University of Baghdad
College of Engineering
JE
JOURNAL OF ENGINEERING

Journal of Engineering
journal homepage: www.jcoeng.edu.iq
Volume 30 Number 4 April 2024

Effect of Soil-Structure Interaction on the Response of Machine Foundation Subjected to Seismic Loading: A Review Study

Bilal Jabbar Noman[1,*], Bushra Suhale Albusoda[2]

[1,2] Department of Civil Engineering, University of Baghdad, Baghdad, Iraq
bilal.noman2001d@coeng.uobaghdad.edu.iq[1], dr.bushra_albusoda@coeng.uobaghdad.edu.iq[2]

ABSTRACT

This review provides a detailed look at the current knowledge and approaches related to Dynamic Soil-Structure Interaction (DSSI) in machine foundation design, focusing on its substantial impact on seismic response and structural stability. The significance of this interaction in structural design, especially in areas prone to seismic activity, is pivotal. The paper begins by exploring various modeling methods, like the Finite Element Method (FEM), highlighting their importance in understanding the intricate aspects of DSSI, such as energy loss and interface behavior. It is evident from the studies that FEM is particularly effective in analyzing settlement under reciprocating loads. Soil-structure interaction (SSI) is a complex phenomenon that can positively and negatively affect the seismic performance of machine foundations. Several factors, including embedment depth, soil stiffness, and foundation properties, govern the influence of SSI. This review discusses the dual nature of SSI and highlights the importance of considering the interaction between soil properties, foundation design, seismic loads, and interaction effects. In addition, it identifies the limitations of the current research and advocates for more accurate and inclusive models and extensive empirical studies to address real-world complexities and uncertainties. In conclusion, this review offers crucial insights and foundational knowledge for future innovative design solutions and advanced research methodologies and significantly contributes to developing resilient and reliable structural designs in seismic-prone regions. The emphasis is on the need for more nuanced and comprehensive studies to further the understanding and application of DSSI in machine foundation design.

Keywords: Dynamic Soil-structure interaction (DSSI), Machine foundation Design, Seismic Behavior, Finite Element Method (FEM), Structural Design.

*Corresponding author
Peer review under the responsibility of University of Baghdad.
https://doi.org/10.31026/j.eng.2024.04.10

Article received: 31/05/2023
Article accepted: 30/12/2023
Article published: 01/04/2024

تأثير التداخل بين التربة والمنشأ على استجابة أساس الماكنة المعرض الى حمل زلزالي: دراسة مراجعة

بلال جبار نعمان*، بشرى سهيل زبار

قسم الهندسة المدنية، جامعة بغداد، بغداد، العراق

الخلاصة

هذه المراجعة تقدم نظرة مفصلة على المعرفة الحالية والأساليب المتعلقة بالتفاعل الديناميكي بين التربة و المنشأ في تصميم أساسات الآلات، مع التركيز على تأثيره الكبير على الاستجابة الزلزالية واستقرار الهيكل. أهمية هذا التفاعل في التصميم الهيكلي، خاصة في المناطق التي تكون عرضة للنشاط الزلزالي، هي حاسمة. تبدأ الورقة البحثية باستكشاف أساليب النمذجة المختلفة، مثل طريقة العناصر المحددة ، مسلطًا الضوء على أهميتها في فهم الجوانب المعقدة مثل فقدان الطاقة وسلوك الواجهة. ومن الواضح من الدراسات أن طريقة العنصر المحددة فعّالة بشكل خاص في تحليل الاستقرار تحت الأحمال المتناوبة. تُبرز هذه الأعمال الطبيعة الثنائية لتفاعل التربة والمنشأ، والذي يمكن أن يعزز الأداء الهيكلي عن طريق تقليل الصلابة الديناميكية وزيادة التخميد أو يمكن أن يؤدي إلى تأثيرات سلبية مثل زيادة الضغوط على الأساس والفشل المحتمل بسبب سلوك التربة المكبر وغير الخطي. تكشف النقاش تأثير العديد من العوامل مثل عمق الغمر، صلابة التربة، وخصائص الأساس على السلوك الزلزالي لأساسات الآلات، مُبرزةً التفاعل الدقيق بين خصائص التربة، تصميم الأساس، الأحمال الزلزالية، وتأثيرات التفاعل. تشير المراجعة أيضاً إلى القيود الموجودة في البحث الحالي، بشكل رئيسي استخدام النماذج المبسطة والمعلمات المفترضة، وتُؤكد على الحاجة إلى نماذج أكثر دقة وشمولية ودراسات تجريبية واسعة لمعالجة التعقيدات والشكوك الواقعية في خصائص التربة ومواد الأساس. في الختام، تقدم هذه المراجعة ليس فقط رؤى حاسمة ومعرفة أساسية لحلول التصميم المبتكرة ومنهجيات البحث المتقدمة في المستقبل ولكن أيضاً تسهم بشكل كبير في تطوير تصميمات هيكلية موثوقة ومتينة في المناطق التي تكون عرضة للزلازل. والتأكيد هو على الحاجة إلى دراسات أكثر دقة وشمولية لتعميق الفهم والتطبيق في تصميم أساس الآلات.

الكلمات المفتاحية: التفاعل الديناميكي بين التربة والهيكل، السلوك الزلزالي ، تصميم أساسات الآلات، طريقة العناصر المحددة، تصميم الهيكل.

1. INTRODUCTION

Analyzing the dynamic response of machine foundations subjected to seismic excitations holds substantial significance for engineers and designers, especially in regions prone to earthquakes. The efficiency and stability of machine foundations in such areas are crucial, particularly for large equipment like power generators. In facilities critical to emergency response, such as electrical power plants, industrial machines, nuclear power plants, and hospitals, the stability of machine foundations is paramount, as it must ensure the machines' functionality during and after seismic events. **(Smith, 1976; Asmis, 1979; Srinivasan and Soni, 1984; Prakash and Puri,1988; Rao and Mirza, 1989; Liu and Novak, 1995; Romo et al., 2000; Naggar, 2000; Naggar, 2003; Logan, 2003; Fattah et al., 2007; Liu, 2013; Vicencio and Cruz, 2021)**. Failures in machine foundations can result in severe or economically undesirable outcomes. **Fig. 1** illustrates the importance of considering Soil-

Structure Interaction (SSI) when designing machine foundations in earthquake-prone regions. SSI can cause excessive lateral displacement, leading to significant damage to the foundation and the machine itself.

Historically, simplistic methods for calculating dynamic loads on foundations involved multiplying static loads by an arbitrary dynamic factor. This approach lacked a clear safety margin, often resulting in excessive dynamic factors and harmful deformations during machine operation. With the emergence of high-capacity machines, these issues became more pronounced, prompting a scientific investigation into dynamic loading. This exploration led to the development of advanced theoretical techniques for accurately calculating the dynamic response of foundations **(Bhatia, 1984; 2006).** The seismic behavior of machine foundations is profoundly affected by the intricate nature of SSI. Various factors, such as soil properties, foundation shape, and the inherent characteristics of the machinery, shape this interaction. A deep understanding of the complex mechanisms involved in SSI during seismic events is crucial for optimizing machine foundation designs. This ensures the foundation's structural integrity and guarantees the equipment's safety and efficiency **(Bhatia, 2008a; An and Qu, 2018; Anand and Kumar, 2018; Bapir et al., 2023)**.

(a) (b)

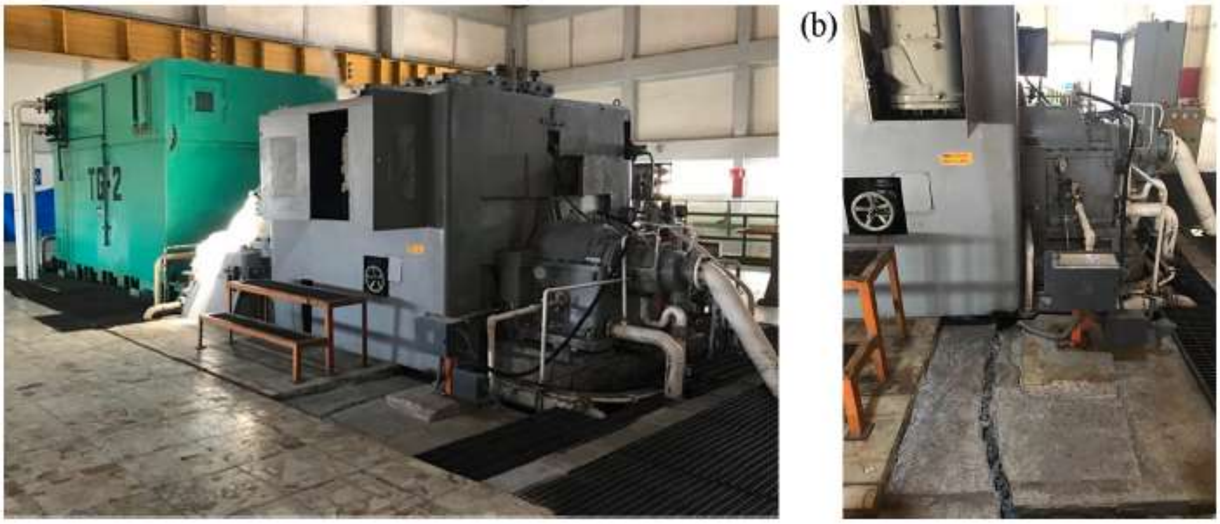

Figure 1. Impacts of excessive lateral displacement caused by the 2017 Mw 8.2 Oaxaca, Mexico earthquake. (a) Effects on electricity generator TG-2, including the turbine, generator, and auxiliary components. (b) Structural damage to the floor slab resulting from collisions between its sections.

