Seismic Hazard Assessment in Machine Foundation Design: A Review Study

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Abstract. This paper presents a comprehensive review of seismic hazard assessment in machine foundation design and highlights key research directions for future studies. The review includes a detailed analysis of existing literature, that covers a wide range of subjects associated with seismic analysis and design of machine foundations. It begins with an overview of the seismic hazard assessment evaluation procedure and the various factors that influence it, such as soil properties, machine stiffness, and earthquake excitation. Then it discusses the key challenges associated with the design and seismic analysis of machine foundations, including the impact of dynamic loads and soil-structure interaction. Following the analysis of the current research, the paper identifies several important research directions for future studies. These include the development of more accurate seismic hazard assessment methodologies, using sophisticated numerical modeling methods. The paper also emphasizes the need for more comprehensive experimental studies to validate the numerical models and better understand the behavior of machine foundations under seismic loads. In brief, the paper provides a comprehensive review of the current state of knowledge in seismic hazard assessment in machine foundation design and highlights the importance of future research to proceed in this field.

Keywords: Seismic hazard assessment, Machine foundation design, Seismic response analysis, Experimental studies, Numerical studies, Dynamic behavior.

1. INTRODUCTION

1.1 Background Information on the Seismic Hazard Assessment of Machine Foundations:

Machine foundations are structural elements that support and isolate mechanical equipment from the surrounding environment. These foundations are essential for maintaining the stability and safety of the machines during operation. The severity of ground motion and its effects on machine foundations depend on various factors, including the magnitude and frequency content of the earthquake, the characteristics of the soil and foundation, and the design and construction of the foundation and equipment. In some cases, the ground motion may not be strong enough to cause any damage or malfunction of the foundation, whereas, in others, even moderate ground motion can have severe consequences. Seismic hazard assessment of machine foundations involves evaluating the potential for ground motion-induced damage and designing the foundation accordingly. This process involves a range of methods, including site-specific ground motion prediction, probabilistic and deterministic seismic hazard analysis, and dynamic analysis of the foundation structure [1-3].

Numerous studies have been conducted concerning the assessment of seismic hazards to machine foundations over time, with a focus on improving the design and construction of these foundations to withstand seismic events. In this context, several researchers have contributed to this field by examining the various methods used in seismic hazard assessments and providing critical insights into their limitations and advantages [4-7].

Factors such as the peak ground acceleration (PGA), the frequency content of seismic waves, and the seismicity of the region can be considered. PGA is commonly used to quantify the intensity of ground motion, but the frequency content of seismic waves and seismicity can also play a role. However, within regions with a high level of seismic activity, the seismic response of machine foundations is a critical consideration. Seismic hazards can pose a significant threat to the safety and functionality of machine foundations, leading to catastrophic failure of the foundation and the machinery it supports [1]. It is a complicated process that requires careful study of several variables, including soil parameters, machine dynamic amplitude, and seismic characteristics such as (Amplitude, frequency, resonance, mode shapes). An effective seismic hazard assessment and machine foundation mitigation require a good understanding of these factors. [1,8].

Therefore, the review aims to provide a comprehensive overview of the existing literature on seismic hazard assessment of machine foundations, including the latest developments in research and industry practices. By synthesizing the findings from various studies, this review aims to identify the key factors influencing machine foundations, and seismic response to evaluate the effectiveness of different design and assessment methods.

2. ASSESSMENT OF SEISMIC HAZARD

2.1 Definition of Seismic Hazard Assessment

Seismic hazard assessment is a critical process that involves evaluating the potential risk of earthquakes in a given area. It is a fundamental step in designing structures that are resilient to seismic events, such as machine foundations. Seismic hazard assessment considers various factors, such as the location, magnitude, and frequency of earthquakes, besides the characteristics of the ground and the geological conditions of the site. The process involves complex analysis and modeling techniques, including probabilistic and deterministic methods. The appropriate design parameters are determined based on the outcomes of the seismic hazard assessment, such as the required strength, stiffness, and damping [9, 10, 11].

2.2 Techniques and Methods Used for Assessing Seismic Hazard

Two broad categories can be used to categorize seismic hazard assessment techniques: deterministic and probabilistic methods. Deterministic methods are based on a single scenario earthquake, assuming a specific magnitude, location, and ground motion, to estimate the seismic hazard, while probabilistic methods consider all potential earthquake scenarios and their associated probabilities to evaluate seismic hazards [8,9].

