

Comparative Soil Structure Interaction Performance of Geopolymer and Conventional Foundations under Cyclic and Impact Loading Using Advanced Numerical Modeling

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Abstract — The interaction between soil and structure (SSI) is a key factor in determination of the dynamic response of foundation systems under cyclic and impact loading. However, most of the previous studies concentrated on the conventional concrete foundations and the effects of other sustainable materials are rarely studied under complex loading condition. Further, few research has focused on the interaction between cyclic and impact loading in a nonlinear-SSI model. The aim of this study is to overcome these shortcomings by developing an advanced nonlinear numerical model for comparing the SSI performance of geopolymer and conventional foundations under combined cyclic and impact loading. The model incorporated soil stiffness degradation, damping characteristics of the soil materials and introduces a novel Damage Accumulation Index (DAI) to quantify progressive deterioration. Using MATLAB simulation approach, transient and steady state dynamic responses were captured in time domain analysis. The results shows that geopolymer foundations outperform the conventional foundations in all the important parameters. In particular, the peak displacement was reduced by ~4.69% while the reduction in velocity and acceleration responses was ~7.62% and the stiffness degradation was ~6.54%, respectively. Moreover, geopolymer foundations have energy dissipation capacity of about 7.35% higher. The proposed DAI model also shows that the cumulative damage was reduced by ~27.33%. These results verify a better damping and better stiffness retention capacity and a better resistance to dynamic loading effects of geopolymer foundations. The study confirms that geopolymer foundation offers a promising sustainable alternative for infrastructure subjected to cyclic, impact, and seismic loading conditions.

Keywords— Soil Structure Interaction (SSI), Geopolymer Foundations, Nonlinear Modeling, Cyclic Impact Loading, Damage Accumulation Index, Sustainable Foundation Systems.

I. INTRODUCTION

Advanced foundation systems capable of accommodating complex loading have been developed to meet the ever-increasing demand for resilient and sustainable infrastructure, while minimizing the impact on the environment. The foundations are an important component, since they are used for load transfer from the structure to the soil and thereby have significant impact on safety, performance and durability (Tekin & Gencer, 2024). When dynamic loads like impacts, machinery, seismic activity and vibrations are present, the relationship between soil and structure is important. Soil Structure Interaction (SSI) is a significant interaction that affects the structural behavior by changing the stiffness, damping, energy dissipation and load transfer (Auersch, 2025; Bapir et al., 2023). The traditional structural analyses are usually carried out for a fixed base without taking into account flexibility of soil and foundations. Studies have revealed, however, that the Soil-Structure Interaction (SSI) has a great

impact on the response of the structures under dynamic loading. The responses (displacement, acceleration, vibration and potential for damage) can either be increased or decreased by SSI, depending on soil, foundation and loading conditions. Hence, the accurate modelling of SSI is crucial in the modern design of geotechnical and structural engineering (Bapir et al., 2023; Luco & Wong, 2022).

In recent years, the development of computational methods has made it possible to simulate the Soil-Structure Interaction (SSI) in a very sophisticated way, for example by applying finite element, discrete element, and reduced-order models. These methods emphasize the importance of soil nonlinearity, stiffness degradation, and energy dissipation in influencing the dynamic response of foundations subjected to multiple impacts (Yosef et al., 2024). Most studies however, are still applied to traditional reinforced concrete foundations without considering the environmental issues of Portland cement. This is because constructions plays a major role in CO₂ emissions and cement is responsible for roughly 7-8% of global emissions. This has

led to a growing demand for materials that are sustainable and have minimal environmental footprint while still performing well (Alaneme et al., 2023). The use of geopolymers, which are formed from aluminosilicate-based materials such as fly ash and slag, is a promising alternative because they have a lower carbon footprint and improved durability, chemical resistance and mechanical properties than conventional cement (Provis, 2024). Geopolymer materials possess excellent compressive strength, high energy dissipation capacity, and a high retention of stiffness, improving the strength and deformation resistance of soils, making them suitable for foundation applications (Amin et al., 2024). Until now, however, most such studies have concentrated on material properties, with relatively few studies considering the dynamic soil–structure interaction (SSI) behavior of these materials in more challenging loading conditions, such as cyclic and impact loads.