Machine foundations are critical components of heavy industrial machinery, connecting the machines to the underlying soil. Depending on the specific site requirements and constraints, machine foundations can take various forms, such as isolated, mat, and pile foundations. The behavior of the machine-foundation system under dynamic forces is significantly influenced by the properties of the soil, such as stiffness, strength, and damping. In addition to vertical forces, machine operations also generate lateral forces. Therefore, it is important to consider the entire dynamic load scenario rather than simply multiplying vertical loads by a dynamic factor **(Bhatia, 1984; 2008b; Thakare and Rangari, 2015)**. Other relevant research **(Naggar, 2000; Zhao and Maisser, 2006; Puri and Prakash, 2007; Prowell et al., 2010; Ja and Wu, 2010; Han, 2010; Hongwang, 2012; Damgaard and Andersen, 2012; Fang et al., 2012; Lombardi et al., 2013; Liu, 2013)** has concurred on the important function of

SSI, particularly in the context of large-scale machinery. They have emphasized the need for continued research into SSI as an essential constituent of seismic response inquiries.
The concern of resonance between soil vibrations and building natural frequencies in soil-structure interaction is critical. **(Rausch, 1950**; **Veletsos, 1993)** presented notable case studies where nearby structures experienced significant vibrations due to resonance with heavy machinery foundations. These instances emphasize the need for a deeper understanding of soil-structure dynamics to prevent resonance-induced structural issues.
This work initiates a comprehensive examination and analysis of existing literature on SSI and its profound effects on machine foundation design. It explores various methods used to model SSI and compiles key findings from studies investigating how SSI affects the earthquake behavior of machine foundations and their dynamic behavior.

2. MACHINE-FOUNDATION SYSTEM

The constituents and parts of the machine-foundation system are outlined below **(Bhatia, 2008a):**

- **Machine**: A machine is an element of heavy industrial equipment mounted on a foundation. It may contain a variety of machinery, including pumps, motors, compressors, turbines, and generators.
- **Foundation:** The supporting structure that attaches the machine to the ground and distributes the loads to the soil beneath the rock strata. Depending on the specific requirements and site constraints, foundations can be of various forms, including isolated, pile, mat, or deep foundations.
- **Soil:** The soil features, such as its stiffness, strength, damping characteristics, and the effect of SSI, significantly modify the dynamic stress response of the machine-foundation system.

The description of soil stiffness under low stresses is typically articulated in terms of a modulus of elasticity. In this context, the conventional representation of soil involves its characterization as a linear elastic half-space. When a shock excitation is applied to this half space, three distinct waves propagate, namely, a compressive wave, a shear wave, and a Rayleigh wave, as depicted in **Fig. 2**. It is noteworthy that these waves carry varying proportions of the shock energy: the compressive wave encapsulates 7% of the total energy, the shear wave conveys 26% of the energy, and the Rayleigh wave predominates by transporting 67% of the total energy **(Richart et al., 1970)**. Of particular interest, the compressive wave emerges as the fastest among these waves, exhibiting a notable velocity of:

$$Vc = \sqrt{\frac{E}{\rho}\frac{1-v}{(1+v)(1-v)}} \tag{1}$$

where E is the elasticity modulus, v is Poisson's ratio, and ρ is the soil density. The shear wave velocity is

$$Vs = \sqrt{\frac{E}{\rho}\frac{1}{2(1+v)}} \tag{2}$$

The Rayleigh wave velocity is

$$Vr = \sqrt{\frac{E}{\rho}\frac{1}{2(1.4+0.8v)(1-v)}} \quad (3)$$

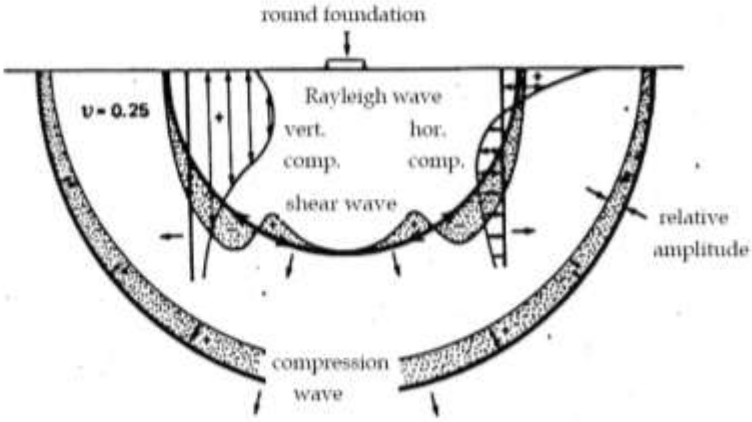

Figure 2. A dynamic point load excited waves in a halve space **(Richart, 1970).**

The velocities of the shear wave and the Rayleigh wave closely approximate each other. Remarkably, the Rayleigh wave, in addition to possessing a higher energy content than the other waves, maintains its propagation exclusively along the surface. Furthermore, it exhibits a diminished rate of energy dissipation during its travel. Consequently, as one moves farther from the source, the Rayleigh wave significantly surpasses the other waves in magnitude and becomes the predominant wave in the vicinity.

2.1 Type of Machine Foundation

Machine foundations are specialized base structures essential for properly supporting and functioning machinery, machine tools, and substantial, weighty equipment subject to diverse loads, speeds, and situations. These foundations were created with shocks and vibrations (dynamic forces) from machinery operations in mind. The following are the common machine foundations as provided by (**ACI 351.3R, 2018):**

2.1.1 Foundation-Dynamic Machines of The Block Type

This type is commonly located at ground level to reduce the disparity between the dynamic forces generated by the machine and the centroid mass of the foundation system. For the machine, as illustrated in **Fig. 3, a**. Furthermore, the positioning at a lower elevation mitigates the moments induced by lateral forces. Block foundations are typically characterized as inflexible constructions in most cases. Dynamic load, mass, dimensions, and soil properties exclusively influence the dynamic behavior of a rigid-block foundation.

2.1.2 Combined Block-type Foundations

Support machines are placed close to each other, as illustrated in **Fig. 3, b**. Therefore, in designing combined block foundations, it is imperative to consider the composite forces emanating from two or more machines. Additionally, it is essential to consider the potential inadequacy of rigidity in a more extensive mat foundation.

