

Investigation of the effect of energy piles on the seismic response of RC high-rise building with piled raft foundation

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Abstract. Energy piles are green foundations that utilize the ground as a heat source or reservoir to provide renewable energy for buildings. However, the thermal cycles induced by energy piles may affect their structural behavior and interaction with the soil under seismic loading. This paper presents the first comprehensive study of the seismic performance of a high-rise building (HRB) on energy piled raft foundation using numerical modeling and simulation. A three-dimensional finite element model of a 15-story building with energy piles is developed and subjected to four different earthquake scenarios. The results show that the energy piles can reduce the seismic demand of the building in the cooling cycle, but they also increase the soil-structure interaction and pile-soil-pile interaction effects in the heating cycle. This paper also provides some insights for improving the seismic performance of high-rise buildings (HRBs) on energy piled raft foundations by using tuned mass dampers (TMDs) which can contribute to reducing the seismic response of the HRB when the soil is heated in the exchange of heat between the piles and the soil in the hot season.

Keywords: energy piles; high-rise building (HRB); numerical modeling; raft foundation; reinforced concrete (RC); seismic mitigation; seismic response; soil-pile-structure interaction; tuned mass damper (TMD)

1. Introduction

Energy piles are a type of green foundation that uses the ground as a heat source or storage to provide renewable energy for buildings. They are structural piles that also serve as ground heat exchangers by integrating heat exchanger pipes within the concrete. Energy piles serve as the primary component in ground source heat pump systems, facilitating the exchange of heat with the ground. Energy piles have many advantages, such as cost-effectiveness, dual functionality, high efficiency, and low environmental impact. They have the potential to decrease both greenhouse

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gas emissions and the energy consumption associated with buildings by up to 75% compared to conventional cooling and heating systems.

However, energy piles also face some challenges and issues, such as complex design, thermo-mechanical interaction, seasonal imbalance, and thermal interference. During the summer, energy piles can release heat into the ground, while in winter, they can absorb heat from the ground. The thermal cycles induced by energy piles may affect their structural behavior and interaction with the soil under seismic loading. The thermal cycles may cause changes in the stiffness, strength, and damping of the energy piles, which in turn may affect their load-bearing capacity and deformation. Thermal cycles may also induce thermal stresses and strains in the concrete and soil, which may lead to cracking, settlement, or uplift of the energy piles. Moreover, the thermal cycles may create thermal gradients and differences between adjacent energy piles, which may result in soil-pile interaction and soil-structure interaction effects. These effects may influence the heat transfer and the mechanical response of the energy piles.

The seismic performance of energy piles is an important aspect that needs to be examined and evaluated. Seismic performance refers to the ability of a structure or a system to withstand earthquake-induced forces and displacements without significant damage or failure. Seismic performance depends on various factors, such as the intensity and frequency of the earthquake, the soil properties and conditions, the pile geometry and configuration, the pile material and properties, the pile-soil interface characteristics, the building structure and design, etc. The seismic performance of energy piles may differ from that of conventional piles due to their thermo-mechanical behavior and soil-pile interaction effects.

High-rise buildings (HRBs) are one of the potential applications of energy piles due to their high energy demand and large foundation area. HRBs are defined as buildings that have more than 10 stories or 35 meters in height. HRBs are subjected to high gravity loads and lateral loads due to wind or earthquake actions. Therefore, they require strong and stable foundations that can support their weight and resist their movements. Energy piles can provide both structural support and thermal energy for HRBs, but they also pose some challenges and risks for their seismic performance.

Campanella and Mitchell (1968) studied the effects of temperature variations on soil behavior and provided valuable insights into the thermal impact on soil stiffness, strength, volume change, consolidation behavior, and stress distribution, crucial for understanding soil behavior in civil engineering applications.

Mitchell (1969) investigated how heat affects soil behavior, focusing on factors like secondary compression rates, water thermal expansion, and soil compressibility. He found that higher temperatures weaken soil strength and emphasized the need for further research on inter-particle forces and phenomena like “salt heave” swelling, influenced by temperature. Additionally, he concluded that partially drying compacted soil before soaking enhances strength, and heating soils at high temperatures can greatly improve stress-deformation properties.

