the implementation of base isolation technique in machine foundation; (iii) to investigate the coupled effects of the SSI on the seismic response of base-isolated machine foundation; (iv) to conduct the extensive parametric studies to investigate the design parameters governing the performance of base isolation systems used in machine foundation while duly considering the SSI effects.

## MODELING OF BASE-ISOLATED MACHINE FOUNDATION

Due to the extensive advantages involved, framed-type machine foundations are the commonly used constructions for supporting high-speed rotary machines. The achievement of low-tuning is possible for high-speed rotary machine by means of providing reinforced concrete columns in framed-type machine foundation. However, this is not possible for medium-speed rotary machines, because it requires more slenderness in columns which maybe structurally unstable even under static loads. Hence, spring-mounted foundations are used for supporting medium-speed rotary machines in which reinforced columns are replaced by springs. In this study, a medium to high-speed rotary machine resting on framed-type machine foundation is analyzed under different earthquake ground motions. Figure 1 shows the actual models of (a) table-mounted and (b) spring-mounted machine foundations founded on a homogenous elastic soil layer, and (c) idealized model. Base-isolators are connected with base raft (also known as isolator raft) and foundation raft, which distribute the loads to subsoil.

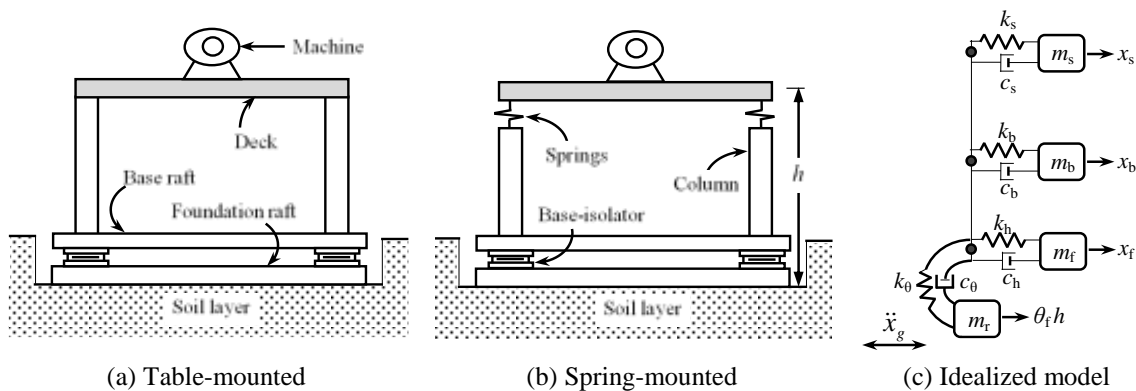


Fig. 1 Schematic diagram of base-isolated machine foundation resting on homogeneous soil medium.

### 1. Modeling of Superstructure

It is known that the fundamental frequency is the key parameter in the design of machine foundation. Natural frequency of foundation ( $\omega_n$ ) shall be minimum 20% away from the operating frequency of the machine ( $\omega_m$ ) to avoid the resonance. In the present study, the natural frequency is well separated (60%) from the operating frequency, so that no further dynamic evaluation due to machine induced forces are required (ACI, 2004). The following assumptions are made for the structural system under consideration: (i) structural components are considered to remain within the elastic limit under earthquake ground motions owing to the use of base isolation, (ii) machine foundations are idealized as a single-story shear frame in which deck is rigid in flexure, (iii) axial deformations of structural components and the effects of axial force on stiffness of columns are neglected, (iv) foundation is subjected to fault normal component of earthquake ground motions only in its lateral direction, and (v) stiffness of machine itself is not considered.

## 2. Modeling of Substructure and Soil

The dynamic response of machine foundation significantly depends on the properties of the supporting soil. According to Arya et al. (1979) the footing embedment has a significant effect on damping; however, embedment without adequate lateral support is ineffective. Hence, to be on the conservative side, it is assumed that the lateral support to the footing is ineffective, hence the effect of embedment is neglected in the present study. Equivalent spring-dashpot model for the foundation-soil system is considered only in lateral and rotational directions. It is assumed that the vertical soil degree of freedom is uncoupled from the lateral and rotational degrees of freedom. The foundation on deformable soil may be represented as a simple spring-dashpot model with following frequency-independent relations (Arya et al, 1979).

$$k_h = \frac{8Ga}{(2-\nu)}; \tag{1}$$

$$k_\theta = \frac{8Ga^3}{3(1-\nu)}; \tag{2}$$

$$c_h = \frac{4.6\rho}{(2-\nu)} v_s a^2; \tag{3}$$

$$c_\theta = \frac{0.4\rho}{(1-\nu)} v_s a^4. \tag{4}$$

Here,  $k_h$  and  $c_h$  are the stiffness and damping properties of the soil in horizontal direction;  $k_\theta$  and  $c_\theta$  are the stiffness and damping properties of the soil in rocking direction;  $G$  is shear modulus of the soil;  $a$  is equivalent radius of circular footing;  $\nu$  is Poisson's ratio of the soil;  $\rho$  is density of the soil;  $v_s$  is shear wave velocity of the soil. Various types of actual soil conditions are classified under the following three categories, based on its standard penetration blow test (SPT) value as per BIS (2002). Well graded gravel and sand gravel mixtures with or without clay binder, and clayey sands or sand clay mixtures with  $SPT > 30$  are categorized under hard soil; all soils with  $SPT$  between 10 and 30, and poorly graded sands or gravelly sands with little or no fines with  $SPT > 15$  are categorized under medium soil; and all other soils with  $SPT < 10$ , medium to soft clay and silts are classified under soft soil. Hence, parametric studies are conducted for (i) hard soil, (ii) medium soil, and (iii) soft soil.

## 3. Modeling of Base Isolator

The present study investigates the effect of rubber isolators on machine foundation against earthquake ground motion. The force-deformation behavior of isolation system is modeled by bi-linear hysteresis loop, which is characterized by post-yield stiffness ( $k_b$ ), bearing yield displacement ( $q$ ), and bearing yield strength ( $F_y$ ). The post-yield stiffness of isolator is generally designed in such a way as to give the specified isolation time period ( $T_b$ ) and damping of isolation system ( $\xi_b$ ) which are expressed as,

$$T_b = 2\pi \sqrt{\frac{M}{k_b}}; \tag{5}$$

$$\xi_b = \frac{c_b}{2M\omega_b}. \tag{6}$$

Here,  $M$  is total mass of the base-isolated machine foundation (including machine mass);  $\omega_b (= 2\pi/T_b)$  is the isolation frequency;  $c_b$  is the damping constant of the isolator.