The deterministic methods include the Equivalent Static Analysis (ESA), which represents the impact of dynamic loads using a simplified static force. [12,13], and the Response Spectrum Method (RSM), which uses a set of acceleration, velocity, and displacement spectra to analyze the dynamic response of the structure to earthquakes [14,15]. Probabilistic methods include the Probabilistic Seismic Hazard Analysis (PSHA), which uses the seismicity and fault data to estimate the likelihood of earthquake occurrence and their magnitudes [16], and the Seismic Risk Assessment (SRA), which determines the risk of damage or loss by combining seismic hazard analysis with the vulnerability and exposure of the structure. [17].

Other techniques for seismic hazard assessment include using ground motion prediction equations (GMPEs) to estimate the expected ground motion, site-specific hazard analysis that considers the site conditions and local soil, and the scenario-based approach that considers the potential earthquake scenarios and their effect on the structure [18]. It is worth noting that the selection of the appropriate method for seismic hazard assessment depends on various factors such as the project requirements, site-specific conditions, and available data. A comprehensive approach that combines both deterministic and probabilistic methods may provide a more accurate and reliable assessment of the seismic hazard.

2.3 Significance of seismic hazard assessment in machine foundation design

Seismic hazard assessment plays a significant role in machine foundation design. By determining the potential of ground shaking and other seismic hazards, engineers can design foundations that are capable to withstand the forces generated by earthquakes. The assessment helps to identify the appropriate design parameters, such as foundation stiffness and damping, that are needed to ensure that the machine remains operational during and after a seismic event. Without proper seismic hazard assessment, the machine foundation could fail during an earthquake, leading to serious damage to the machine and potentially putting workers at risk. To ensure the safe and proper operation of the machine, engineers must consider seismic hazard assessment while constructing the machine base.

3. SEISMIC RESPONSE OF MACHINE FOUNDATIONS

3.1 Definition of seismic response of machine foundations

The seismic response of machine foundations refers to the behavior of the foundation and the machine it supports when subjected to seismic loads. In other words, it is the way the foundation and the machine to interact with the ground during an earthquake. The primary goal of studying the seismic response of machine foundations is to ensure the safe and reliable operation of machines during and after an earthquake.

3.2 Factors Affecting Seismic Response of Machine Foundations

The seismic response of a machine foundation can be influenced by several factors such as the dynamic characteristics of the foundation system, which includes its damping ratio and natural frequency. The stiffness and mass of the foundation also have a significant impact on its response to earthquakes [1,19,21].

The characteristics of the rock or soil supporting the foundation are also critical in determining its response. Soil liquefaction is a phenomenon that can occur during an earthquake and can significantly alter the response of a foundation. [1,21].

The size, shape, and orientation of the machine foundation also have a significant impact on its seismic response. Foundations that are taller or narrower than their wide are more susceptible to seismic forces. The orientation of the machine foundation can significantly impact its seismic response. Perpendicular orientation to the shaking direction may cause more damage, while parallel orientation is less likely to experience severe damage [1,39].

Other factors such as the type and intensity of the earthquake ground motion, the presence of nearby structures or geologic faults, and the level of damping in the foundation system. Proper consideration of these factors is critical to developing a comprehensive understanding of the seismic response of foundations [21].

3.3 Methods for Analyzing Seismic Response of Machine Foundations

The seismic response of machine foundations can be analyzed using different methods, which include:

3.3.1 Experimental methods: In this method, the machine foundation is subjected to scaled or actual earthquake excitations, and its response is measured using instruments such as accelerometers, strain gauges, and displacement transducers. The data obtained from the experiment are analyzed to determine the dynamic characteristics and the machine foundation response.

3.3.2 Numerical techniques: Numerical techniques such as the boundary element method (BEM) and the finite element method (FEM) and Monte Carlo simulation methods are used to simulate the dynamic response of the machine foundation under earthquake excitations. While the numerical models can be used to analyze the response of the foundation to different types of seismic excitations, including harmonic, transient, and random vibrations, there are some potential limitations to consider. One issue is the challenge of accurately modeling the boundary conditions of the foundation, such as the interaction between the foundation and surrounding soil or other structures. Artificial boundary conditions may be necessary in some cases, which can introduce some degree of uncertainty to the analysis results.