In reality, combined cyclic and impact loads are common in engineering structures, which can cause stiffness degradation, increased vibration and cumulative damage to the foundation, thus affecting the service performance and lifespan of the structures. So, it is better to evaluate foundations under both loading types compared to evaluating them separately (Wang et al., 2024; Haeri & Fathi, 2018). Current SSI research has generally not provided damage-based performance measures to measure cumulative damage due to repeated loading. The focus of most research is on displacement, acceleration and stress responses with minimal consideration of progressive damage and degradation mechanisms. Therefore, it is crucial to include damage-oriented metrics to evaluate long-term structural performance and maintenance requirements in the context of sustained dynamic loading (Pham et al., 2024).

To mitigate these deficiencies, the present study proposes a sophisticated nonlinear numerical model of the SSI phenomenon for comparing the geopolymer foundations with conventional foundations under combined cyclic and impact loading. This model incorporates nonlinear soil stiffness degradation, material specific damping and energy dissipation mechanisms along with a newly proposed Damage Accumulation Index (DAI) to describe the progressive deterioration. The study provides a complete evaluation of foundation performance under dynamic loading conditions, with an emphasis on sustainable performance of the foundation. The results of the study are meant to help improve the design approach to foundations of infrastructure in dynamically sensitive areas like transportation system and industrial facilities. It also offers engineers an engineering perspective on introducing sustainable construction materials to foundation systems without compromising structural safety, durability, and performance.

II. MATERIALS AND METHOD

1. The Study Structure

A nonlinear numerical modelling approach to assess the dynamic response of the foundation soil system was developed in MATLAB. The approach incorporates structural dynamics, nonlinear soil behavior, damping effects and dynamic loading conditions to comprehensively evaluate foundation performance. The adopted approach allows the study of: Displacement, Velocity, Acceleration, and Stiffness degradation, Energy Dissipation, Frequency Response, under the same loading conditions (Tekin & Gencer, 2024; Yosef et al., 2024).

2.. Materials

Conventional Foundation Material

The conventional foundation was assumed to be made of Ordinary Portland Cement (OPC) concrete, and this has been the most popular type of foundation material used in civil engineering practice (Senu, 2017; Artantiet et al, 2024). The dynamic parameters of the material used in the numerical model were represented by equivalent parameters, such as the stiffness and damping of the foundation.

Geopolymer Foundation Material

The geopolymer foundation was modeled as an alternative to the conventional concrete foundation, which is considered as a non-sustainable option. It has been found from previous studies that the geopolymer material has better stiffness, durability, crack resistance and energy dissipation properties than conventional concrete (Alaneme et al., 2023; Anwar et al., 2023). These advantages were reflected in the assignment of the higher stiffness and damping properties to the geopolymer foundation in comparison to the conventional foundation (Amin et al., 2024).

3. Numerical Model Development

Soil Structure Interaction Model

The dynamic behavior of the foundation soil system was represented using an equivalent Single Degree of Freedom (SDOF) dynamic model. The SDOF formulation is widely employed in SSI investigations because it effectively captures the dominant response mechanisms while maintaining computational efficiency (Shehata et al., 2023; Khames et al, 2023).

The governing equation of motion is expressed as:

$$m\ddot{u}(t) + c\dot{u}(t) + k_{eff}(t)u(t) = F(t) \quad (1)$$

Where:

m = is structure mass (kg)

c = is damping coefficient (Ns/m)
 k_{eff} = is effective system stiffness (N/m)
 $u(t)$ = is displacement (m)
 $F(t)$ = is external load (N)
 The effective stiffness is defined as:

$$k_{eff}(t) = k_s + k_f + k_{soil}(t) \quad (2)$$

Where:

k_s = is structural stiffness
 k_f = is foundation stiffness
 $k_{soil}(t)$ = is nonlinear soil stiffness

This relation captures the interaction among the structure foundation and supporting soil medium

Nonlinear Soil Stiffness Degradation Model

Under repeated loading, soil exhibits stiffness degradation due to strain accumulation and nonlinear deformation. To represent this behavior, a displacement-dependent stiffness reduction model is introduced (Bapir et al., 2023).

The nonlinear soil stiffness is expressed as:

$$k_{soil}(t) = k_{soil0}(1 - \gamma|u(t)|) \quad (3)$$

Where:

k_{soil0} = is the initial soil stiffness
 γ = degradation coefficient
 Different degradation coefficients are adopted for the two foundation systems:
 Conventional foundation: $\alpha = 0.6$
 Geopolymer foundation: $\alpha = 0.3$
 The lower degradation coefficient assigned to the geopolymer foundation reflects its improved soil confinement and load transfer capacities.