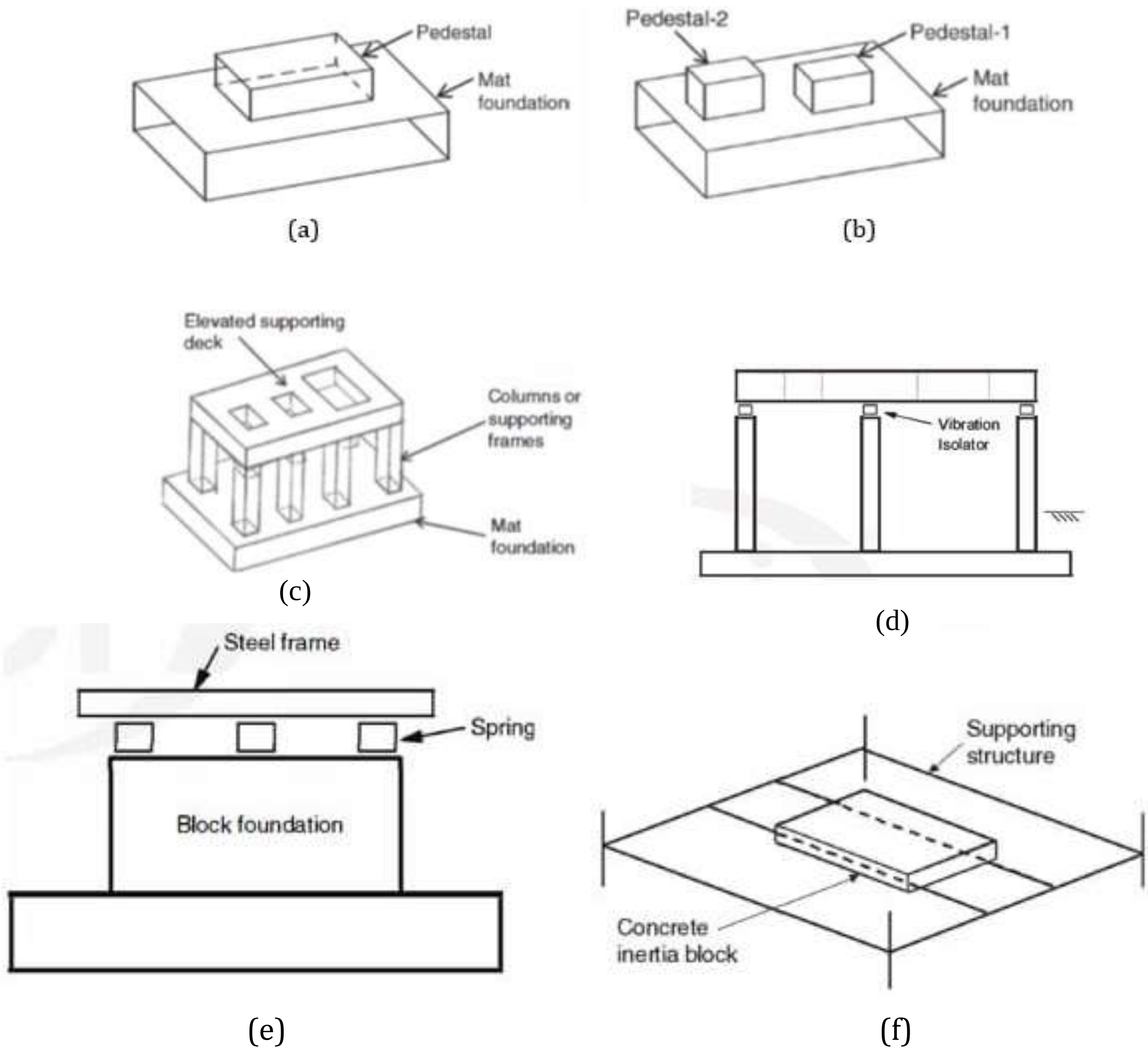

Figure 3. Type of machine foundations: (a) Block-type, (b) Combined block-type, (c) Tabletop-type, (d) Tabletop with isolators, (e) Spring-mounted equipment on a block foundation, (f) Inertia block, **(ACI 351.3R, 2018).**

2.1.3 Tabletop-style foundation

Elevated support should be considered if access to the bottom of the machinery is required for piping, ducting, and maintenance platforms or if the machine must be elevated for process-related reasons **Fig. 3, c**. Tabletop structures are typically considered flexible, and their responses to dynamic loads can be complex. This is due to the movement of their structural components, such as beams, columns, and footing, as well as the supporting subgrade.

2.1.4 Tabletop with isolators

In certain instances, the reaction to dynamic stress can be minimized by utilizing isolators (absorbers and springs) lying on top of the columns that support **Fig. 3, d.** The degree of isolation or effectiveness of isolators depends on the natural frequency generated from the foundation, the speed of the machine (RPM) cycle per minute, and the damping level.

2.1.5 Spring-mounted equipment with a block foundation

Springs are sometimes incorporated into machines to mitigate the impact of forces from connecting the pipework **Fig. 3,e.** The springs were then supported on a base composed of blocks. The dynamic effect of this configuration is comparable to that of tabletops with vibrational isolators.

2.1.6 The inertial block-dynamic equipment

It can have dimensions slightly smaller than those of the structure it is installed on. Therefore, supported inertia blocks are commonly incorporated in the construction of dynamic machines in this condition to move the fundamental frequencies of the structure and machine away from operational speeds and to lower amplitudes by increasing inertia, **Fig. 3, f**. For instance, a block foundation is a rigid foundation that can vibrate in six distinct vibration modes: movement along the X, Y, and Z axes and rocking around the X, Y, and Z axes, as illustrated in **Fig. 4.**

The mass of the foundation plays a crucial component in identifying its natural frequencies in various modes, along with its dimensions and the soil properties beneath it. The design of the foundation should ensure that its natural frequencies substantially exceed the vibrations produced by the machine. This will ensure that the foundation does not resonate with the machine, which could lead to excessive vibration and damage to the foundation and the machine **(Prakash and Puri, 2006)**.

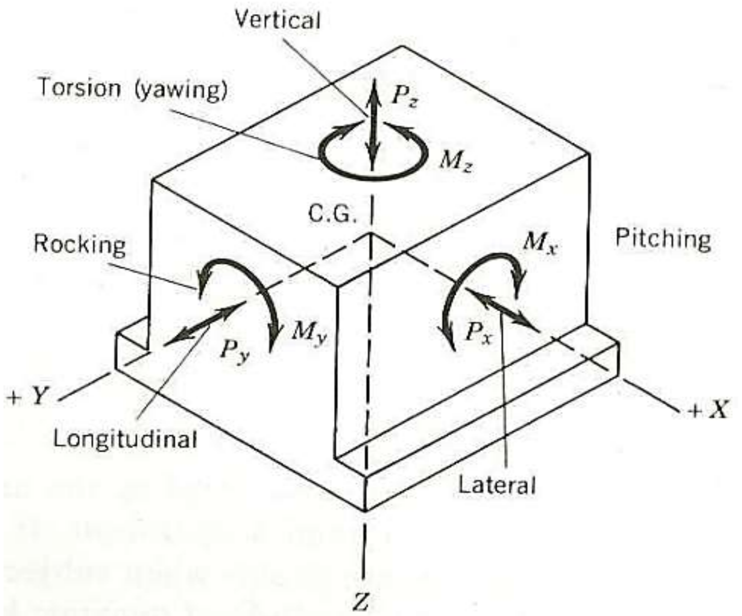

Figure 4. A block foundation exhibits six distinct vibration modes **(Prakash and Puri, 2006)**.

3. SEISMIC BEHAVIOR OF MACHINE FOUNDATIONS

Damage to machinery during earthquakes is a global concern, with most reported cases involving static electrical and mechanical equipment. Incidents of damage to rotating electrical and mechanical equipment are infrequent. Within machine foundation systems, earthquakes impact both the foundation and the machine as seismic forces transfer from the ground through the foundations.

Apart from ensuring that the machine foundation system remains sufficiently distant from a state of resonance, it is imperative to maintain the vibration amplitude of the machine within prescribed tolerances. As illustrated in **Fig. 5 a and b**, these tolerances delineate acceptable limits for vibration amplitudes across various disturbance frequencies.

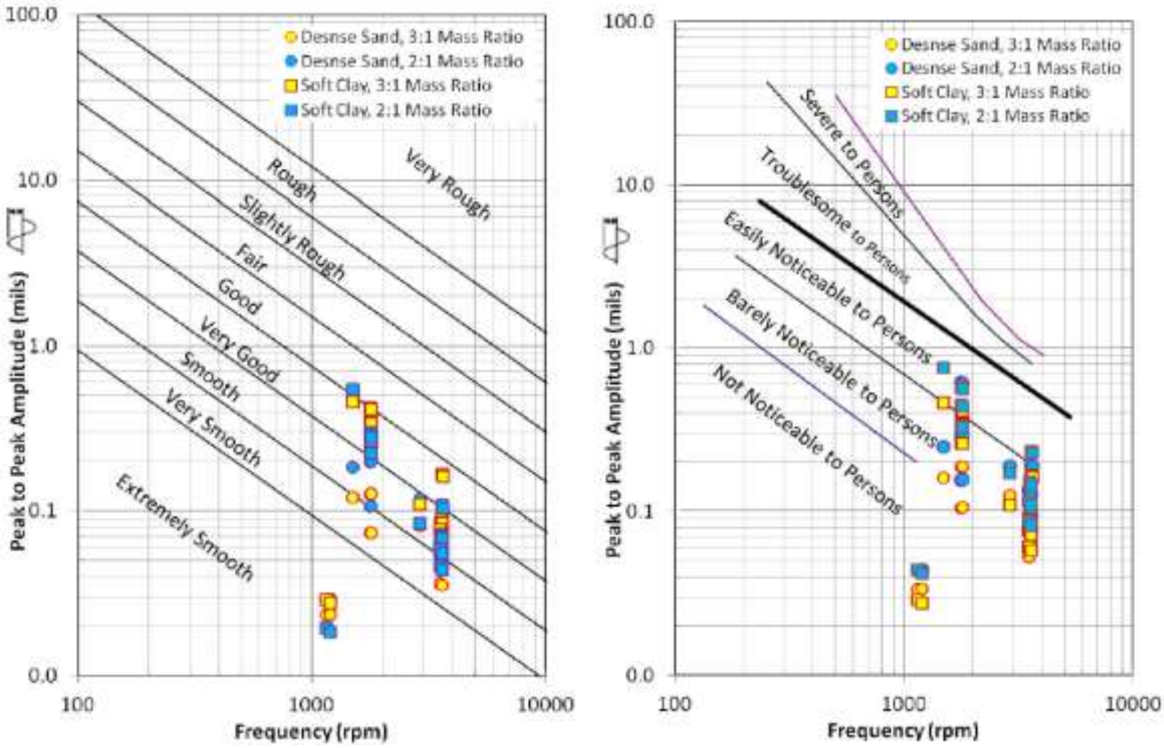

Figure 5. Chart depicting machinery vibration severity according to ACI 351.3R-18. (a) Machinery vibration requirements. (b) Human tolerance to vibration.