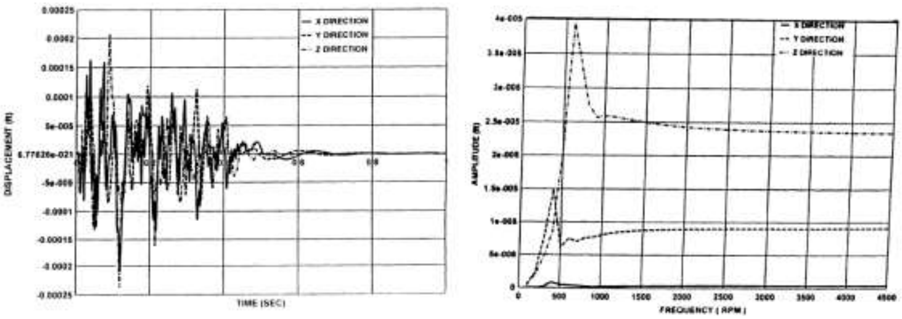
3.3.3 Mathematical methods: Mathematical methods involve the analytical solution of the equations of motion of the machine foundation under earthquake excitations. These methods are based on simplifying assumptions, such as the foundation being rigid or elastic, and can provide insight into the dynamic response of the machine foundation. Such as Calculus, Linear algebra methods, and Differential equations methods.

4. EXPERIMENTAL INVESTIGATIONS OF SEISMIC RESPONSE OF MACHINE FOUNDATIONS

Experimental investigations involve subjecting the foundation to dynamic excitation and measuring the resulting response. These studies aimed to assess the foundation’s performance and determine its dynamic characteristics.

Earlier studies such as [22] investigated the appropriate loading machine stiffness for simulating the strain development process before earthquake failure. The inelastic deformation in a test specimen relative to the loading machine corresponds to that in a spherical seismic region relative to the surrounding earth, according to the similarity condition proposed by the authors. The correct ratio between the stiffness of the machine and the specimen is determined to be 1.5 to 2.3. According to the scaling assumption, the authors' preliminary experiments with sandstone samples revealed a qualitative difference in the acoustic emission sequences, depending on whether the conditions were similar to or different from those on Earth. In the first instance, clear and systematic subsidence in acoustic emission activity was observed before the main fractures.

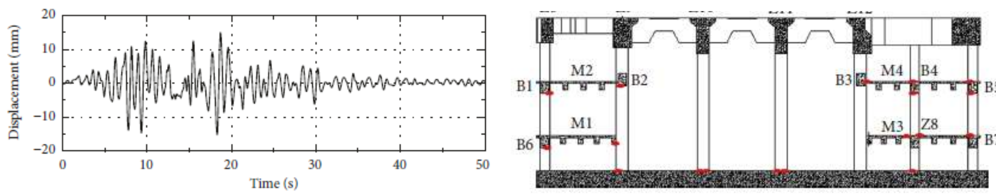
[23] conducted an experimental study on the effectiveness of a machine foundation when subjected to blast-induced excitation. The results show that the maximum response was found to be 0.0837 mm in the vertical direction, which is near the stated acceptance of 0.0762 mm. The total number of amplitudes of vibration were within satisfactory dynamic performance but may exceed the specified tolerance due to normal machine operation. It is assumed that during one period, the entire foundation vibrates by an order of two to three. But it is expected to reduce amplitudes of vibration by about 50%. Consequently, it is anticipated that the maximum vibration amplitude caused by a blast with an acceleration time history equivalent to the final design will be less than 0.0381 mm. It concluded that the seismic response of the machine foundation was within the acceptable tolerance levels and demonstrated satisfactory dynamic performance, even though the total vibration amplitudes may exceed the specified tolerance when considering the amplitudes of vibration caused by normal machine operation as shown in Figure 1.



(a) (b)

Figure 1: (a) Foundation response to blast loading and (b) The response of foundation frequency to operational loads.

[24] presented research on the seismic response of turbine-generator foundations subjected to varying horizontal earthquake loads. A 1/10-scaled model was created and tested under eight seismic waves traveling in opposite directions. In the region of elastic deformation, a magnitude 7 earthquake causes the greatest longitudinal displacement of the foundation to be 15.20 mm, and the seismic response to earthquake input varies depending on the direction as shown in Figure 2, a. The foundation remained in a fine functioning order despite the 8-magnitude earthquake, which frequently occurred. The study discovered that fractures mostly developed at the locations of beam-column joints and the range of their propagation and extension. Columns between the beams and platforms were easily damaged under longitudinal stress see figure2, b.



(a) (b)

Figure 1: (a) Displacement response curve of synthetic (longitudinal input) intensity of 7 fortifications. and (b) The foundation model shows the location of the main cracks.