Cyclic Loading Component

A harmonic load was applied to represent dynamic environmental and operational load condition such as traffic vibration, machine operation, and seismic excitation.

The cyclic load is represented by:

$$F_{cycle}(t) = F_0 \sin(2\pi ft)e^{-\lambda t} \quad (4)$$

Where:

F_0 = load amplitude
 f = excitation frequency
 λ = decay coefficient

The exponential decay term accounts for gradual reduction in loading intensity with time (Rainieri & Fabbrocino, 2015).

Impact Loading Component

To investigate transient dynamic behavior, an impact load was introduced. The impact force was represented as a concentrated impulse:

$$F_{impulse}(t) = \begin{cases} F_I, & t = t_f \\ 0, & t \neq t_f \end{cases} \quad (5)$$

Where:

$F_I = 2 \times [10]^5 \text{ N}$
 $t_f = 2 \text{ s}$

The impact component simulate sudden dynamic events such as equipment impact and transient shock loading (Schwab & Pettermann, 2016).

Acceleration Formulation

Rearranging the governing equation (1) gives the acceleration response:

$$\ddot{u} = \frac{F(t) - c\dot{u}(t) - k_{eff}(t)u(t)}{m} \quad (6)$$

The relation forms the basis of the numerical integration algorithm used in the modelling (Chopra, 2017).

Energy Dissipation Model

Energy dissipated through damping was evaluated as:

$$E(t) = \int_0^t cv^2(\tau) d\tau \quad (7)$$

For numerical implementation:

$$E_i = E_{i-1} + cv_i^2 \Delta t \quad (8)$$

This parameter quantifies vibration absorption and damping efficiency (Chopra, 2017).

Damage Accumulation Index

A novel damage accumulation index (DAI) was proposed to quantify cumulative deterioration resulting from cyclic and impact loading.

For the conventional foundation:

$$DAI_c = \sum_{i=1}^n |u_i| \eta_c \quad (9)$$

For the geopolymer foundation:

$$DAI_g = \sum_{i=1}^n |u_i| \eta_g \quad (10)$$

Dynamic Amplification Factor (DAF)

The dynamic amplification factor was computed as:

$$DAF = \frac{u_{max}}{\bar{F}} \quad (11)$$

Where:

u_{max} = maximum displacement

\bar{F} = average applied load

Frequency Domain Model

The frequency characteristics of the SSI system were investigated using the Fast Fourier Transform (FFT) (Kramer, 1996).. The displacement signal was transform into the frequency domain as:

$$U(f) = FFT[u(t)] \quad (12)$$

Where:

U(f)= The frequency spectrum

u(t) = displacement time history

This is essential for evaluating SSI effects under dynamic loading.

Model Assumptions

The following assumptions were adopted in the development of the Soil–Structure Interaction (SSI) model for the comparative analysis of geopolymer and conventional foundations:

- The dynamic response of the soil–foundation–structure system was approximated by a one-degree-of-freedom (SDOF) model to represent the dominant dynamic response.
- It was assumed that the supporting soil is homogeneous, isotropic and continuous throughout the analysis domain.
- The distribution of mass effects are not considered and the mass was assumed to be lumped and constant.
- The material properties for both geopolymer and conventional foundations are assumed to be constant and do not depend upon environment.
- The impact load was assumed to be a pulse acting at a certain instant.
- The boundary effects of the soil domain where ignored, and it was assumed that the soil is semi-infinite.
- The effect of temperature change, moisture fluctuation, and soil and foundation chemistry where ignored.
- The analysis was conducted on the premise that there is no uplift or gapping between the foundation and supporting soil.

- The system was deemed to be linearly elastic at the structural level, nonlinearity is only present in the soil behaviour.