The lead-rubber bearing (LRB) also known as New-Zealand (N-Z) rubber bearing is the commonly used elastomeric type isolator. The LRB consists of rubber and thin steel plates in alternate layers, which are mounted at top and bottom mounting plates as shown in Figure 2(a). It absorbs horizontal movements caused by temperature, vibration, and impact. A lead core is inserted in its middle to provide initial stiffness and increase the damping. This isolator can isolate earthquake by providing flexibility in horizontal direction, and lead core provides an additional means of energy dissipation. High vertical stiffness to carry loads to foundation is achieved by the steel plates. The idealized model of the LRB is shown in Figure 2(b).



Fig. 2 Schematic representation of lead rubber bearing (LRB)

The force-deformation behavior of the LRB is generally represented by non-linear characteristics. Wen (1976) model is used to characterize the hysteretic behavior of the LRB. The restoring force developed in the LRB is given by,

$$F_b = c_b \dot{x}_b + k_b x_b + (1 - \alpha) F_y Z \quad (7)$$

where,  $Z$  is a non-dimensional hysteretic displacement component satisfying the non-linear first order differential equation expressed as,

$$q\dot{Z} = A\dot{x}_b + \beta|\dot{x}_b||Z||Z|^{n-1} - \tau\dot{x}_b|Z|^n \quad (8)$$

where,  $\dot{x}_b$  and  $x_b$  are the velocity and displacement of the isolator, respectively;  $\alpha$  is an index which represents the ratio of post to pre-yielding stiffness; dimensionless parameters  $\beta$ ,  $\tau$ , and  $A$  are selected such that the results predicted from the model closely matches with the experimental results;  $n$  is an integer constant which controls the transition from elastic to plastic response, i.e. nonlinearity. The LRB is characterized by the time period ( $T_b$ ), damping of isolation system ( $\xi_b$ ), and normalized yield strength ( $F_0$ ), i.e.  $F_y/W$  (where,  $W = Mg$  is the total weight of the machine foundation including machine).

## GOVERNING EQUATIONS OF MOTION

For the system under consideration, the governing differential equations of motion are obtained by considering the equilibrium of forces at the location of each degree of freedom. The equations of motion for the base-isolated machine foundation considering the SSI under the earthquake ground motion (Figure 1(c)) are expressed in the matrix form as,

$$\begin{bmatrix} m_s & 0 & m_s & m_s h \\ 0 & m_b & m_b & 0 \\ m_s & m_b & m_s + m_b + m_f & m_s h \\ m_s h & 0 & m_s h & m_r \end{bmatrix} \begin{Bmatrix} \ddot{x}_s \\ \ddot{x}_b \\ \ddot{x}_f \\ \ddot{\theta}_f \end{Bmatrix} + \begin{bmatrix} c_s & -c_s & 0 & 0 \\ -c_s & c_s + c_b & 0 & 0 \\ 0 & 0 & c_h & 0 \\ 0 & 0 & 0 & c_\theta \end{bmatrix} \begin{Bmatrix} \dot{x}_s \\ \dot{x}_b \\ \dot{x}_f \\ \dot{\theta}_f \end{Bmatrix} + \begin{bmatrix} k_s & -k_s & 0 & 0 \\ -k_s & k_s + k_b & 0 & 0 \\ 0 & 0 & k_h & 0 \\ 0 & 0 & 0 & k_\theta \end{bmatrix} \begin{Bmatrix} x_s \\ x_b \\ x_f \\ \theta_f \end{Bmatrix} = - \begin{Bmatrix} m_s \\ m_b \\ m_s + m_b + m_f \\ m_s h \end{Bmatrix} \ddot{x}_g \quad (9)$$

where,  $\ddot{x}$ ,  $\dot{x}$ , and  $x$  are the unknown acceleration, velocity, and displacement in lateral direction, respectively;  $\ddot{\theta}$ ,  $\dot{\theta}$ , and  $\theta$  are the unknown acceleration, velocity, and displacements in rotational direction, respectively. The subscripts  $s$ ,  $b$ , and  $f$  denote the corresponding unknown quantities at deck, base isolator, and foundation raft levels, respectively;  $m_s$  is the lumped mass of the deck (including machine mass);  $m_b$  is the lumped mass of the base raft including isolator;  $m_f$  is the mass of foundation raft;  $h$  is the foundation to deck height;  $k_s$  and  $k_b$  are the lateral stiffness of the frame and isolator, respectively;  $c_s$  and  $c_b$  are the damping of superstructure and isolator, respectively;  $m_r$  is the mass moment of inertia of the foundation raft which is expressed as  $I_f + m_s h^2$ , where  $I_f$  is the moment of inertia of the foundation raft. Note that, the deck displacement is relative to the base mass; and other displacements are relative to the ground, whereas, the acceleration is absolute.

### SOLUTION OF EQUATIONS OF MOTION

In the present study, numerical program is developed to solve the equations of motion for base-isolated machine foundation considering coupled effect of the SSI in time domain. The system used for the current analysis has non-classical damping properties, i.e. damping of foundation, isolator, and soil are significantly different from each other. In addition, the characteristics of force-displacement behavior of isolators are highly non-linear in nature. Therefore, the equations of motion are solved numerically by using Newmark’s method of step-by-step integration, adopting linear variation of acceleration over a small interval of time,  $\Delta t$ . The time interval for solving the equations of motion is taken as 0.02/100 sec (i.e.  $\Delta t = 2 \times 10^{-4}$  sec).

### VALIDATION

The dynamic analysis of framed structure considering soil-structure interaction (SSI) is carried out using the developed numerical program and the results are compared with the results reported by Wu (1997). The input parameters used for the validation are shown in Table 1. Figures 3 and 4 shows the results obtained from the developed numerical program and the published results for two different cases (i.e. rigid and flexible superstructure). It is observed that the dynamic responses are in close agreement.