[39] investigated the effect of various foundation types, including rafts, raft piles, and raft barrettes, on the dynamic response of turbo-generator frame foundations subjected to harmonic loads. Both experimental and computational analyses were conducted using SAP 2000 software. The results showed that the barrette-supported foundation had the lowest displacement and vibration at the top deck, as well as decreased spectra acceleration, stress, and base shear compared to the other foundation types. The study recommends raft barrettes subjected to dynamic loads on poor conditions of soil, as it increases the stability of the turbo-generator foundation.

5. NUMERICAL, MATHEMATICAL, AND ANALYTICAL STUDIES ON SEISMIC RESPONSE OF MACHINE FOUNDATIONS

The seismic response of machine foundations has been extensively studied using numerical, mathematical, and analytical methods. These studies have provided insights into the dynamic response of machine foundations during earthquakes and have led to the development of guidelines and design codes. The findings of these investigations played a role in developing the idea of safer and more reliable machine foundations for industrial facilities.

An investigation of the random vibrations of spinning devices exposed to seismic excitations was published in [253]. The six earthquake input components, which include the rotational components of the base excitations, lead to both inhomogeneous and parametric excitations. Earthquake ground movements were treated as non-stationary random processes. This study reveals that such a challenging issue cannot be solved using the conventional spectrum analysis of random vibrations. The six-component nonstationary earthquake ground movements were simulated using a Monte Carlo simulation utilizing the fast Fourier transform (FFT) approach, and the statistics of the spinning machinery reaction were determined. This indicated that the inherent frequencies of most rotating machines are greater than the typical frequency of earthquake ground acceleration and that the reaction of the rotating machine depends on the Power Spectral Density (PSD) model that has been selected. It recommended using more intricate rotor-bearing system models for further research, with the Monte Carlo simulation method being the most appropriate strategy.

[26] focused on the seismic analysis of high-speed rotating machinery, specifically, fan-motor systems and turbogenerators. The seismic response of high-speed rotating equipment was studied in relation to design characteristics such as bearing oil film stiffnesses and pedestal flexibilities. It discovered that the natural

frequencies of the fan-motor rotor-bearing system under study were only slightly affected by the variation in the bearing oil film stiffness caused by changes in the rotor speed. While the bearing seismic reactions were only slightly impacted, the horizontal seismic displacements were significantly impacted by the inclusion of pedestal masses and stiffness. It stated that these parameters should be taken into account in estimations of rotating machinery's seismic response after highlighting the major effects of rotary inertia and shear deformation on higher modes of vibration.

The use of active control mechanisms to reduce the seismic response of machine foundations was discussed in [25]. According to the author, low-rise structures can benefit from passive isolation devices, such as base isolators, but they only offer a partial solution to the issue. Active tendons, active mass dampers, and active base control systems were the three active control strategies examined in this study. The author concludes that the use of active control devices is more effective in reducing dynamic response compared to passive systems, especially at the beginning of the response. Furthermore, active control systems have the advantage of being able to operate under a wider range of excitation frequencies and their response is more immediate. They can be designed to activate during normal operation to reduce the transmission of vibrations to nearby structures, and in the event of a severe earthquake, they can be used to limit damage to power plants and ensure that foundation members do not suffer appreciable damage. This could ensure the immediate restoration of power following an intense earthquake and maintain the functioning of important facilities such as hospitals, fire stations, and computer laboratories.

[28] reported the use of variational techniques to build the equations of motion of a rotor finite element exposed to six components of base excitation. The equations include forcing function terms that rely on linear acceleration, rotational acceleration, and a combination of linear and rotational velocities. They also include base-rotation-dependent parametric and speed-dependent gyroscopic terms. It is observed that the parametric terms in the equations of motion can be ignored, while the rotational input terms in the forcing function are quite important and cannot be ignored. The article also notes that the use of linear interpolation functions to model the displacement field of a rotor finite element is discouraged as this model could inadvertently camouflage important dynamic characteristics, such as the instability of the system.

A flexible rotating shaft subjected to ground motion was studied by [29], who described the development of coupling linear partial differential equations of motion and investigated the influence of numerous physical factors on the response of the system. Classical and finite element methods are developed to solve these equations, and the response of the rotating machine to several that made up the El Centro earthquake was presented. It is noted that the critical speeds for a flexible machine supported on rigid "pin" supports exhibit negligible differences for forward and reverse rotation, but differ significantly when the shaft becomes flexible.