Notably, specific data points have been provided in **Figs. 5(a) and 5(b)** to represent the peak-to-peak amplitudes noticed in several extant API (American Petroleum Institute) pump foundations, each characterized by distinct mass ratios and soil conditions. The depicted figures reveal that the recorded amplitudes consistently fall within the acceptable range conducive to optimal machine operation. However, it is worth highlighting that a subset of foundations, characterized by a mass ratio of 2:1 and situated on soft clay substrates, exhibited amplitudes that extended into the category termed "Easily Noticeable to Persons," signifying vibrations perceptible to human senses **(Wey et al., 2013)**.

During seismic events, the permissible amplitudes specified by these criteria may undergo amplification, potentially leading to detrimental consequences for the foundation and the machinery housed within it. Such situations can result in failures or abrupt shutdowns, incurring substantial financial losses. Additionally, it is noteworthy that the predominant failure modes in these scenarios typically involve sliding or rocking, often compounded by settlement issues. Moreover, the potential for resonance phenomena exists, particularly during the second mode of vibration.

The behavior of shallow foundations during earthquakes also involves their vulnerability to rocking and sliding movements when subjected to earthquake forces. **(Heron et al., 2014)** conducted numerous centrifuge tests to investigate how different factors, such as structural stiffness, soil relative density, aspect ratio, and magnitude of the earthquake, affect the

sliding encountered by the foundation and the extent of rotation. The results indicate that permitting such movements can partially isolate the structure from the surrounding soil and alleviate the ductility requirements of the supporting structure. However, they also noted that the soil-foundation interface behavior is complex and needs further research to be fully modeled and predicted. The results revealed that structures with higher centers of gravity tended to experience greater sliding, while stiffer structures exhibited increased rotation compared to their flexible counterparts. Furthermore, the type of soil, particularly dense sand versus loose sand, played a significant role in foundation response.
Some codes, such as the International Building Code (IBC), prescribe a general threshold for sliding movements, typically limited to approximately 2-3% of the structural height. Furthermore, it stipulates a constraint on rotational displacement measured in degrees, generally not exceeding 1/150 of the structure's height.
Unlike structures where ductility can help mitigate seismic forces, machine foundation systems typically lack provisions for ductility. Consequently, even controlled damage to foundations is not permissible. A reduction factor (R) of 3, as applied to ordinary moment resisting frames, should be employed to identify the seismic factor of the system of machine-foundation. The assigned importance factor for a machine may vary based on its functionality within the manufacturing cycles. Still, the value should not be lower than 1.5 (as per **Table 2** of **(IS 1893 (Part 4), 2005**)**).**
The interaction of machinery-supported foundations and the soil during seismic occurrences is of extreme importance. Despite the significance of machine-foundation systems in critical infrastructure, current seismic design codes do not adequately address their failure.

3.1 Factors Influencing the Seismic Performance of Machine Foundations

The dynamic characteristics of the foundation system, such as stiffness, damping, and mass, significantly influence the seismic behavior of machine foundations by shifting their natural frequencies, altering their mode shapes, and amplifying or attenuating their response amplitudes. The findings emphasize the crucial significance of geotechnical elements in the seismic foundation design process. Furthermore, it highlights the imperative for further research endeavours aimed at enhancing comprehension, modeling, and experimental assessment of soil-foundation interaction subjected to seismic loading **(Romo et al., 2000; Puri and Prakash, 2007; Bhatia, 2008b; Liu, 2013; Thakare and Rangari, 2015; Hassan, 2017).** The characteristics of the rock or soil providing support significantly influence the response of the foundation. Soil liquefaction, a phenomenon occurring during an earthquake, can bring about substantial changes in how a foundation reacts **(Bhatia, 2008b; Bounds et al., 2004).** The earthquake behavior of a machine foundation is also significantly affected by its size, form, and direction. Seismic forces are more likely to damage higher or narrower foundations than wide ones.

4. DYNAMIC SOIL-STRUCTURE INTERACTION IN MACHINE FOUNDATION DESIGN

It is a fact that a portion of the soil beneath a foundation undergoes vibrations simultaneously with the foundation itself **(Barkan, 1962; Bhatia and Sinha, 1977; Prakash and Puri, 1988; Naggar, 2000; Naggar, 2003; Bhatia, 2006; 2008b; Liu, 2013)**. Several critical questions necessitate examination:

- What is the extent of the soil that experiences vibrations in conjunction with the foundation?

- Does the vibration of the soil mass vary depending on the mode of vibration?
- Does seismic foundation type impact the damping and stiffness characteristics of the soil?
- Can these factors be accurately measured?

Diverse viewpoints exist among different scholars concerning the participation of soil mass. Some argue that the mass of soil in motion with the foundation is contingent upon factors such as dead load, excitation force, vibration mode, base contact area, and soil type. Conversely, some researchers contend that the size of the involved soil mass correlates with a stress distribution curve resembling a bulb shape due to uniformly distributed load. Currently, there is a lack of a comprehensive formulation that measures the involvement of soil mass across various soil types. Additionally, the validation of these findings requires attention. The common consensus is the involvement of the mass of soil which increases the total effective mass of a machine foundation system, consequently diminishing the natural frequency. However, this aspect remains unquantifiable in the context of machine-foundation design.
For practical design considerations, **(Bhatia, 2008b)** therefore proposes:
a) Neglecting soil mass participation for under-tuned foundations.
b) Increasing the frequency margin by an additional 5% for over-tuned foundations, ensuring that natural frequencies are maintained 25% apart from the operating speed instead of the customary 20%.
"Dynamic Soil-Structure Interaction" (DSSI) describes the interaction during seismic occurrences between the machine foundation and the environment around the soil. Considering DSSI when designing machine foundations is important because the foundation's behavior and underlying soil interact. In general, the two phenomena that generate the SSI, as revealed in **Fig. (6 a,b,c),** are as follows **(Wolf, 1985)**:

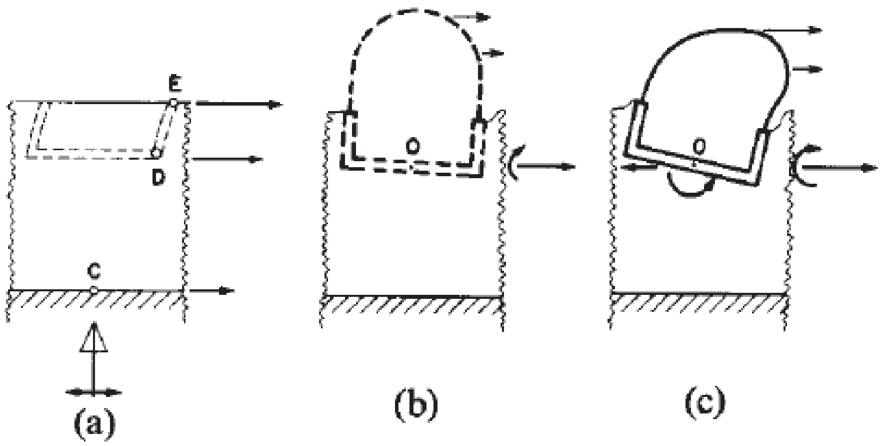

Figure 6. Seismic behavior of a structure resting on the soil. a) free field response., b) kinematic interaction response., c) inertia interaction response **(Wolf, 1985).**

- **Kinematic Interaction** results from rigid foundation materials on or within the soil. This leads to a deviation in the movement of the foundation that originates from the free fields. In addition, this phenomenon arises when foundation elements exhibit greater stiffness than the adjacent soil when an inclined wave collides with the foundation or when there is a lack of coherence in ground motions. For instance, **(Luco et al.,1989)** found that kinematic interaction can increase the peak ground acceleration by up to 20% in stiff soils.

- **Inertial interaction**, as the term is known, occurs when a mass of structure transmits an inertial force to the earth that causes further soil deformation. In other words, it occurs due to the overturning moments and base shears generated by the structure's vibration. The flexible soil may deform due to inertial forces induced by the motion of the earthquake foundation, which in turn may impact the inertial forces acting on the superstructure. For example, **(Gazetas, 1991)** found that inertial interaction can increase peak ground acceleration by up to 50% in soft soils.

4.1 Significance of DSSI

Dynamic soil-structure interactions occur due to the proportional displacement between the surrounding soil and foundation caused by a ground motion. The interaction may influence the overall behavior of the foundation by affecting its dynamic properties, including damping, mode shapes, and natural frequencies.
Various methods for assessing dynamic soil properties and behavior, as highlighted by **(Woods and Stokoe, 1985),** are available for laboratory and field applications. In the context of ground vibrations, investigations have shown multiple peaks beyond the primary resonance peak corresponding to the wave source's forced vibrations. Researchers **(Kijhler, 1932; Barkan, 1962)** have attributed these additional peaks to wave interference and the alignment of natural soil layer frequencies with vibration frequencies. These phenomena are essential to comprehend and mitigate vibration-related geotechnical issues. Notably, machine foundation vibrations can intensify when they operate at frequencies below the natural soil profile frequency, as suggested by **(Singh and Nagral, 1993**). Moreover, studies have revealed that severe damage during earthquakes tends to occur when the base frequency of the soil profile closely aligns with the frequency of the structure, as documented by **(Dobry et al., 1976)** and **(Roesset, 1977).**
To prevent underestimating or overestimating the performance of a foundation, it is imperative to consider the effects of SSI while designing machine foundations.