**Table 1: Input Properties for Validation**

Model	Parameter	Value	Unit
Structure	No. of storey	5	-
	Floor mass, $m_s$	60,000	Kg
	Column stiffness (for rigid structure), $k_s$	1,80,000	kN/m
	Column stiffness (for flexible structure), $k_s$	12,500	kN/m
	Storey height, $h$	3.5	M
	Floor moment of inertia, $m_r$	2,45,000	kg m <sup>2</sup>
Foundation raft	Equivalent radius, $a$	3.5	M
	Mass, $m_f$	1,20,000	Kg
	Moment of inertia, $I_f$	4,90,000	kg m <sup>2</sup>
Soil	Mass density, $\rho$	1,700	kg/m <sup>3</sup>
	Shear wave velocity, $v_s$	1/3	-
	Poisson’s ratio, $\nu$	150	m/s

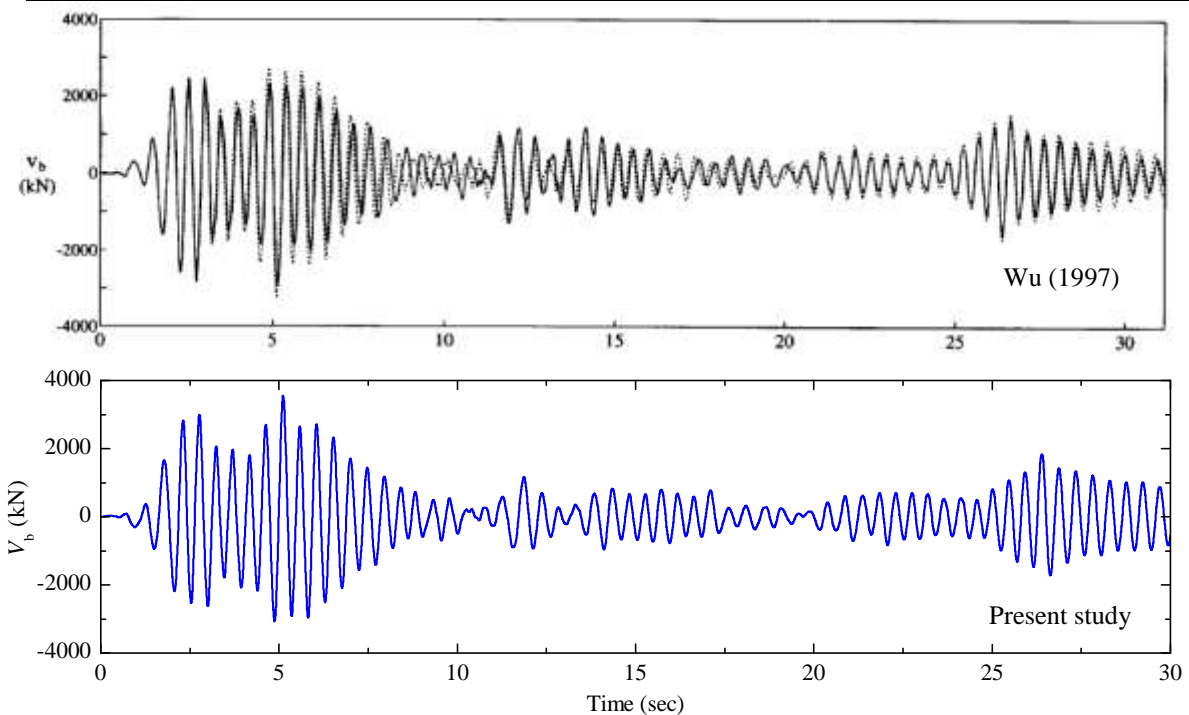


Fig. 3 Comparison of base shear variation for rigid framed structures considering SSI: (a) published results by Wu (1997), and (b) present study

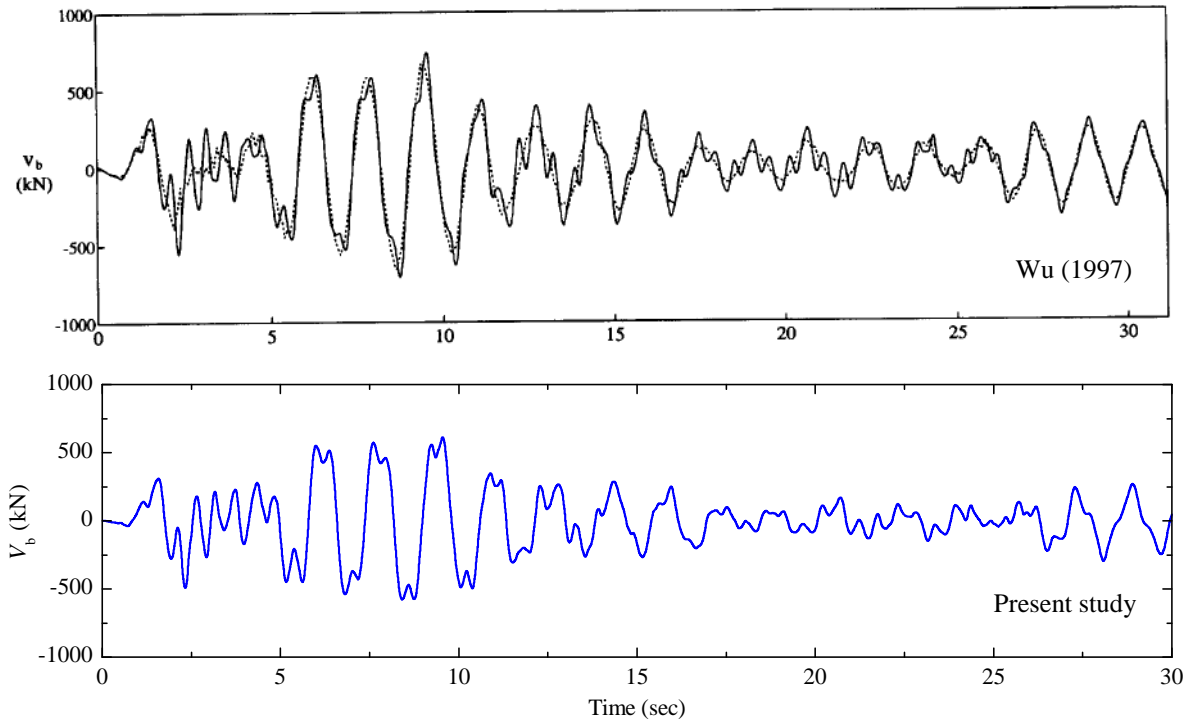


Fig. 4 Comparison of base shear variation for flexible framed structures considering SSI: (a) published results by Wu (1997), and (b) present study