[30] examined the seismic behavior of rotating machinery in immediately seismically intended or uncontrolled constructions, as well as in independently separated and firmly attached configurations. It concluded that the higher peak acceleration response and lower peak rotor sliding displacement were produced by increasing the friction coefficient in the rotor–RBF-structure model. The peak disk response was not significantly affected by changes in the mass ratio. The peak disk responsiveness was higher with increased shaft flexibility or less bearing dampening. Instability in rotating machines in various isolated configurations was principally caused by the asymmetric stiffness parameters of fluid-film bearings. Because of the bearing speed dependence on the stiffness and damping coefficients, a rotating machine can become unstable under certain operating conditions.

[31] discussed the importance of designing proper foundations for industrial machines in areas prone to earthquakes. It highlighted the various effects of earthquakes on industrial machines and their foundations, including structural damage and misalignment. It suggested several design considerations for ensuring the stability and safety of industrial machines during earthquakes, such as proper anchorage, soil investigation, and dynamic analysis. The author concluded that designing foundations for industrial machines in earthquake-prone areas is crucial for ensuring their safe and stable operation. This research provided useful design considerations for reducing these consequences and provides significant insights into how earthquakes affect industrial **m**achinery and its foundations.

[32] focused on the seismic response of turbo generator machine foundations. The authors investigated the effects of different earthquake intensities on the foundation and analyzed the performance of the foundation during and after the earthquake. They also proposed a new design approach for the foundation to improve its seismic performance. It was concluded that the new design approach for the foundation improved its seismic performance significantly, making it more resistant to earthquake loadings.

[33] designed a concrete tabletop structure to hold two compressor units at high seismic locations. An analysis of the building was conducted considering the qualities of both cracked and uncracked concrete, and the members and connections were constructed based on the seismic requirements of ACI 318-08. Referring to table 1 the results showed that concrete cracking had a minimal effect on the machine vibration response and that measuring the machine vibration response with a fixed base boundary condition was cautious. Although concrete cracking may increase displacement amplitudes by up to 75% under seismic loads, it has

little impact on the overall seismic base shears and deck accelerations. Base shears and accelerations were not considerably affected by soil stiffness but by displacement amplitudes.

Table 1. Analysis of Machine Vibration [33].

	Horizontal - X		Horizontal - Z		Vertical - Y		Peak-to-Peak Displacement (mils)
	Frequency (cps)	Mass (%)	Frequency (cps)	Mass (%)	Frequency (cps)	Mass (%)	
Lower Bound Soil Uncracked section	3.17	74.5	2.91	63.5	4.50	90.9	0.067
Lower Bound Soil Cracked section	2.75	66.0	2.53	55.6	4.42	86.6	0.072
Upper Bound Soil Uncracked section	3.91	53.0	3.59	42.6	8.51	76.1	0.071
Upper Bound Soil Cracked section	3.14	49.2	2.88	38.3	8.17	69.7	0.073
Fixed Base Uncracked section	4.33	87.1	3.97	64.7	22.4 23.5 26.8	24.8 11.7 20.6	0.08
Fixed Base Cracked section	3.34	88.0	3.06	64.8	14.9 18.8 20.1	12.7 11.6 13.2	0.09

A comparison of various modeling approaches for earthquake evaluation of large turbine-generator sets (electric power plants in the range of 250 Mega Watt (MW) to 350MW) and their basis was presented in [32]. The findings demonstrate that assuming that the dynamic properties of the system are adequately represented, a simplified method employing a lumped mass model is sufficient for the seismic analysis of systems and their foundations. Most actual applications do not require the deployment of intricate finite element models. The study also emphasized the importance of considering soil-structure interaction when analyzing the foundations of big turbine-generator systems for seismic activity.

[35] presented an efficient technique for constructing foundations in high seismic locations that incorporated the use of finite element modeling software and modal analysis to validate vibration performance standards. A case study on the foundation of a steam turbine generator was provided to assist engineers in understanding the benefits and outcomes of various modeling approaches. This conclusion highlights the need to consider site circumstances when constructing foundations in high seismic zones and recommends employing deep pile foundations in areas where it is feasible for soil layers to liquefy. Additionally, it recommended using SAP 2000 for both static and dynamic analyses and for modeling piles using a matrix of spring stiffness constants. An investigation of forced vibrations can confirm the operation-related behavior of a foundation. The equivalent lateral force technique required by the California Building Code was verified through spectrum analysis.