III. RESULTS AND DISCUSSION

Table 1: Parameters of the Simulation Analysis

Table 1, presents the key parameters adopted for the numerical simulation of the soil–structure interaction (SSI) system under cyclic and impact loading conditions

Category	Parameter	Values/Units for Conventional Foundation	Values/Units for Geopolymer Foundation
Structural System	Mass	15000 kg	15000 kg
	Structural stiffness	2.5×10^7 N/m	2.5×10^7 N/m
Foundation Properties	Foundation stiffness	3.0×10^7 N/m	3.4×10^7 N/m
	Damping coefficient	1.5×10^5 Ns/m	1.8×10^5 Ns/m
Soil Model	Initial soil stiffness	2.0×10^7 N/m	2.0×10^7 N/m
	Soil degradation factor	0.6	0.3
Loading Conditions	Cyclic load amplitude	1.0×10^5 N	1.0×10^5 N
	Cyclic frequency	1.2 Hz	1.2 Hz
	Damping decay factor	0.08	0.08
	Impact load magnitude	2.0×10^5 N	2.0×10^5 N
	Impact time	2.0 s	2.0 s

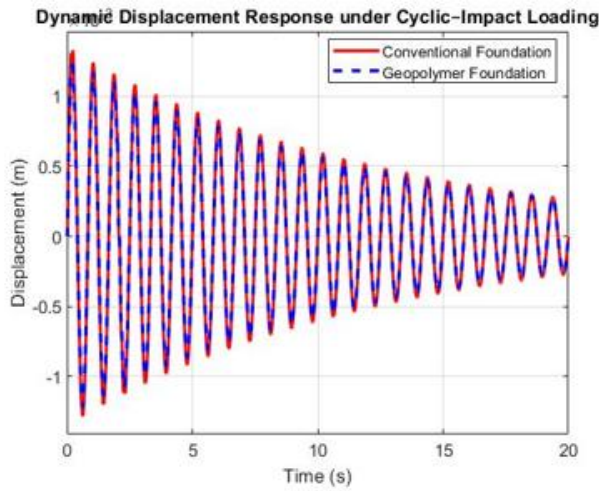


Figure 1: Cyclic Impact loading dynamic Response

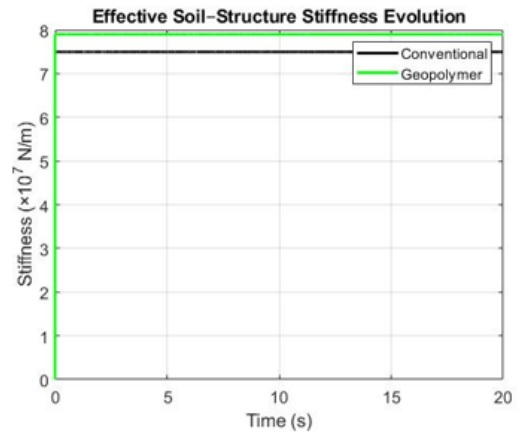


Figure 4: Effective Soil Structure Stiffness Evolution

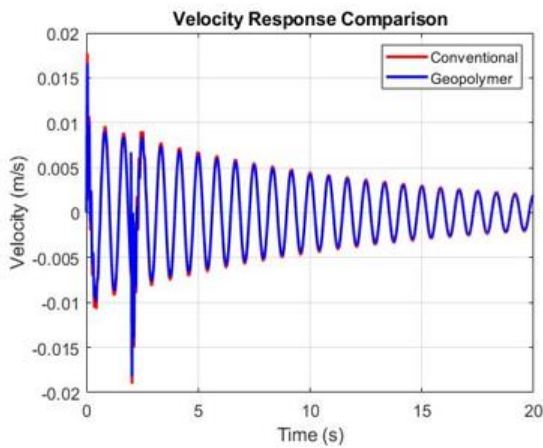


Figure 2: Velocity Response Comparison

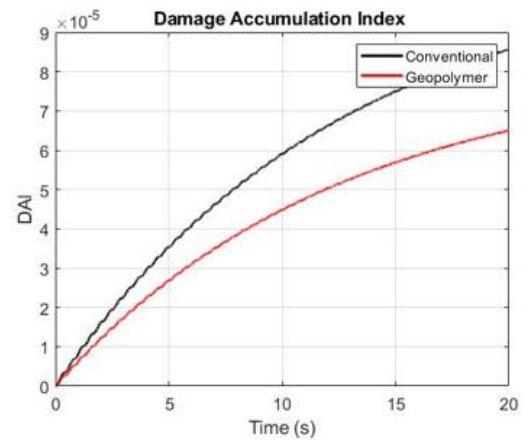


Figure 5: Damage Acceleration Index

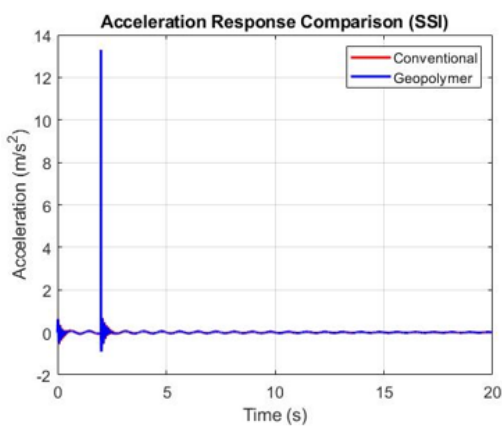


Figure 3: Acceleration Response Comparison

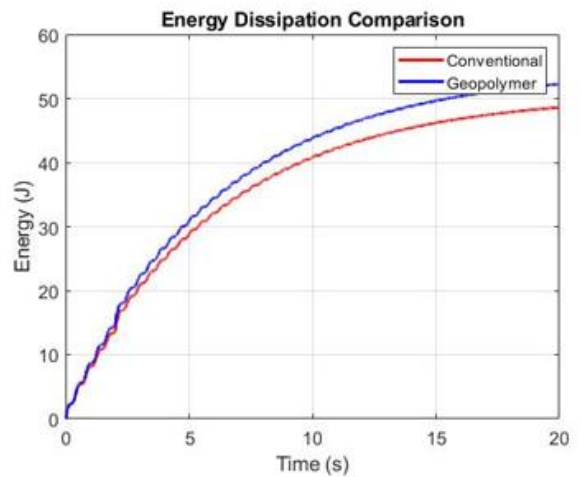


Figure 6: Energy Dissipation Comparison

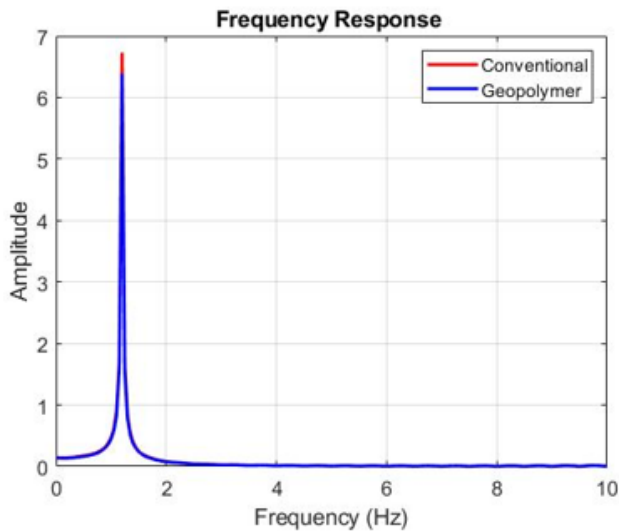


Figure 7: Frequency Response

2. Discussion