#### NUMERICAL STUDY

In framed-type machine foundations, the force from the machine is transferred to the subsoil through the frames, whereas in case of earthquake, the force flow is in the reverse order. Hence, it is essential to limit the amplitude of motion for the effective functioning of the machine. Table-mounted foundations are idealized by assuming a single-story shear frame in which all the masses are lumped at deck level, supported by linear spring elements having lateral stiffness of frames. In the present study, seismic response of base-isolated machine foundation is investigated under various real earthquake ground motions while duly considering the SSI. The lateral stiffness of the frame is adjusted such that a specified fundamental time period of the machine foundation is achieved. For the proposed model, the lumped mass of the superstructure ( $m_s$ ) including the machine is assumed  $6 \times 10^4$  kg and the mass of foundation raft ( $m_f$ ) is considered twice the superstructure mass (Srinivasulu and Vaidyanathan, 1980), i.e.  $m_f/m_s = 2$ . The isolator raft is considered such that the mass ratio,  $m_b/m_s$  is unity (Jangid, 2007). The foundation to deck height ( $h$ ) is 5m. The equivalent radius ( $a$ ) and the mass moment of inertia of the foundation raft ( $I_f$ ) are assumed 2.5 m and  $49 \times 10^4$  kg-m<sup>2</sup>, respectively. For all the cases, the superstructure damping of 2% is considered. Input properties for different soils are shown in Table 2. The fault normal component of earthquake ground motions selected for the present study are shown in Table 3.

**Table 2: Soil Properties**

Soil properties (units)	Hard soil	Medium soil	Soft soil
Mass density, $\rho$ (kg/m <sup>3</sup> )	2000	1800	1600
Shear wave velocity, $v_s$ (m/s)	500	300	150
Poisson's ratio, $\nu$	0.25	0.30	0.35

**Table 3: Earthquake Ground Motions**

Name of earthquake	Peak acceleration (g)
October 15, 1979 Imperial Valley, California (Array # 5)	0.36
October 15, 1979 Imperial Valley, California (Array # 7)	0.45
June 28, 1992 Landers, California (Lucerne Valley station)	0.71
January 17, 1994 Northridge, California (Sylmar station)	0.72
January 1, 1995 Kobe, KJM station	0.83

The response quantities of interest are the displacement at deck relative to the base mass and isolator (bearing) levels relative to the ground, and absolute acceleration at deck level. These response quantities are of importance because deck acceleration developed in the superstructure is proportional to the force exerted due to earthquake ground motion. Acceleration and displacement at deck level are the direct measure to check the limiting amplitude of vibration in the machine foundation. If the acceleration is higher than prescribed permissible limits, the superstructure may not satisfy the functional requirements. For efficient operation of machine, the amplitude of motion also needs to be within prescribed permissible limits otherwise the design becomes unacceptable. On the other hand, the relative bearing displacement is essential in the design of base-isolated machine foundation. If the bearing displacement is higher, there may be a chance of impact on adjacent structure, resulting damages. Therefore, to limit the response of machine foundation within the permissible limits, it is essential to understand the different parameters affecting the response of machine foundation against earthquake ground motion.

To understand the coupled effect of the SSI in machine foundations, a typical framed-type machine foundation ( $T_s = 0.2$  sec, where  $T_s$  is the fundamental time period of non-isolated machine foundation without considering the SSI, i.e. fixed-base) is analyzed under harmonic excitations of various frequencies ( $\omega_m$ ). The peak acceleration at deck level for both non-isolated and base-isolated machine foundation is shown in Figure 3 for different soil types. In case of non-isolated machine foundation, it is observed that the SSI significantly reduces the fundamental frequency. As stiffness of the soil decreases, the natural frequency of the entire system decreases. However, in case of base-isolated machine foundation, the natural frequency in fundamental mode is not altered due to the SSI as observed from Figures 5(a)-(b), because fundamental frequency pertains to isolation frequency. Very low horizontal stiffness (generally, lesser than stiffness of soil) in base isolator is provided such that the isolation frequency is well separated from dominant frequency content of earthquake ground motions. However, as stiffness of the underlying soil decreases (i.e. if the horizontal stiffness of the soil is close to the stiffness of isolator), the natural frequency at higher modes decreases and hence, resonance is possible in the higher modes. The reduction in natural frequency is in the range up to 30% in case of hard soil, 50% in case of medium soil, and 75% in case of soft soil. The change in natural frequency not only depends on the properties of substructure (foundation raft) and soil, but also depends on properties of superstructure (frame). Up to  $T_s = 0.2$  sec, there is significant reduction in natural frequency due to the SSI; after that the reduction in natural frequency is insignificant. Generally, the machine foundations are rigid as compared to the conventional low-rise buildings; hence, the coupled effect of the SSI is significant in machine foundations as observed from Figures 5(a)-(b). From Figure 5(d), it is observed that the peak accelerations are amplified due to coupled effect of the SSI for soft soil in base-isolated machine foundation. Thereby, it is crucial to study higher mode response in base-isolated machine foundation, especially considering the SSI, otherwise seismic forces for superstructure are underestimated.

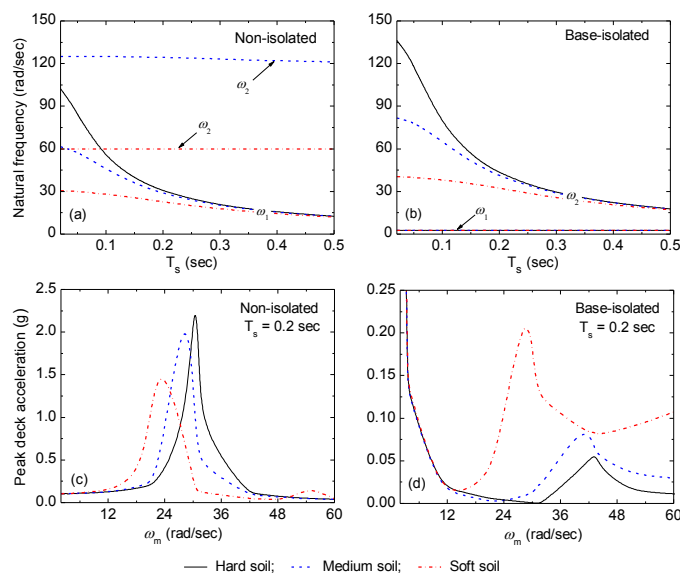


Fig. 5 Variations of natural frequency and peak deck acceleration of machine foundation under different frequencies of harmonic excitation ( $T_b = 2.5$  sec,  $\xi_b = 0.1$ ,  $F_0 = 0.05$ , and  $q = 2.5$  cm).