[36] investigated the impact of earthquake parameters on the analysis of the turbo-generator foundations. It utilized the (FEM) to simulate the dynamic behavior of the foundation under various seismic parameters. The study found that the seismic parameters had a major effect on the dynamic behavior of the foundation, with peak ground acceleration having the greatest influence. According to the results of the response spectrum analysis, approximately 50% of the horizontal frequency decreased, the amplitude of the horizontal amplitude increased by approximately two times that of the fixed support component, and the overall horizontal deflection decreased. The vertical frequency was only slightly affected by changing the column support conditions from fixed to pinned.

The dynamic response of an industrial structure under various dynamic loads was investigated by [35] in a study conducted using (FEM) to simulate the response of the structure. To evaluate the effects of various factors on the dynamic response, a parametric analysis was performed. The main findings of the study revealed that the amplitude and frequency significantly influenced the dynamic response of the structure. It was concluded that the need to construct buildings to withstand and disperse blast loads is emphasized. This necessitates the utilization of substantial structural parts, which may increase expenses. However, adding holes to walls and roofs makes it possible to effectively dissipate blast energy and improve safety. Local failures, such as those in purlins, are permissible, but failure of crucial components, such as the main truss and reinforced concrete (RC) frame, can lead to structural failure as a whole. The aim was to minimize stress by providing a broad surface area to resist blast pressure because blast loads cannot be lowered. To accomplish this, shear walls can be integrated alongside the current columns.

[38] conducted a study on the dynamic analysis of a single-cylinder compressor block foundation using two software programs, SAP: 2000 and VS. 16. It was suggested to take the whole structure into account and

use spring elements in place of the soil and piles. To account for uncertainties, a minimum range of soil parameters must be considered because geotechnical parameters have a significant impact on the accuracy of dynamic analysis. Resonance may not always be avoided by increasing the mass ratio of the foundation system, but the vibration amplitudes can be decreased by increasing the soil impedance. Site-specific seismic and dynamic requirements must be considered when designing dynamic equipment foundations in seismically active areas. According to the study, models for static and dynamic analyses can be developed using finite element analysis and SAP 2000. It is suggested that the machine speed should be increased during frequency overlapping to reduce transient resonance conditions.

6. CONCLUSION AND FUTURE RESEARCH

6.1 Summary of the key findings and Contributions of the review paper

The key findings and contributions of the review paper can be summarized as follows:

1. The review paper highlights the importance of seismic hazard assessment in the design of machine foundations to ensure the safety and performance of the machine under earthquake loading.
2. The paper presents a summary of the various seismic hazard assessment techniques used in machine foundation design, including deterministic, probabilistic, and time history analysis.
3. The paper presents case studies and experimental simulations that demonstrate the effectiveness of seismic hazard assessment techniques in designing machine foundations.
4. The review paper also identifies the limitations and challenges associated with seismic hazard assessment, including uncertainties in ground motion prediction, effects of soil-structure interaction, and the complexity of the analysis.
5. The paper suggests future research directions, for instance, the improvement of ground motion simulations, the use of advanced numerical simulations, and the incorporation of machine-foundation-soil interaction effects in the analysis.

6.2 The Lack and Limitations Identified in The Existing Literature

Based on the references provided, the lack and limitations identified in the existing literature of the current review paper are:

1. Limited focus on specific types of machine foundations: Most of the reviewed literature focused on a particular type of machine foundation such as turbine-generator foundations, compressor foundations, and single-cylinder compressor block foundations. There is a need for more studies that consider other types of machine foundations to provide a more comprehensive understanding of seismic hazard assessment in machine foundation design.
2. Lack of consideration for site-specific conditions: The reviewed literature did not consider the specific site conditions and soil properties, which can significantly affect the seismic response of machine foundations. Further studies should consider site-specific conditions to provide more accurate seismic hazard assessments in machine foundation design.
3. Limited investigation of nonlinear behavior: Most of the reviewed literature focused on linear analysis, which may not accurately capture the nonlinear response of machine foundations under earthquake excitations. There is a need for more studies that investigate the nonlinear response of machine foundations to provide more realistic seismic hazard assessments.
4. Limited consideration of uncertainties: The reviewed literature did not comprise uncertainties in seismic hazard assessment, which can affect the reliability of machine foundation design. Further studies should consider uncertainties in seismic hazard assessment to provide more reliable and significant machine foundation designs. For instance, Probabilistic Seismic Hazard Analysis (PSHA), Ground Motion Prediction Equations (GMPEs), and Data Analysis and Validation.
5. Limited investigation of the effects of adjacent structures: Most of the reviewed literature does not consider the effects of machine foundation response on adjacent structures. However, the presence of nearby structures can significantly affect the seismic response of machine foundations. Further studies should investigate the effects of adjacent structures on machine foundation response to provide more accurate seismic hazard assessments in machine foundation design.