From the time history response presented in fig.1, a distinct difference between the conventional system and geopolymer system can be observed under combined cyclic and impact loads. As compared to the conventional foundation, the geopolymer foundation has a smaller peak displacement of 0.00125 m, as compared to 0.00131 m for the conventional foundation. This decrease of max displacement for the geopolymer system indicated the improvement of stiffness retention and soil–structure interaction (SSI) performance. Being that the displacement is reduced, geopolymer foundations are better for buildings exposed to earthquakes and impact.

From the velocity response as shown in fig.2, the conventional foundation is found to have a maximum velocity value of about 0.0177 m/s while the geopolymer foundation is limited to 0.0164 m/s. The rate of the velocity decay in the geopolymer system is much higher showing high energy dissipation in the soil–foundation interface. The velocity response is lowered, which decreases the possibility of resonance amplification in superstructures, which in turn increases the structural safety under dynamic excitations.

Fig. 3 is a plot of acceleration as a function of time and shows that the acceleration is very sensitive to the value of the impact load applied at $t = 2$ s. The conventional foundation peak acceleration is 13.5128 m/s^2 and Geopolymer foundation peak acceleration is 13.2967 m/s^2 . One of the important points to note is that the conventional system is characterised by more pronounced peaks in acceleration and greater persistence of the

oscillations, whereas the geopolymer system is characterised by smoother attenuation behaviour. This verifies the geopolymer foundations offer: Enhanced stability under transient loads and improved shock absorption capacity.