Chen *et al.* (2016) studied increasing the temperature (above 100°C) in soft clays and concluded that while the soil is subjected to higher temperatures over extended durations, its volume decreases due to water and steam discharge, particle movement caused by steam pressure, and chemical and physical reactions.

Yavari *et al.* (2016) discovered that the shear stress of clay and sand demonstrates a hardening behavior while that of clay/concrete interface displays a softening one, the temperature effect (between 5°C-40°C) on the shear strength of clay, sand, and clay/concrete interface is negligible.

Maghsoodi *et al.* (2019) investigated the effects of temperature changes on the mechanical

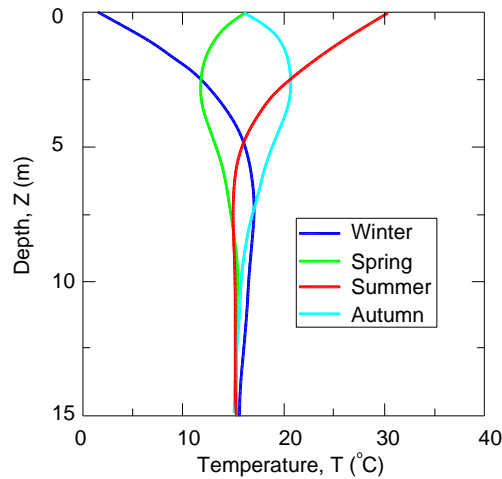


Fig. 1 Drawing of typical temperature changes with depth during the year for a moderate climatic zone (Laloui and Rotta Loria 2020)

behavior of soils and the soil-structure interface, and the findings displayed that the thermal variations had a slight impact on the shear strength of the sand-structure interface and the sand, however in clay samples, an increase in the temperature led to a rise in the cohesion and subsequently boosted the shear strength.

Xiao *et al.* (2019) studied how temperature cycles impact the soil-concrete interface behavior. They found that the shear strength in rough interfaces was reduced by up to 11% after a heating half-cycle but increased slightly after a cooling half-cycle. They also observed increased shear strength as water content was reduced and a higher volume change rate in heating cycles compared to cooling cycles (about 4 times higher).

Owoyemi and Afolagboye (2020) investigated the cyclic heating and cooling on the properties of soil and concluded that with repeated heating and cooling, the maximum dry density decreased while the optimal moisture content increased. The California bearing ratio exhibited an increase with repeated heating and cooling, reaching up to 23.5%. A reduction in liquid limit by up to 25% was noted, while in all samples the plasticity index and plastic limit were reduced.

Attah and Etim (2020) investigated the temperature effect on the properties of soil and concluded that with a temperature increase, the Atterberg limit decreased, the unconfined compression strength of soils also decreased, while the maximum dry density increased, and scanning electron microscopy revealed that there is an obvious change in the morphology.

Dry density increases and saturation decreases with longer exposure, particularly between 105°C and 150°C. Additionally, saturated clay soil experiences notable alterations in morphology, marked by heightened particle agglomeration and densification following exposure to temperatures surpassing 100°C.

As shown in Fig. 1 (Laloui and Rotta Loria 2020), the temperature of the soil up to 6 m is noteworthy affected by the weather conditions, day-night temperature changes, and seasonal changes, but below the 6 m depth of the soil, the temperature is mostly constant at nearly 15°C all times of the year so, this constant degree in both winter and summer can be used for cooling or heating conditions purposes (Narsilio *et al.* 2014).

Energy geo-structures serve several functions in heat exchange. These functions encompass: (a)

regulating temperatures (heating and cooling) within buildings for comfort, (b) aiding in the generation of hot water for various purposes like human consumption, agriculture, or industrial processes, (c) supplying heat to avoid the development of ice on surfaces such as roads, platforms, bridges, airstrips, etc., and (d) storing heat underground for future utilization.

In the context of systems of heat exchange, closed-loop systems employ a mixture that is based on water and circulates through sealed pipes to facilitate the heat transfer between the superstructure and the ground bidirectionally.

As soil, rock, or concrete become denser, the pores decrease in size and the contact points between solid grains increase. Minerals exhibit higher thermal conductivity compared to water and air. Consequently, when the pores of geomaterials are filled with the same fluid, a higher dry density results in a greater overall effective thermal conductivity of the medium. Geomaterials filled with water in their pores exhibit higher thermal conductivity than those filled with air.