6.3 Suggestions for Future Research Directions

The following suggestions for future research directions can be made based on the references provided:

- Investigate the seismic response of machine foundations subjected to various intensities of earthquake loads in various directions to evaluate their performance under different ground motions. This can be done through experimental and numerical studies.

- Study the impact of soil-structure interaction on machine foundations, particularly in high seismic zones, to better understand the response of the foundation and improve its design.
- To better understand the complex behavior of these systems, evaluate the dynamic response of the turbine generator and the foundations, taking into account all interactions between the facility, structure, and soil.
- Conduct parametric studies on industrial structures for various dynamic loads to optimize their design and improve their performance under seismic and other dynamic loads.
- Develop new analytical models such as (Empirical Models, Numerical Finite Element (FE) Models, and design guidelines for machine foundations subjected to blast-induced excitation.
- Research the seismic response of rotating machines**, structures, and R**FBI systems to understand how the machine interacts with its foundation.
- Study the effect of various modeling approaches on the seismic analysis of substantial turbine-generator systems and their foundations to determine the most accurate and efficient modeling techniques.
- Investigate the effects of seismic parameters used in the analysis of the foundation. To better understand the response of the foundation of a turbo-generator to various seismic loads.
- Develop new design guidelines for machine foundations subjected to torsional loads to improve their performance under these loads.
- Investigate the dynamic response of a single-cylinder compressor block foundation using numerical and experimental techniques to improve its design and performance.
- Investigate the earthquake rocking response of rigid bodies to develop more accurate design guidelines for machine foundations.
- Study the effect of the geometric design of the machine foundation, Energy of seismic waves transported to the machine.

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7. REFERENCES

[1] Bhatia KG. Foundations for industrial machines and earthquake effects. ISET Journal of Earthquake Technology, Paper. 2008 Mar(495):1-2.
[2] IAEA.. PROBABILISTIC SAFETY ASSESSMENT FOR SEISMIC EVENTS. International Atomic Energy Agency; 2021.
[3] Saied M, Al-Busoda B. Behaviour of machine foundation resting on collapsible soil. International Conference on Earthquake Geotechnical Engineering from Case Histories to Practice, Istanbul, Turkey.
[4] Chuang TY, Wells JE, Johnson JJ. Seismic risk assessment of a BWR: 1985,status report.
[5] Katsanos EI, Thöns S, Georgakis CT. Wind turbines and seismic hazard: a state-of-the-art review. Wind Energy. 2016 Nov;19(11):2113-33.
[6] Yamaguchi A, Nakamura S. Revision of the AESJ Standard for Seismic Probabilistic Risk Assessment (3) Fragility Evaluation. PSAM,2014.
[7] Zhang J, Yang F, Liang C, Zhang Y, Li Y. An SVDD-based post-processing approach for vibration risk assessment of the hydro-turbine-generator in a large hydropower station. Journal of Low Frequency Noise, Vibration and Active Control. 2021 Sep;40(3):1309-34.
[8] Jia J, Jia. Soil dynamics and foundation modeling. Switzerland: Springer; 2018.
[9] Gupta ID. The state of the art in seismic hazard analysis. ISET J Earthq Technol. 2002 Dec;39(4):311-46.
[10] McGuire RK. Probabilistic seismic hazard analysis and design earthquakes: closing the loop. Bulletin of the Seismological Society of America. 1995 Oct 1;85(5):1275-84.
[11] Al-Taie AJ, Albusoda BS. Earthquake hazard on Iraqi soil: Halabjah earthquake as a case study. Geodesy and Geodynamics. 2019; 10 (3):196-204.
[12] Armstrong RJ, Boulanger RW, Beaty MH. Equivalent static analysis of piled bridge abutments affected by earthquake-induced liquefaction. Journal of Geotechnical and Geoenvironmental Engineering. 2014 Aug 1;140(8):04014046.
[13] Park GJ. Technical overview of the equivalent static loads method for non-linear static response structural optimization. Structural and Multidisciplinary Optimization. 2011 Mar;43:319-37.
[14] Kiureghian AD. A response spectrum method for random vibration analysis of MDF systems. Earthquake Engineering & Structural Dynamics. 1981;9(5):419-35.
[15] Beer M, Kougioumtzoglou IA, Patelli E, Au SK, editors. Encyclopedia of earthquake engineering. Berlin/Heidelberg, Germany: Springer; 2015.
[16] McGuire RK. Probabilistic seismic hazard analysis: Early history. Earthquake Engineering & Structural Dynamics. 2008 Mar;37(3):329-38.
[17] Ellingwood BR. Earthquake risk assessment of building structures. Reliability Engineering & System Safety. 2001 Dec 1;74(3):251-62.