4.2 Methods for Modeling DSSI

The techniques for simulating the DSSI in machine foundation design are examined in this section. Firstly, the analysis of SSI can be conducted using either the substructure or the comprehensive (direct) approach.
The supporting system approach divides the soil-structure system into two parts: a finite region enclosing the structure and the nearby soil and a half-space outside the soil-structure interface in general. The half space is modeled with characteristics of frequency-dependent impedance functions obtained from either theoretical or experimental studies. For example, **(Lysmer and Waas, 1972)** developed a method for calculating the impedance functions for layered soils.
The comprehensive approach integrates the soil and the foundation-building system into a single model, typically constructed using FEM. In addition, the artificial boundary is introduced within the model to compensate for the absence of the layered medium outside the interaction area. For example, **(Kausel, 1974)** developed a finite element method for analyzing SSI problems.
The substructure and complete approaches can capture the relevant issues of SSI phenomena. However, the complete approach is more computationally demanding.

The soil and foundation were discretized into finite elements using the Finite Element Method (FEM), a frequently utilized technique for solving the coupled system's equations of motion. It offers thorough illustrations of SSI effects and can capture intricate phenomena such as wave reflections and energy loss.

The soil-structure interface was modeled, and wave propagation within the soil mass was modeled using the boundary element method (BEM). Portraying the soil as a border simplifies the issue and is ideal for unbounded soil domains or when interface behavior is a major concern.

Simplified approaches, such as empirical formulas and analytical solutions, are occasionally employed for preliminary designs or scenarios with restricted data availability. Although they might not fully account for the complexity of SSI, they offer accurate predictions of the foundation's response and are computationally effective.

Modern modeling methods, including the hybrid finite element and boundary element methods (H-FE/BEM), combine the benefits of FEM and BEM to offer more precise and effective answers to challenging SSI issues.

The problem complexity, accessible data, computational resources, and desired accuracy play a role in the appropriate choice and application of the modeling technique. The models must be calibrated using experimental data or validated case studies to accurately forecast the foundation response to seismic loads. The single portal frame analysis depends on the assumption that the beams in the longitudinal direction forming the foundation of the frame possess adequate flexibility to enable the independent vibration of transverse frames **(Barkan, 1962; IS 2974 (Part 3), 1992).**

Various techniques have been explored to evaluate the surface-mounted vibration elements of machine foundations. These approaches include:

A. Linear Elastic Spring Method (Saran, 1999): Often referred to as the IS code method, this technique involves modeling the soil as elastic springs. It simplifies the analysis by neglecting damping effects and the participation of soil mass. Given that, as a general rule, resonance zones are avoided in the machine foundation design. The influence of damping on amplitudes calculated at the frequency of operations remains negligible.

B. Elastic Half-Space Analog Method (Barkan, 1962): This approach relies on the elastic half-space concept to identify equivalent springs of soil and damping values. It subsequently employs vibration theory to ascertain foundation responses. While this method offers a more theoretically sound framework, it is comparatively intricate. The importance of equivalent soil spring and damping hinges on factors such as properties and soil type, foundation geometry, layout, and the nature of vibrations induced by dynamic loads that are not in equilibrium.

C. Arya, Neill, and Pincus Method (Arya et al., 1979): This method (**Arya et al., 1979)** is utilized to conduct the dynamic analysis of embedded machine foundations through the method of the elastic half-space analogy, as well as coefficients of embedment. The process of embedding the foundation increases the amount of contact that can be made between the soil and the surface foundation.

4.3 Factors Influencing DSSI

DSSI in machine foundation design is influenced by several factors, including soil characteristics, foundation properties, loading characteristics, the effect of boundary conditions, and embedment. Soil characteristics significantly influenced determining the extent of DSSI. The characteristics of damping and stiffness of the soil, density, and saturation can significantly influence the seismic behavior of the foundation **(Rao and Mirza, 1989; Ja and Wu, 2010; Anand and Kumar, 2018).**

Many authors have studied the effect of embedment on machine foundations with varying results. **(Barkan, 1962; Richart, 1970; Srinivasulu and Vaidyanathan, 1980; Swami; Bhatia, 1981; 1999 Bhatia, 2008b)**. Some have reported that embedment increases the natural frequency, while others have reported that it reduces vibration amplitudes.

There is a prevailing consensus that the act of embedment tends to diminish the amplitude of the dynamics. The contributing factors to this reduction could be alterations in the stiffness of the soil, variations in damping, or involvement of the mass. However, the precise effects, especially on different soil types, are yet to be understood entirely. Therefore, it is prudent to disregard the influence of embedment during the design processes to ensure errors on the side of caution, as the soil condition can also have significant implications on the dynamic behavior of the overall system. **(Mylonakis and Gazetas, 2000)** conducted a comprehensive literature assessment on the interaction between soil and structures during building seismic activities. It concluded that it is a complicated event involving many elements, such as soil properties, structural characteristics, and seismic events.

In parallel, soil–structure interaction (SSI) can augment amplification and exhibit nonlinear properties of the soil, leading to escalated stresses within the foundation and the possibility of subsequent failure. **(Mylonakis and Gazetas, 2000)** argued that SSI should be avoided whenever possible in foundation design because of its capacity to generate resonance and amplify seismic waves, potentially inflicting substantial damage on the foundation and nearby structures.

(Fattah et al., 2007) focused on developing machine foundations, specifically addressing vertical mode vibration in block foundations. Empirical design methodologies and computer simulations were utilized, employing the MATHCAD software to develop practical design charts that serve as valuable references for engineers. These charts are based on various factors, including soil properties, machine characteristics, and foundation attributes. The research found that as shear modulus increased, maximum displacement generally decreased, particularly in sandy soils compared to clayey soils. Additionally, the study observed that maximum displacement decreased with higher machine operating frequencies, soil unit weights, shear moduli, internal damping, and Poisson's ratios.

Through a comprehensive experimental program, **(Al-Busoda and Alahmar, 2014)** investigated the dynamic response of a foundation situated on soil-type collapsible soil in both dry and moist conditions. The resonance frequency increased when comparing the results with the same dynamic force level in the dry state. Gypsum dissolution, loss of cementation, and particle binding cause increased compressibility in gypseous soil when wet, which may account for the smaller displacement amplitude of wet gypseous soil than that of dry gypseous soil. The findings demonstrated that increasing the eccentric mass of the oscillator induced a proportional increase in the maximum displacement of vibration amplitude. This indicates the oscillator's eccentricity affects gypsum's behavior when subjected to vertical vibration loading.

(Kjørlaug and Kaynia, 2015) investigated the vertical seismic behavior of large-scale megawatt wind turbines, considering soil-structure interaction (SSI) influences that are frequently neglected during the design process. A three-step analytical approach analyzes SSI effects on natural frequencies, displacement responses, and base shear forces for two turbine types and various soil conditions. The findings reveal that SSI effects decrease natural frequencies, especially vertically, and increase displacement responses and the base shear forces, particularly in the vertical direction. Consequently, this research demonstrates

why SSI is so crucial. Wind turbine design and analysis effects suggest using more realistic soil models and earthquake data in future research.
Foundation properties, such as stiffness and damping, can also significantly impact SSI. **(Al-Azawi et al., 2006)** investigated characterizing damping and stiffness is a crucial aspect of embedded machine foundations. An analytical model was formulated to ascertain the natural frequency related to the machine foundation and damping ratio. The model depended on the dynamic stiffness properties associated with the soil and the foundation. The study revealed a significant correlation between the soil and foundation properties, the machine foundation's natural frequency, and the soil damping ratio. The sensitivity of a soil foundation system to vibrational forces is investigated **(Al-Mosawi et al., 2015),** specifically how that sensitivity relates to the saturation level of sandy soil. A sequence of laboratory experiments conducted on a simulated foundation system found that the displacement foundation amplitude increased with increasing soil saturation level.
The earthquake behavior of buildings was examined by **(Stewart et al., 1999)** using analytical and numerical models to evaluate the SSI effect. The findings indicate that the seismic response of structures can be either amplified or attenuated by SSI, dependent upon the conditions of the soil and structural characteristics. **(Zohra et al., 2022)** carried out the study on the effect of the SSI on the seismic response of reinforced concrete structures. It is common knowledge that the interaction between soil and building structures affects the seismic response of a building.
(Mohammed, 2022) investigated the dynamic characteristics of the machine foundations that are laid on stratified soil under the influence of seismic loads utilizing numerical modeling (FEM), which was subsequently used for conducting a parametric analysis. Considering the impact of soil properties, stratification, and equipment characteristics on the dynamic behavior of the base that supports the machine. The results indicate the behavior of the foundation was notably impacted by the soil properties, as well as the type and positioning of the machinery.
The boundary conditions of the foundation, such as shape and size, can also affect SSI. **(Allawi and Mohammed, 2022)** analyzed numerically the behavior of concrete foundations subjected to combined harmonic and seismic loads. A FEM was employed to construct a foundation model, which was subjected to a range of loads. The response of the foundation was observed to have a strong correlation with the soil parameters as well as the specific location and type of machinery involved.
On the other hand, the application of SSI can potentially enhance the dynamic response characteristics of a foundation by reducing the dynamic rigidity and increasing the damping of the system, resulting in decreased seismic demands and improved performance **(Zohra et al., 2022)**. Additionally, (SSI) can cause substantial changes in the ground motion characteristics and distribution of seismic loads within a soil-structure system. **(Al-Azawi et al., 2006)** showed that embedding machine foundations can achieve higher seismic performance by increasing damping and decreasing rigidity owing to SSI. Boundary conditions, such as the shape and size of the foundation, can also affect SSI.