Figure 6 shows the time variation of deck acceleration and bearing displacement of framed-type machine foundation isolated by the LRB system under Imperial Valley, 1979 (Array # 5) earthquake ground motion. The responses are shown for three different types of soil with  $T_b = 2.5$  sec,  $\xi_b = 0.1$ , and  $q = 2.5$  cm. In order to study the effect of bearing yield displacement on the dynamic response, two different values (i.e.  $F_0 = 0.05$  and  $0.15$ ) were considered as suggested by Jangid (2007). It can be observed that the deck acceleration in base-isolated machine foundation is significantly reduced as compared to that in case of the non-isolated machine foundation. The reduction in deck acceleration is almost similar for the both the values of yield strengths, however, significant reduction in bearing displacement is achieved at higher yield strength. In addition, the deck acceleration for soft soil is amplified as compared to that on hard soil. However, the amplification in bearing displacements due to the SSI is negligible, because the damping of the structure-foundation-soil system is dominated by base isolator (Spyrakos, 2009). Also, the bearing displacement shown are relative to ground or foundation level.

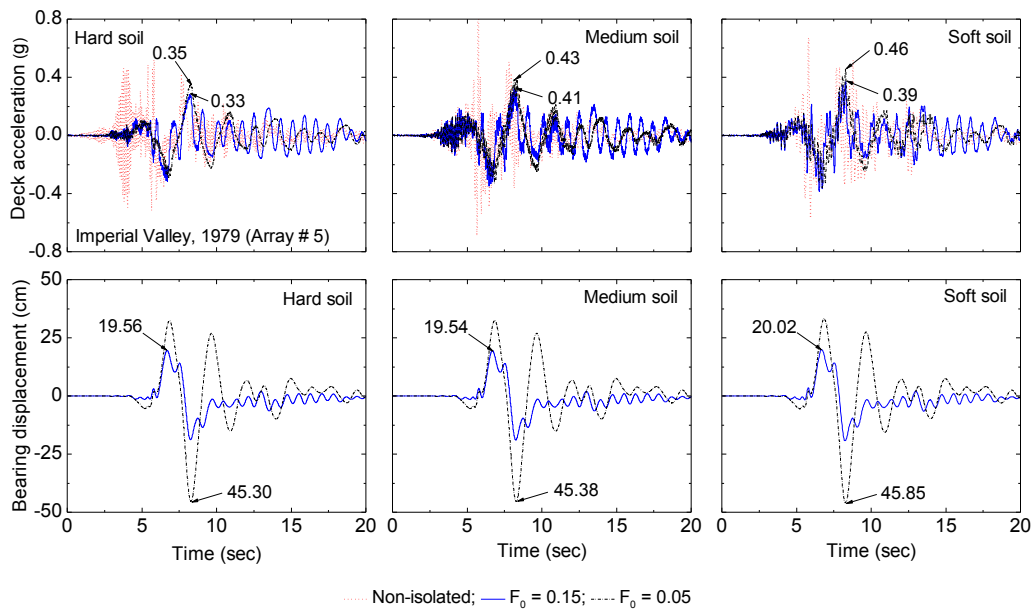


Fig. 6 Deck acceleration and bearing displacement of a base-isolated machine foundation under the Imperial Valley, Array #5, 1979, earthquake ( $T_s = 0.1$  sec,  $T_b = 2.5$  sec,  $\xi_b = 0.1$ , and  $q = 2.5$  cm)

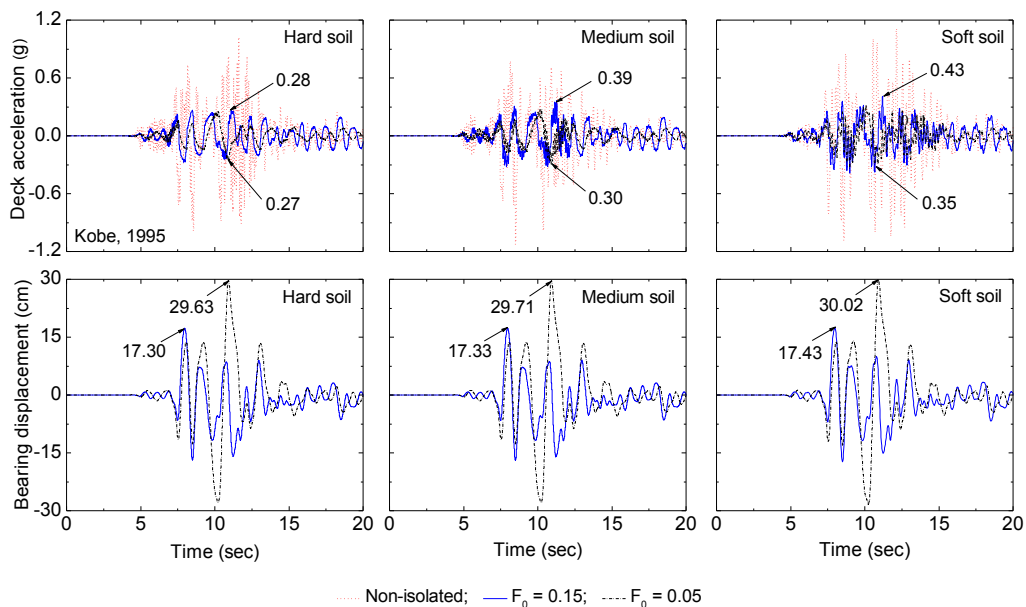


Fig. 7 Deck acceleration and bearing displacement of a base-isolated machine foundation under the Kobe, 1995, earthquake ( $T_s = 0.1$  sec,  $T_b = 2.5$  sec,  $\xi_b = 0.1$ , and  $q = 2.5$  cm)

Similar trend of response of both non-isolated and base-isolated machine foundations are observed in case of 1995 Kobe earthquake motion (recorded at KJM) shown in Figure 7. Therefore, it is concluded that bearing displacements in base-isolated machine foundation under earthquake ground motions can be reduced considerably by increasing bearing yield strength, with insignificant increase in deck acceleration, i.e. marginal compromise in effectiveness of isolation. And, neglecting the SSI in base-isolated machine foundation under-estimates deck acceleration, with marginal effect on estimating bearing displacement.