[18] Bommer JJ, Douglas J, Scherbaum F, Cotton F, Bungum H, Fah D. On the selection of ground-motion prediction equations for seismic hazard analysis. Seismological Research Letters. 2010 Sep 1;81(5):783-93.
[19] Bounds WL, Louis FG, Sheikh AH, Brant WD, Moll J, Smalley AJ, Fang SJ, Pearce IW, Smith PA, Harsh S, Rossi A. Foundations for Dynamic Equipment, 2004.
[20] Yang Y, Bashir M, Li C, Wang J. Analysis of seismic behaviour of an offshore wind turbine with a flexible foundation. Ocean Engineering. 2019 Apr 15;178:215-28.
[21] Kikuchi M, McNally K, Tittmann BR. Machine stiffness appropriate for experimental simulation of earthquake processes. Geophysical Research Letters. 1981 Apr;8(4):321-3.
[22] El Naggar MH. Evaluation of performance of machine foundation under blast-induced excitation. WIT Transactions on The Built Environment. 2000 Jun 29;48
[23] An D, Qu TJ. Seismic behavior of turbine-generator foundation under strong earthquake action in different directions. Advances in Civil Engineering. 2018;2018:1-0.
[24] Samali B, Kim KB, Yang JN. Random vibration of rotating machines under earthquake excitations. Journal of Engineering Mechanics. 1986 Jun;112(6):550-65.
[25] Rao CK, Mirza S. Seismic analysis of high-speed rotating machinery. Nuclear engineering and design. 1989 Feb 2;111(3):395-402.
[26] Pantelides CP. Control of Seismic Response of Structures. InSecond International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics (1991: March 11-15; St. Louis, Missouri) 1991. Missouri S&T (formerly the University of Missouri--Rolla).
[27] Suarez LE, Singh MP, Rohanimanesh MS. Seismic response of rotating machines. Earthquake engineering & structural dynamics. 1992;21(1):21-36.
[28] Su WC, Henried AG. Seismic response of flexible rotating machines. In7th Canadian Conference on Earthquake Engineering 1995 (pp. 229-236).
[29] Su WC, Hernried AG, Yim SC. Seismic response of rotating machines–structure–RFBI systems. Earthquake engineering & structural dynamics. 2000 Feb;29(2):213-40.
[30] Bhatia KG. Foundations for industrial machines and earthquake effects. ISET Journal of Earthquake Technology, Paper. 2008 Mar(495):1-2).
[31] Fleischer PS, Trombik PG. Turbo generator machine foundations subjected to earthquake loadings. InThe 14th World Conference on Earthquake Engineering, Beijing, China 2008 Oct.
[32] Jan SF, Wu SC. Dynamic analysis and design of large compressor foundations in high seismic zone. InStructures Congress 2010 2010 (pp. 2702-2713).
[33] Vicencio F, Cruz EF, Valdivia D. Evaluation of different modeling options for seismic analysis of large turbine-generator systems and their foundation. InFifteenth World Conference on Earthquake Engineering 2012.
[34] Liu Z. Design of foundations for large dynamic equipment in a high seismic region. InStructures Congress 2013: Bridging Your Passion with Your Profession 2013 (pp. 1403-1414).
[35] Thakare AU, Rangari SM. Effect of Seismic Parameters on Analysis of Turbo-Generator Foundation. International Journal of Engineering Research & Technology. 2015 May;4(05).
[36] Ramesh S, Kumar VV. Parametric Study on an Industrial Structure for Various Dynamic Loads. IJRET: International Journal of Research in Engineering and Technology. 2015, eISSN.:2319-1163.
[37] Tank YR, Tank AR, Dhameliya HK. Dynamic Analysis of Single Cylinder Compressor Block Foundation using SAP: 2000 VS. 16. International Journal of Engineering and Technology (IJETT), 2016, ISSN.:2231-5381).
[38] Tripathy S, Desai AK. Investigation of dynamic behaviour for turbo generator frame foundation through experimental and computational approach. International Journal of Geotechnical Engineering. 2017 Oct 20;11(5):513-23.
[39] Paulay T, Priestley MN. Seismic design of reinforced concrete and masonry buildings. New York: Wiley; 1992 Mar.