5. RELEVANT WORK

Assessment of the seismic performance of machine foundations is a crucial aspect of constructing resilient and dependable structures. **(Aslam et al.,1980)** investigated the reactions of rigid bodies, specifically large concrete blocks, to seismic ground vibration.

These blocks exhibit unique behavior compared to traditional structural systems, lack distinct natural frequencies, and are sensitive to various factors.

Key findings:

- Blocks may experience rocking and potential overturning when subjected to horizontal and vertical ground motion.
- The responses differ significantly among flexible structural systems.
- The study focused on interconnected blocks that rock together.
- The coefficient of restitution plays a crucial role; lower values generally reduce responses, but exceptions exist owing to nonlinearity.
- The stability of these blocks during earthquakes depends on several factors.
- Their responses are highly sensitive to parameter variations.
- Boundary conditions at the base affect stability.
- Vertical tie-downs can enhance stability but require careful foundation design.

The following table summarizes the key findings from the literature review.

Table 1. Summary of key findings from recent literature on the seismic behavior of machine foundations.

Author	Method	Key Findings
(Aslam et al., 1980)	Theoretical analysis and experimental validation	Rigid blocks exhibit unique behaviors under seismic loads, including rocking and potential overturning. Their response is highly sensitive to parameter variations such as the coefficient of restitution, boundary conditions, and vertical tie-downs.
(Pantelides, 1991)	Literature review and discussion	Active, passive, and hybrid control methods can be used to mitigate the earthquake behavior of rotating machines. The efficiency of various control techniques depends on the specific application; however, active control methods hold promise for mitigating the seismic behavior of rotating machines.
(Suarez et al., 1992)	Numerical analysis	Soil characteristics and foundation geometry significantly influence the seismic response of machine foundations. The foundation's response to seismic activity was more significant in the horizontal orientation, and seismic loads in the 5-10 Hz frequency range were of utmost importance. The seismic resilience of the foundation can be enhanced by manipulating design characteristics such as stiffness and damping.
(Su and Henried, 1995)	Comparative study of three models: conventional fixed-base, flexible-base, SSI	The conventional fixed-base model tends to underestimate the seismic response of turbine-generator systems, whereas the flexible base models and soil-structure interaction yield more realistic outcomes. The model incorporating soil-structure interaction is the most precise, describing the crucial interplay between the foundation and soil, which is a pivotal factor in making accurate predictions regarding the seismic behavior of rotating machines.
(Liu and Novak, 1995)	Hybrid method of frequency response analysis	Soil anisotropy affects the low frequencies of the system but not the bending moments. Under unbalanced horizontal rotor excitation, the casing increases vibrations due to horizontal inertial loads. The soil anisotropy had a minimal impact. Seismic excitation behaves like a rigid body because of the system's rigidity. The casing and soil anisotropy affect the horizontal displacement, not the shear forces or bending moments.

Abdel-(Rohman and Al-Sanad, 1996)	Numerical simulations	Sandy soil nonlinearity significantly impacts the response of foundation vibration, potentially leading to system breakdowns and sudden changes. Control devices, especially nonlinear springs, effectively reduce vibrations and enhance system stability.
(Su et al., 2000)	Finite element analysis	Increasing the friction coefficient increases the maximum peak limit of acceleration and decreases the maximum sliding value of the rotor displacement. The limit of the peak disk behavior is unaffected by variations in the mass ratio and increases with increasing shaft adaptability or decreasing bearing damping. Changes in bearing rigidity did not significantly impact the peak disk response. The instabilities exhibited by the rotating machinery are predominantly attributed to the asymmetrical stiffness components of fluid-film bearings. The RFBI system can effectively safeguard critical rotating machinery against seismic harm by isolating the structure.
(Fleischer and Trombik, 2008)	Numerical analysis	SSI substantially impacts the foundation's earthquake response, emphasizing the importance of precise modeling of this interaction for accurate seismic analyses of turbine-generator foundations.
(Luo et al., 2009)	Literature review and discussion	Two strategies for mitigating the earthquake behavior of turbine foundations are lowering the base frequency of the structure and enhancing system damping. The vibration isolation system in springs, implemented to isolate the turbine generator (TG) deck from the supporting column, effectively addresses both considerations.
(Vicencio et al., 2012)	Numerical analysis	The SSI significantly impacts the seismic response of nuclear steam turbine-generator foundations. The evaluation of the earthquake behavior of the foundation subjected to various values of ground motion inputs and the assessment of the effectiveness of various seismic design approaches were investigated. The primary contribution of this study is to offer thorough insight into the seismic response of foundations for nuclear steam turbine generators and to propose design recommendations for such foundations.
(Kourkoulis et al., 2014)	Nonlinear finite element analysis	The foundation may undergo accumulated rotation when subjected to both environmental and seismic forces, potentially compromising the operational integrity of the turbine post-earthquake.
(Bhandari and Sengupta, 2014)	Elastic half-space analogy approach	Embedding reduces the amplitudes of the vibrations and the natural frequencies of the foundation. Resonance can occur in shallow embedded foundations when the foundation's natural frequency approaches the machine's operating frequency.
(Thakare and Rangari, 2015)	Physical and analytical methodologies	The foundation's response highly depends on the input motion properties and soil-foundation interaction. The depth of the foundation and SSI affect the fundamental frequencies of the foundation.
(An and Liu, 2021)	Extensive testing and numerical simulations	The innovative foundation design for nuclear plant turbo-generators effectively reduces acceleration responses, especially in the horizontal direction, and enhances safety and reliability by decreasing internal forces and structural displacement.

(Alhasso and Qasim, 2021)	FEM	The FEM is an effective tool for settlement analysis, offering precise results compared to conventional methods. However, further research is needed on the complex soil behaviors and interactions.
(Najm et al., 2022)	Theoretical method and experimental validation	The foundation embedment depth ratio, dimensionless frequency (ao), and dimensions of the square foundation significantly affected the resonance frequency of the foundation. These findings can be used to design foundations that are less susceptible to resonances.
(Desai et al., 2022)	Barkan's simplified model	Barkan's model provides reasonable predictions in most instances. However, for softer soils or when the amplitude ratios are high, more advanced methods, such as finite element analysis, are recommended to obtain more accurate results.

6. CONCLUSIONS

Dynamic soil-structure interaction (DSSI) plays a critical role in the seismic behavior of machine foundations. This review paper analyzed the current state of knowledge on DSSI in machine foundation design, highlighting the following key findings:

- The DSSI can have beneficial or detrimental effects on the seismic response of machine foundations, depending on the specific design parameters and soil conditions.
- The rigidity and damping characteristics of the foundation play vital roles in determining its dynamic response.
- Numerical modeling techniques and experimental testing are essential for gaining insights into the behavior of machine foundations subjected to seismic events.
- Recent advances in modeling techniques have improved the accuracy and efficiency of simulations, enabling engineers to assess the seismic performance of machine foundations better.
- In addition to machine-induced vibrations, machine foundations are susceptible to various failure modes under seismic loading, such as sliding, rocking, differential settlement, internal damage, and resonance.
- The judicious application of base isolators, foundation stiffening, dampers, and piles can mitigate these failure modes.

Some study limitations can be identified based on the previous discussions and analyses.
First, the review included only a limited number of studies, and further research is necessary. Complete knowledge of the seismic behavior exhibited by machine foundations is necessary, and it is imperative to analyze this phenomenon thoroughly. Hence, further studies are required to examine the seismic performance of machine foundations in other types of structures, such as high-speed rotating machines, electrical machines, and residential and commercial buildings.
Second, most of the presented studies used simplified models or assumed certain parameters that may not accurately reflect real-world conditions. Thus, future research should prioritize the development of more precise and comprehensive models for seismic analysis of machine foundations.
Finally, the effects of uncertainties and variations in soil properties and foundation materials on the earthquake behavior of machine foundations require further investigation. This can be achieved through extensive field or small-scale physical modeling measures.

NOMENCLATURE

Symbol	Description	Symbol	Description
E	Modulus of elasticity, kPa	Vs	Shear wave velocity, m/s
Vc	Compression wave velocity, m/s	ρ	Soil density, kg/m³
Vr	Rayleigh wave velocity, m/s	ν	Poisson's ratio, unitless

Acknowledgements

The author is grateful for the academic support and resources provided by the Department of Civil Engineering, College of Engineering, University of Baghdad which significantly facilitated this study. Additionally, the author acknowledges the independent funding provided for this project through personal resources

Credit Authorship Contribution Statement

All the authors have read and approved the manuscript. The 1st author, Bjlal Jabar Writing – original draft of the manuscript. The 2nd author, Bushra Suhale, reviewed and edited the manuscript.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

REFERENCES

Abdel-Rohman, M., and Al-Sanad, H., 1996. Control of Nonlinear Vibrations of Foundations Built in Sandy Soil. *Journal of Vibration and Control*, 2(1), pp.53-68. Doi:10.1177/107754639600200104

ACI 351.3R, 2018. Foundations for Dynamic Equipment. *Farmington Hills*, MI: American Concrete Institute.