To understand the SSI effect in framed-type machine foundation under earthquake, different machine foundations (varying  $T_s$ ) are analyzed under five earthquake ground motions (Table 3). Figure 8 shows the variation of peak deck acceleration and deck displacement (average of peak response from all the five earthquakes) for different soil conditions along with the non-SSI condition. In case of hard soil, considering the SSI does not alter the responses as compared to the non-SSI condition. Up to a certain fundamental time period of machine foundation, the peak deck acceleration and displacement increase. Higher deck accelerations are induced when the frequency contents of the earthquakes are in the vicinity of  $T_s$  (i.e. acceleration-controlled zone). Subsequently, the peak acceleration decreases with increasing time period of the machine foundation. However, the deck displacement increases with increasing time period because of increased flexibility. Framed-type machine foundations supporting medium to high-speed rotary machines are generally rigid as compared to the conventional buildings. As discussed above, the SSI effect is significant in rigid structures. Hence, the response amplification due to the SSI is significant in rigid structures (i.e. machine foundations) as compared to the flexible structures (i.e. buildings). From Figure 8, it is observed that for  $T_s \leq 0.2$  sec (which is equivalent to conventional framed-type machine foundations), the acceleration are amplified in soft soil conditions. However, when  $T_s = 0.5$  sec (which can be treated equivalent to a conventional five story building), the deck acceleration decreases as the stiffness of underlying soil decreases.

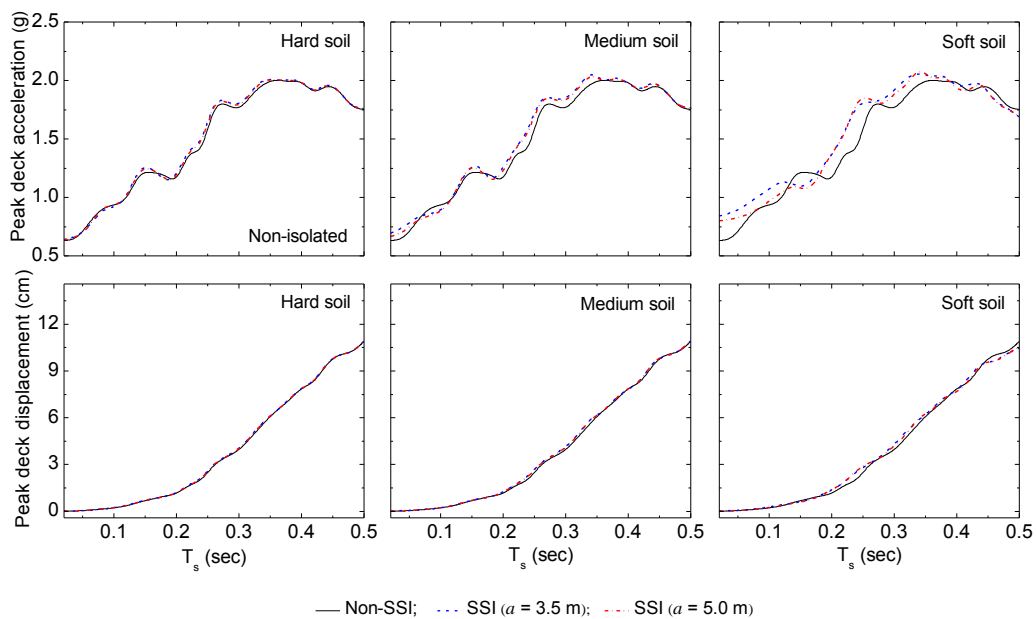


Fig. 8 Variations of peak deck acceleration and deck displacement of different non-isolated machine foundations

Similarly, to understand the SSI effect in base-isolated machine foundation under earthquakes, different machine foundations are analyzed under five earthquake ground motions. Figure 9 shows the variation of peak acceleration and displacements at deck level for different base-isolated machine foundations by considering different soil types along with fixed-base condition. In case of hard soil or rock strata, the deck acceleration is significantly reduced by using the LRB. However, in case of the soft soil, there is significant increase in the deck acceleration as compared to the hard soil condition, when  $T_s \leq 0.2$  sec (which is equivalent to conventional framed-type machine foundations). It is observed that when flexibility of soil is incorporated in the analysis, the deck acceleration has increased, especially for soft soil. Hence, the assumption of fixed-base condition (ignoring the SSI) underestimates the response of base-isolated machine foundation.

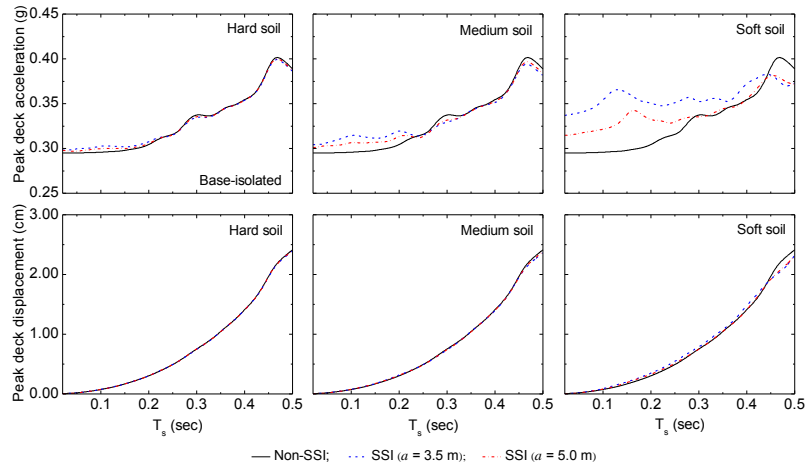


Fig. 9 Variations of peak deck acceleration and deck displacement of different base-isolated machine foundations ( $T_b = 2.5$  sec,  $\xi_b = 0.1$ , and  $q = 2.5$  cm)

To understand the role of geometry of raft foundation in the SSI, responses of machine foundation are plotted for two different values of foundation size (i.e.  $a = 3.5$  m and 5 m), as shown in Figures 8-9. It is observed from the figures that as the foundation dimension increases, the corresponding amplification in the responses due to the SSI effect decreases. From the frequency-independent relations given in Eqs. (1)-(4), the stiffness and damping of foundation-soil system is directly proportional to the foundation dimension. Hence, the stiffness and damping of foundation-soil system can be increased by using raft foundation with wider plan dimensions.