Sarkar and Maheshwari (2012) investigated the effect of liquefaction and soil nonlinearity on the dynamic stiffness of pile groups by performing nonlinear dynamic analyses of a 3-D finite element soil-pile model without and with the generation of pore water pressure. They concluded that the nonlinearity reduced the dynamic stiffness by about 50% and that the generation of pore water pressure and work-hardening soil plasticity have an important influence on pile groups' dynamic behavior.

Strömblad (2014) studied a laterally loaded component of an offshore rig and in what way to model the submerged soil to best describe the SSI, and concluded that 3D FEM analysis is proper for SSI problems as it is capable of modeling soil continua and incorporating the damping and inertial effects of soil, and is a better alternative to non-linear springs.

Ng *et al.* (2014) presented a centrifuge modeling of energy piles in clay exposed to heating and cooling cycles. Two experiments were conducted to investigate how cyclic heating and cooling affect the energy pile displacement in heavily overconsolidated and lightly overconsolidated kaolin clay. Both energy piles exhibited a ratcheting displacement mechanism under a constant load over 5 cycles of heating and cooling. Additionally, the pile settled more in the lightly overconsolidated clay compared to the one in the heavily overconsolidated clay.

Batini *et al.* (2015) studied the geotechnical and energy behavior of energy piles for different design configurations.

Saha *et al.* (2015) studied how the stiffness of both rafts and piles impacts the seismic response of soil-piled raft-structure systems. Their study employed a simplified model that considered the interaction between piles, soil rafts, and superstructures across a range of soil conditions, from very soft to moderately stiff. Their findings suggested that an increase in the relative stiffness of the raft and pile could lead to a substantial increase in pile head shear. Furthermore, they observed that stiffer pile groups had an even greater impact on this phenomenon.

Miyamura *et al.* (2016) performed a large-scale seismic analysis of a high-rise steel frame with SSI and concluded that the results obtained by models with and without the ground were very similar because the ground was assumed to be hard.

Faizal *et al.* (2018) studied the axial and radial thermal responses of a bored cast-in-place energy pile installed beneath a 6-story building in unsaturated dense sand during a heating-cooling cycle, and found that axial thermal strains were more restricted than radial strains across all depths, and radial thermal stresses were considerably lower than axial stresses, suggesting minimal impact of radial expansion on axial strains and stresses. Additionally, the distribution of temperature across the pile's cross-section exhibited low variations at all depths.

Huang *et al.* (2018) studied experimentally the thermal effects on 4 pipe energy pile (PEP)

models made from aluminum in saturated sand, and found that the PEP temperature variations are higher than the solid energy pile, and the PEP bearing capacity presented a similar trend with the solid energy pile under different temperature variations. Throughout the complete heating-cooling cycle, the pile head experienced upward heaving as the temperature rose, with the upward displacements gradually decreasing post-heating. Conversely, during the subsequent cooling period, the displacements of the pile head were downward due to the contraction occurring under cooling.

Elzeiny *et al.* (2018) studied the axial pull-out response of a small-scale concrete pile exposed to cyclic thermal loading in sand, using an instrumented concrete energy pile subjected to various thermal cycles under pull-out loading, and found that the pile exposed to thermal cycles exhibited 28% higher ultimate shaft resistance compared to the pile tested at room temperature.

Tulebekova *et al.* (2019) used fiber-reinforced concrete instead of hoop reinforcement to resist the tensile stress in energy piles using compressed air in the pipes around these piles and studied their nonlinear structural response and post-cracking behavior considering concrete grade, fiber content, and pile section thickness in their study, and that study proved the ability of fiber concrete in resisting compressed air in such energy storage piles.

Zhu *et al.* (2019) examined how clay soil interacts with piles when subjected to heating and cooling. They explored how strain rate and temperature affect pre-consolidation pressure and devised a thermal viscoplastic model to characterize the mechanical properties of unstructured clay. By comparing predicted outcomes with experimental data, they found that their model effectively accounts for the impact of bonding degradation on the strain rate and the temperature-dependent soft clay behavior under one-dimensional conditions.