Al-Azawi, T.K., Al-Azawi, R.K., and Al-Jaberi, Z.K., 2006. Stiffness and damping properties of embedded machine foundations. *Journal of Engineering*, 12(2), pp.429-444. Doi:10.31026/j.eng.2006.02.19.

Al-Busoda, B.S., and Alahmar, M.M., 2014. The behavior of gypseous soil under vertical vibration loading. *Journal of Engineering*, 20(1), pp.21-30. Doi:10.31026/j.eng.2014.01.02

Alhasso, N.K., and Qasim, Q.N., 2021. Settlement Analysis of machine foundation Under Reciprocating Load using FEM. *Al-Rafidain Engineering Journal (AREJ)*, 26(1), pp.37-43. Doi:10.33899/rengj.2020.128010.1057.

Allawi, A.A., and Mohammed, Q.S., 2022. Numerical analysis of a concrete foundation under a combination of a dynamic and a seismic load. *Journal of Engineering*, 28(2), pp.18-39. Doi:10.31026/j.eng.2022.02.02

Al-Mosawi, M.J., Fattah, M.Y., and Al-Ameri, A.F., 2015. Effect of saturation of sandy soil on the displacement amplitude of soil foundation system under vibration. *Journal of Engineering*, 21(2), pp.20-36. Doi:10.31026/j.eng.2015.02.02

An, D., and Liu, T., 2021. Seismic test and simulation of spring vibration isolated foundation for turbo-generator. Shock and Vibration, 2021, pp.1-16. Doi:10.1155/2021/8884920

An, D., and Qu, T.J., 2018. Seismic behavior of turbine-generator foundation under strong earthquake action in different directions. *Advances in Civil Engineering*, pp. 1-10. Doi:10.1155/2018/2506264

Anand, V., and Kumar, S.S., 2018, November. Seismic soil-structure interaction: a state-of-the-art review. *In Structures* (Vol. 16, pp. 317-326). Doi:10.1016/j.istruc.2018.10.009

Arya, S.C., O'Neill, M.W., and Pincus, G., 1979. Design of structures and foundations for vibrating machines. *Golf publishing Company*, London.

Aslam, M., Godden, W.G., and Scalise, D.T., 1980. Earthquake rocking response of rigid bodies. *Journal of the Structural Division*, 106(2), pp.377-392. Doi:10.1061/jsdeag.0005363

Asmis, G.J.K., 1979. Response of rotating machinery subjected to seismic excitation. *In Engineering design for earthquake environments,* 12(4), 215-225.

Bapir, B., Abrahamczyk, L., Wichtmann, T., and Prada-Sarmiento, L.F., 2023. Soil-structure interaction: A state-of-the-art review of modeling techniques and studies on seismic response of building structures. *Frontiers in Built Environment*, 9, P. 1120351. Doi:10.3389/fbuil.2023.1120351

Barkan, D.D.,1962. Dynamics of Bases and Foundations, *McGraw-Hill Book Company*, New York, U.S.A.

Bhandari, P.K., and Sengupta, A., 2014. Dynamic analysis of machine foundation. *International Journal of Innovative Research in Science*, Engineering and Technology, 3(4), pp.169-76.

Bhatia, K.G.,1981. Soil Structure Interaction Effects on the Response of 210 MW TG Frame Foundation, *Proceedings of the International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics*, St. Louis, U.S.A., Vol. 1, pp. 319–322.

Bhatia, K.G.,1984. Machine Foundation in Power Plant and Other Industries—Case Studies. *Proceedings of the International Conference on Case Histories in Geotechnical Engineering*, St. Louis, U.S.A., 2, pp. 775–779.

Bhatia, K.G.,2006. Machine Foundation Design—A State of the Art, *Journal of Structural Engineering*, SERC, 33(1), pp. 69–80.

Bhatia, K.G., and Sinha, K.N., 1977. Effect of Soil-Structure Interaction on the Behaviour of Machine Foundations. *In Proceedings of the International Symposium on Soil-Structure Interaction*, Roorkee, pp. 399-404.

Bhatia, K.G., 2008a. *Foundations for industrial machines: a handbook for practicing engineers, rotary machines, reciprocating machines, impact machines, vibration isolation system*. CRC Press.

Bhatia, K.G., 2008b. Foundations for industrial machines and earthquake effects. *ISET Journal of Earthquake Technology,* Paper, (495), pp.1-2.

Bounds, W.L., Louis, F.G., Sheikh, A.H., Brant, W.D., Moll, J., Smalley, A.J., Fang, S.J., Pearce, I.W., Smith, P.A., Harsh, S., and Rossi, A., 2004. Foundations for dynamic equipment, *ACI Committee*.

Damgaard, M., and Andersen, J.K., 2012, June. Natural frequency and damping estimation of an offshore wind turbine structure. *In ISOPE International Ocean and Polar Engineering Conference* (pp. ISOPE-I). ISOPE.

Desai, K.Y., Dhut, V.R., and Sheth, K.N., 2022. Dynamic analysis of block-type machine foundation using barkan's model for various soil parameters. *In ASPS Conference Proceedings*, 1(4), pp. 1025-1031. Doi:10.38208/acp.v1.616

Dobry, R., Oweis, I., and Urzua, A., 1976. Simplified procedures for estimating the fundamental period of a soil profile. *Bulletin of the Seismological Society of America*, 66(4), pp.1293-1321.

El Naggar, M.H., 2000. Evaluation of performance of machine foundation under blast-induced excitation. *WIT Transactions on The Built Environment*, 48.

Fang, M., Wang, T., and Li, H., 2012. Dynamic behavior of turbine foundation considering full interaction among facility, structure and soil. *In Proceedings of the 15th World Conference on Earthquake Engineering*, Lisbon, Portugal (pp. 24-28).

Fattah, M.Y., Al-Mufty, A.A.A.A., and Al-Badri, H.T., 2007. Design charts for machine foundations. *Journal of Engineering*, 13(4). Doi:10.31026/j.eng.2007.04.07.

Fleischer, P.S., and Trombik, P.G., 2008. Turbo generator machine foundations subjected to earthquake loadings. *The 14th World Conference on Earthquake Engineering*, October 12-17, Beijing, China.

Gazetas, G. ,1991. *Soil-structure interaction in seismic engineering*. *Prentice Hall*. London.

Han, Y.C., 2010. Dynamic analysis for foundation of vibrating equipments considering soil-structure interaction. In *Soil Dynamics and Earthquake Engineering* (pp. 71-76). Doi:10.1061/41102(375)7

Hassan, M.M., 2017. Parameters affecting the dynamic behavior of the machine foundations: case study. *In: Proceedings of the 6th CSCE-CRC International Construction Specialty Conference*, Vancouver, Canada, 31 May-3 June 2017. Canadian Society for Civil Engineering, pp. 1-10.

Heron, C., Haigh, S., and Madabhushi, G., 2014. Susceptibility of shallow foundation to rocking and sliding movements during seismic loading. *In Seismic Evaluation and Rehabilitation of Structures*, pp. 419-432. Doi:10.1007/978-3-319-00458-7_23

Hongwang, M., 2012. Seismic analysis for wind turbines including soil-structure interaction combining vertical and horizontal earthquake. *In 15th World Conference on Earthquake Engineering*. Lisbon, Portugal.

IS 1893 (Part 4), 2005. Indian standard criteria for earthquake resistant design of structures. *Bureau of Indian Standards, Bureau of Indian Standards*, New Delhi. *Part*, *4*.

IS 2974 (Part 3), 1992. Indian standard design and construction of machine foundations—Code of Practice, Part 3: Foundations for Rotary Type Machines (Medium and High Frequency) (Second Revision), *Bureau of Indian Standards*, New Delhi.

Jaimes, M.A., and Candia, G., 2020. Seismic risk of sliding ground-mounted rigid equipment. *Engineering Structures*, 204, P. 110066. Doi:10.1016/j.engstruct.2019.110066

Jan, S.F., and Wu, S.C., 2010. Dynamic analysis and design of large compressor foundations in high seismic zone. *In Structures Congress* 2010, pp. 2702-2713. Doi:10.1061/41130(369)244

Kausel, E. ,1974. Finite element analysis of dynamic soil-structure interaction problems. *Earthquake Engineering and Structural Dynamics*, 2(3), pp. 287-302.