Figure 10 shows the variation of the peak acceleration and bearing displacement against normalized bearing yield strength under the five earthquake ground motions (Table 3). The responses are shown for the three different type of soils and two different values of bearing yield displacement (i.e.  $q = 2.5$  cm and 5 cm) with  $T_s = 0.1$  sec,  $T_b = 2.5$  sec, and  $\xi_b = 0.1$ . From Figure 10, it is observed that in case of the hard soil, the deck acceleration remains almost constant for  $F_0 = 0.05$  to 0.15, which then gradually increases with  $F_0$ . However, in case of the soft soil, as the bearing yield strength increases the deck acceleration significantly increases for higher  $F_0$ . In addition, the bearing displacement decreases significantly up to  $F_0 = 0.05$ , and then remains almost constant. From Figure 10, it is also observed that the LRB with lower yield displacement ( $q = 2.5$  cm) performs better under earthquake ground motions.

On the other hand, from the responses for  $T_s = 0.5$  sec as shown in Figure 11, it is observed that for higher bearing yield strength ( $F_0 \geq 0.1$ ) the LRB with higher yield displacement ( $q = 5$  cm) performs better than that with lower yield displacement ( $q = 2.5$  cm). In addition, as the stiffness of soil decreases, i.e. medium to soft soil, peak acceleration at deck level decreases for higher bearing yield strength ( $F_0 \geq 0.1$ ) as compared to the hard soil. In other words, in case of highly flexible structure, the optimum value of  $F_0$  increases as the stiffness of soil decreases.

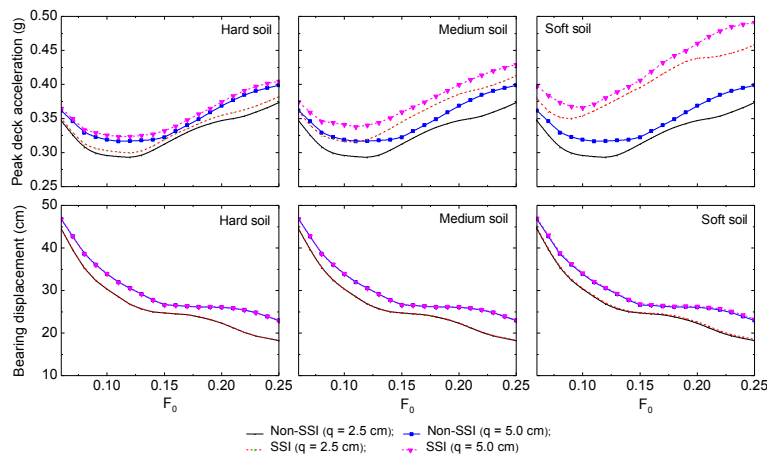


Fig. 10 Variations of peak deck acceleration and bearing displacement of base-isolated machine foundation against normalized yield strength ( $T_s = 0.1$  sec,  $T_b = 2.5$  sec, and  $\xi_b = 0.1$ )

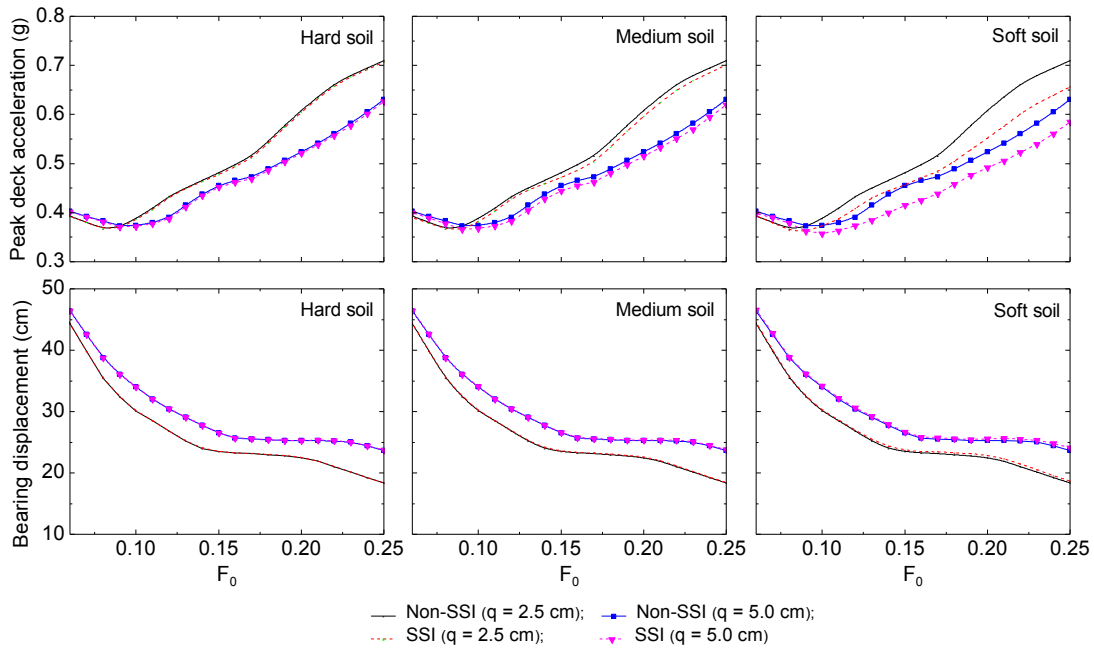


Fig. 11 Variations of peak deck acceleration and bearing displacement of base-isolated machine foundation against normalized yield strength ( $T_s = 0.5$  sec,  $T_b = 2.5$  sec, and  $\xi_b = 0.1$ )

From the above information, it is concluded that, for higher bearing yield displacement ( $q$ ), the LRB performs better in flexible structures such as conventional base-isolated buildings supported on weak soil. However, in case of the base-isolated machine foundations, low value of the bearing yield displacement is suitable for improved performance.