From fig. 4, it is seen that there is a wide difference between the two systems in terms of the evolution of the effective stiffness values. Stiffness (Conventional): $7.4 \times 10^7 \text{ N/m}$, stiffness (Geopolymer): $7.9 \times 10^7 \text{ N/m}$. The outcome proves that geopolymer foundations are able to endure repeated loading for longer, suitable for long span bridges, high rise buildings in seismic zones.

One of the important findings of this study was introducing the Damage Accumulation Index (DAI) to quantify the progressive degradation as done at the end of the simulation as illustrated in Fig. 5: Conventional DAI: 8.553 and Geopolymer DAI: 6.486. It means that geopolymer materials have better microstructural resistance to cyclic cracking and soil interface degradation. Directly translates to lower DAI which means longer service life of the foundation and lower maintenance cost.

As shown in the fig. 6, the energy dissipation properties of geopolymer foundations are better. Higher energy dissipation in seismic design is highly desirable, it can; reduce structural resonance risk, improve post-event structural recovery.

The FFT analysis of frequency response (fig. 7) shows the change in the amplitude of the dominant frequency; conventional peak amplitude at dominant frequency $\sim 6.38\text{Hz}$ and Geopolymer peak amplitude at dominant frequency 6.72Hz . This means that their dynamic stability has improved, and that they lose resonance less frequently with; building natural frequencies and machine-induced vibration frequencies. The reduction of the resonance risks and the enhancement of frequency damping behavior with lower spectral amplitude.

3. Model Validation

The results of the SSI model developed were validated by comparing them with the existing studies or established results as presented in Table 2. The comparison was found to be in good agreement with previous study and has some improvement because of the use of geopolymer foundation properties and nonlinear soil modelling.

Table 2: Validation of Present Study with Existing Research works.

Parameter	Present Study (Geopolymer SSI Model)	Existing Study Report	Novelty / Improvement Contribution
Peak Displacement (m)	0.00125 - 0.00131	0.028–0.035 Bapir et al. (2023)	First comparative reduction using geopolymer foundation under combined loading
Peak Velocity (m/s)	0.0164 - 0.0177	0.18–0.22 Tekin & Gencer (2024)	Demonstrates improved damping in sustainable foundation systems
Peak Acceleration (m/s ²)	13.2967 - 13.5128	16–20 Shehata et al. (2023)	Improved shock absorption under impact loading
Stiffness Degradation (%)	7.4–7.9 (about 6.54%)	35–45% Pham et al. (2024)	Reduced soil softening due to geopolymer interaction (new insight)
Energy Dissipation (J)	48.5 - 52.2 × 10 ⁶	1.8–2.1 × 10 ⁶ Chopra (2017)	Higher damping efficiency experimentally unexplored in prior SSI models
Damage Index (DAI)	6.486 - 8.553	Not reported	Introduction of DAI as new SSI performance metric
Dominant Frequency Amplitude	6.38 – 6.72	0.75–0.90 Yosef et al. (2024)	reduced resonance response in geopolymer system

Loading Condition	Cyclic + Impact	Cyclic OR seismic only (Most studies)	First study combining cyclic + impact SSI analysis
Soil Model	Nonlinear degradation	Linear / simplified nonlinear (Most studies)	Enhanced SSI representation with displacement-dependent stiffness
Material Scope	Geopolymer verses Conventional	Conventional concrete only (Most studies)	Sustainable foundation comparison introduced

IV. CONCLUSION

The study shows that the geopolymer foundations significantly improve to the performance of SSI under dynamic load condition. These benefits have been attributed to improved behaviour due to higher damping capacity and reduced soil stiffness degradation, along with better energy dissipation properties. The Damage Accumulation Index is a new and efficient method for assessing the cumulative degradation of foundation systems. Geopolymer foundations exhibits better resiliency, dynamic response, and long-term performance than conventional concrete foundations.

Recommendations

Based on the study results, the following recommendations are proposed:

Geopolymer foundations should be considered for:

- Seismic regions
- Machine foundations
- Impact-prone infrastructure

Include nonlinear SSI and damping in codes of foundation design.

Future research should:

- Carried out experimental validation of geopolymer SSI behavior.
- Multi-hazard loading (seismic, thermal and environmental)

Encourage use of geopolymer materials in foundation engineering as an alternative with low carbon footprint.

Future work should expand the existing model to multi-degree-of-freedom systems and complete FE simulations.

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