Kjørlaug, R.A., and Kaynia, A.M., 2015. Vertical earthquake response of megawatt-sized wind turbine with soil-structure interaction effects. *Earthquake Engineering & Structural Dynamics*, 44(13), pp. 2341-2358. Doi:10.1002/eqe.2590

Kourkoulis, R.S., Lekkakis, P.C., Gelagoti, F.M., and Kaynia, A.M., 2014. Suction caisson foundations for offshore wind turbines subjected to wave and earthquake loading: effect of soil–foundation interface. *Géotechnique*, 64(3), pp. 171-185. Doi:10.1680/geot.12.p.179

Lee, T.H., and Wesley, D.A., 1973. Soil-structure interaction of nuclear reactor structures considering through-soil coupling between adjacent structures. *Nuclear engineering and design*, 24(3), pp. 374-387. Doi:10.1016/0029-5493(73)90007-1

Liu, W., and Novak, M., 1995. Dynamic behaviour of turbine-generator-foundation systems. *Earthquake engineering & structural dynamics*, 24(3), pp. 339-360. Doi:10.1002/eqe.4290240304

Liu, Z., 2013. Design of foundations for large dynamic equipment in a high seismic region. In Structures Congress 2013: *Bridging Your Passion with Your Profession*, pp. 1403-1414. Doi:10.1061/9780784412848.124

Logan Jr, E., 2003. *Handbook of turbomachinery*. CRC Press. Doi:10.1201/9780203911990

Lombardi, D., Bhattacharya, S., and Wood, D.M., 2013. Dynamic soil–structure interaction of monopile supported wind turbines in cohesive soil. *Soil dynamics and earthquake engineering*, 49, pp.165-180. Doi:10.1016/j.soildyn.2013.01.015

Luco, J.E., Wolf, J.P., and Seed, H.B.,1989. Clas si: A computer program for the analysis of soil-structure interaction problems. Report No. UCB/EERC-89/19, *University of California*, Berkeley, CA.

Luo, G.S., Fang, J.X., and Wang, J., 2009. Aseismic performance of spring supported turbo-generator foundation. *Engineering Journal of Wuhan University*, 42(S1), pp. 436-442.

Lysmer, J., and Waas, G. ,1972. Finite element method for soil-structure interaction problems. *Journal of the Engineering Mechanics Division*, 98(6), pp. 859-877.

Mohammed, Q.S., 2022. Dynamic Behavior of Machine Foundations on layered sandy soil under Seismic Loadings. *Journal of Engineering*, 28(8), pp. 1-20. Doi:10.31026/j.eng.2022.08.01

Mylonakis, G., and Gazetas, G., 2000. Seismic soil-structure interaction: beneficial or detrimental?. *Journal of earthquake engineering*, 4(3), pp. 277-301. Doi:10.1080/13632460009350372

Naggar, M.H.E., 2003. Performance evaluation of vibration-sensitive equipment foundations under ground-transmitted excitation. *Canadian geotechnical journal*, 40(3), pp. 598-615. Doi:10.1139/t03-014

Najm, A.A., AL-Sulayvani, B.J., and Jaro, M.N., 2022. Vertical Displacement Analysis of Embedded Square Foundation Under Vertical Dynamic Load. *Geotechnical Engineering and Sustainable*

Construction: Sustainable Geotechnical Engineering, pp. 409-421. Singapore: Springer Singapore. Doi:10.1007/978-981-16-6277-5_33

Pantelides, C.P., 1991. Control of Seismic Response of Structures. *In Second International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics*, Missouri S&T.

Prakash, S., and Puri, V.K. ,1988. Foundations for machines: analysis and design, John Wiley and Sons, Inc., New York.

Prakash, S., and Puri, V.K., 2006. Foundations for vibrating machines. *Journal of structural Engineering*, 33(1), pp. 13-29.

Prowell, I., Elgamal, A., and Lu, J., 2010. Modeling the influence of soil structure interaction on the seismic response of a 5 MW wind turbine. *Fifth International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics*, San Diego, California, USA.

Puri, V.K., and Prakash, S., 2007. Foundations for seismic loads. *In Dynamic Response and Soil Properties* (pp. 1-10). Doi:10.1061/40904(223)11

Rajkumar, K., Ayothiraman, R., and Matsagar, V.A., 2021. Effects of soil-structure interaction on torsionally coupled base isolated machine foundation under earthquake load. *Shock and Vibration*, pp. 1-8. Doi:10.1155/2021/6686646

Rao, C.K., and Mirza, S., 1989. Seismic analysis of high-speed rotating machinery. *Nuclear Engineering and Design*, 111(3), pp.395-402. Doi:10.1016/0029-5493(89)90250-1

Rausch, E.,1950. *Maschinen fundamente*. VDI, Dusseldorf, Germany (in German).

Richart, F.E., 1970. *Vibrations of soils and foundations.* Prentice-Hall. Inc., Englewood Cliffs, New Jersey.

Roesset, J.M., 1977. Soil amplification in earthquakes, *Numerical Methods in Geotechnical Engineering*, CS Desai and JT Christian, eds.

Romo, M.P., Mendoza, M.J., and Garcia, S.R., 2000. Geotechnical factors in seismic design of foundations state-of-the-art report. *Bulletin of the New Zealand Society for Earthquake Engineering*, 33(3), pp. 347-370. Doi:10.5459/bnzsee.33.3.347-370

Saran, S., 1999. *Soil Dynamics and Machine Foundations*. New Delhi, India: Galgotia Publications pvt ltd.

Singh, Y., and Nagpal, A.K., 1993. Estimating fundamental period of soil profiles. *Geotechnical Engineering*, *24*(2), pp.167-74. http://worldcat.org/issn/00465828

Smith, C.B., 1976. Seismic and operational vibration problems in nuclear power plants. *Shock and Vibration Digest*, 8(11), pp. 3-13. Doi:10.1177/058310247600801103

Srinivasan, V., and Soni, A.H., 1984. Seismic analysis of a rotor-bearing system. *Earthquake Engineering & Structural Dynamics*, 12(3), pp. 287-311. Doi:10.1002/eqe.4290120302

Stewart, J.P., Seed, R.B., and Fenves, G.L., 1999. Seismic soil-structure interaction in buildings. II: Empirical findings. *Journal of geotechnical and geoenvironmental engineering*, *125*(1), pp. 38-48. Doi:10.1061/(asce)10900241(1999)125: 1(38)

Su, W.C., and Henried, A.G., 1995. Seismic response of flexible rotating machines. *In 7th Canadian Conference on Earthquake Engineering*, pp. 229-236.

Su, W.C., Hernried, A.G., and Yim, S.C., 2000. Seismic response of rotating machines–structure–RFBI systems. *Earthquake engineering & structural dynamics*, 29(2), pp. 213-240. Doi:10.1002/(sici)1096-9845(200002)29:2%3C213::aid-eqe900%3E3.0.co;2-4

Suarez, L.E., Singh, M.P., and Rohanimanesh, M.S., 1992. Seismic response of rotating machines. *Earthquake engineering & structural dynamics*, 21(1), pp. 21-36. Doi:10.1002/eqe.4290210102

Thakare, A.U., and Rangari, S.M., 2015. Effect of seismic parameters on analysis of turbo-generator foundation. *International Journal of Engineering Research & Technology,* 4(05). Doi:10.17577/ijertv4is050554

Tripathy, S., and Desai, A.K., 2017. Investigation of dynamic behaviour for turbo generator frame foundation through experimental and computational approach. *International Journal of Geotechnical Engineering*, 11(5), pp. 513-523. Doi:10.1080/19386362.2016.1239037

Veletsos, A.S., 1993. Design concepts for dynamics of soil-structure interaction. In *Developments in dynamic soil-structure interaction* (pp. 307-325). Dordrecht: Springer Netherlands. Doi:10.1007/978-94-011-1755-5_13

Vicencio, F., and Cruz, E.F., 2021. A high order nonlinear study to evaluate the seismic response of rotating machines–structure–soil foundation systems. *Journal of Earthquake Engineering*, 25(14), pp.2775-2807. Doi:10.1080/13632469.2019.1651422

Vicencio, F., Cruz, E.F., and Valdivia, D., 2012. Evaluation of different modeling options for seismic analysis of large turbine-generator systems and their foundation. *Fifteenth World Conference on Earthquake Engineering.*

Wey, E., Wong, S., and Bounds, W., 2013. Vibratory machine foundation design: when to perform a dynamic analysis. In Structures Congress 2013*: bridging your passion with your profession*, pp. 1437-1446. Doi:10.1061/9780784412848.127

Wolf, J., 1985. *Dynamic soil-structure interaction*. Prentice Hall, Inc.

Woods, R.D., and Stokoe, K.H., 1985. Shallow seismic exploration in soil dynamics. *In Richart commemorative lectures* (pp. 120-156). ASCE.

Zhao, X., and Maisser, P., 2006. Seismic response analysis of wind turbine towers including soil-structure interaction. *Proceedings of the Institution of Mechanical Engineers, Part K: Journal of Multi-body Dynamics*, *220*(1), pp. 53-61. Doi:10.1243/146441905X73691

Zohra, B.F., Fouad, B.A., and Mohamed, C., 2022. Soil-structure interaction interfaces literature review. *Arabian Journal of Geosciences*, 15(12), pp. 1130. Doi:10.1007/s12517-022-10336-7