To study the SSI effect on bearing flexibility, the framed-type machine foundations are analyzed for three values of isolation time period of the LRB (i.e.  $T_s = 2, 2.5,$  and  $3$  sec) with  $\xi_b = 0.1$  and  $q = 2.5$  cm. The variations of peak deck acceleration and bearing displacement against normalized bearing yield strength under five earthquake ground motions is shown in Figure 12. It is observed that the deck acceleration are significantly reduced by increasing the time period of the isolator, i.e. increasingly flexible bearing. The improved performance with increased isolation time period is attributed to the increased flexibility of the base-isolated machine foundation.

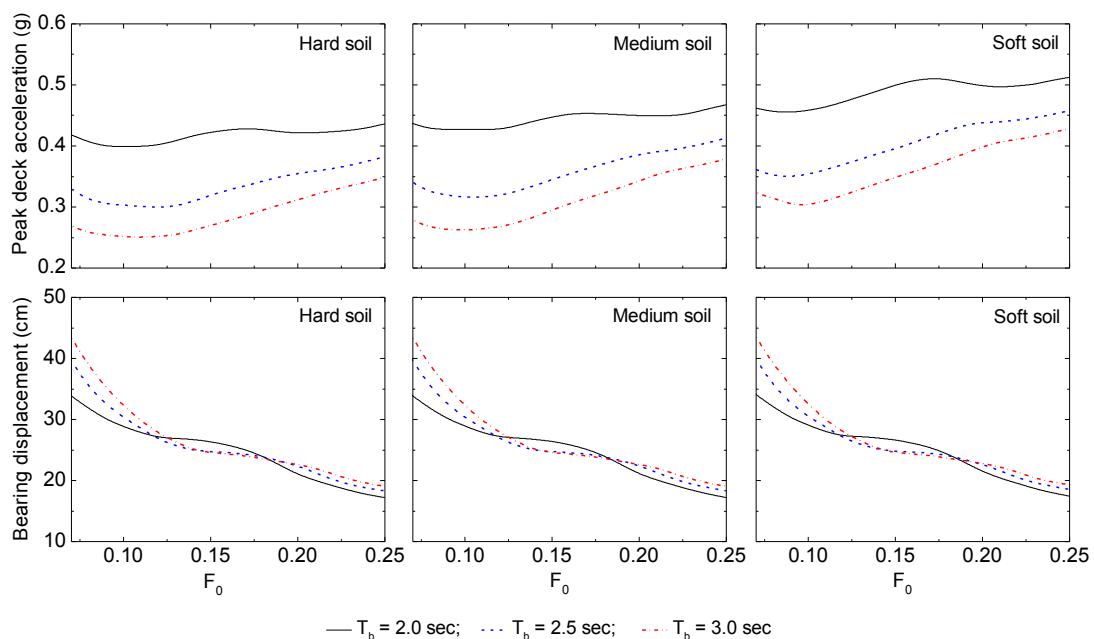


Fig. 12 Variations of peak deck acceleration and bearing displacement of base-isolated machine foundation against normalized yield strength ( $T_s = 0.1$  sec,  $q = 2.5$  cm, and  $\xi_b = 0.1$ ).

In addition, the amplification in the response of base-isolated machine foundation due to the SSI effect is significant for isolator having low time period. As the stiffness of the soil decreases, peak acceleration at deck level increases for higher bearing yield strength ( $F_0 \geq 0.1$ ). In case of the hard soil, the optimum value of the  $F_0$  is 0.15 to 0.2, however, in case of the soft soil  $F_0$  shall be lower so that the deck acceleration may be reduced.

## CONCLUSIONS

The method to evaluate the dynamic response of base-isolated machine foundation subjected to earthquake ground motions is presented along with presenting parameters influencing the response. Typical framed-type machine foundation is modeled using lumped-mass approach which is analyzed numerically using Newmark's method of step-by-step integration. Different soil conditions are compared with the fixed-base condition and the seismic response for each soil condition is plotted. An extensive parametric study is carried out to investigate the SSI effect and the parameters affecting base-isolated machine foundation. From the trend of the results of the present study, the following conclusions are drawn.

1. The SSI effect decreases the natural frequency of the structure-foundation-soil system, which is significant in higher modes, especially for rigid machine foundation resting on weak soil strata. Though, the fundamental frequency of machine foundation is well separated from dominant frequency content of earthquake ground motion by the LRB, resonance is still possible in the higher modes resulting in amplified response of the base-isolated machine foundations.
2. Since, framed-type machine foundations are rigid as compared to the conventional low-rise buildings, the forces exerted on the superstructure are severe under earthquake ground motions. Hence, the base isolators are beneficial in framed-type machine foundations, by which the superstructure accelerations are greatly reduced.
3. Though, the deck accelerations are significantly reduced by using the LRB, in case of the soft soil, the involvement of higher mode participation amplifies the seismic response. Hence, neglecting the SSI in dynamic response of base-isolated machine foundations leads to under-estimation of the dynamic response.
4. By increasing the bearing yield strength, bearing displacements are considerably reduced. As the stiffness of soil decreases, the optimum value of bearing yield strength increases for flexible structures like conventional base-isolated buildings. However, in case of the base-isolated machine foundations, the optimum value of bearing yield strength decreases with soil stiffness.
5. The bearing yield strength may be optimized in such a manner that without much compromise with the increase in the deck acceleration, the bearing displacement can be substantially reduced.
6. For higher bearing yield displacement, the LRB performs better in flexible structures such as the conventional base-isolated buildings. However, in case of the base-isolated machine foundations, low value of bearing yield displacement is appropriate for enhanced performance. For higher isolator time period, the deck acceleration is significantly reduced by using the LRB, even in the soft soil conditions.
7. For the properties considered in the analysis, the SSI effect in base-isolated machine foundation is reduced by increasing the plan dimension of the foundation raft.

## ACKNOWLEDGMENTS

This research work had been funded by the Deutscher Akademischer Austausch Dienst (DAAD), IIT Master Sandwich Scholarship, which is gratefully acknowledged.

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