Hoseinimighani and Szendefy (2019) studied the soil-concrete interface behavior subjected to temperature change and concluded that the sandy soil-concrete interface is not affected by temperature change whereas the clayey soil-concrete interface is mostly affected by such change. Cyclic heating and cooling could increase the shear strength of the interface and can change the interface friction angle by 3-4°. Cyclic heating could increase cohesion while cooling has a small effect on interface cohesion. The behavior of the soil-pile interface was mostly ascribed to different types of soil, stress history, moisture content, and particle rearrangement at the interface surface.

Bao *et al.* (2020) experimentally evaluated the thermo-mechanical behavior of a large cross-section concrete energy pile with 3 cycles of thermal loading in saturated sandy soil and emphasized the significance of water flow rate and temperature difference in heat transfer, with higher flow rates enhancing heat transfer between the pile and the surrounding soil but reducing the temperature difference. Soil temperature changed significantly within 24 hours, with horizontal influence exceeding the pile's diameter by a factor of more than three. Energy pile displacement fluctuated with cyclic temperature, leading to settlement due to thermal strain and soil consolidation. The soil pressure was predominantly influenced by temperature, decreasing horizontally and significantly at deeper locations. Pore water pressure mirrored soil pressure horizontally but exhibited greater variation vertically.

Zhao (2020) investigated experimentally and analytically the thermally-induced ratcheting behavior of laterally-loaded RC energy piles in sand. Essential to capturing the pile's pre-peak load-displacement response was considering the soil nonlinearity involving an equivalent mobilized shear modulus. Comparisons between measured and predicted results showcased that models omitting strain softening could effectively approximate the load-displacement response of the laterally-loaded pile, despite the soil exhibiting a strong softening response.

Pan *et al.* (2020) conducted a study on the seismic response of pile-supported transmission towers situated on layered ground, considering soil-structure interaction (SSI). Their research revealed that SSI can notably influence dynamic characteristics by modifying the vibration frequencies of various modes.

Ebadi-Jamkhaneh *et al.* (2021) investigated the seismic behavior of a soil-pile system in liquefiable soil using three-dimensional numerical FEM analysis, including soil-pile interaction. It was concluded that, in the presence of liquefaction, it is imperative to undertake an effective stress-based ground response analysis to ascertain the maximum bending moment and shear force generated within the pile.

Mohamad *et al.* (2021) concluded that energy piles are difficult to study due to the multiplicity of variables involved in the structural and thermal analysis of single or group piles, and irreversible settlement can arise when axial loads surpass the ultimate resistance by 30%-40%.

Agibayeva *et al.* (2021) investigated an energy pile system utilizing various steel-concrete composite pile foundations. These foundations served both as energy storage mediums and load-resistant foundations, considering structural loading, internal air pressures, and soil boundary forces. That study emphasized the significance of inner and outer tubes for reliable storage and better pile constructability, respectively. Furthermore, it was concluded that the inclusion of steel tubes in composite pile foundations improves serviceability and durability compared to traditional RC pile systems.

Yazdani *et al.* (2021) studied the long-term shaft resistance enhancement of an energy pile in clays and concluded that an increase in the interface strength was noticed in the tests conducted under constant normal load condition, which is mainly related to the clay stiffening at the interface. Nevertheless, the rise in shaft resistance under the constant normal stiffness condition is mainly due to the elevation of effective lateral stress caused by heating, even though the stiffening of clay at the interface also plays a role in the overall increase in shaft resistance.

Abbasi *et al.* (2021) investigated how pile cap stiffness influences the seismic response of soil (sand)-pile-structure systems when exposed to near-fault ground motions, and their FEM results showed that as the cap stiffness value increases, the structure drift ratio decreases, while the relative displacement of the piles increases. Additionally, the piles' residual deformations are because of the surrounding soil's non-linear behavior.

Heidari *et al.* (2022) examined analytically and numerically the seismic response of energy piles in clayey and sandy soils, the results were validated against experimental data, and they concluded that the maximum lateral bearing capacity can be increased either by elevating the temperature or by reducing the external moment. Furthermore, heating was observed to intensify the maximum lateral displacements and internal moments of piles embedded in clayey soil, while it exhibited the inverse impact on piles embedded in sandy soil.

Saggu (2022) studied the effects of cyclic soil-pile interaction on the load-displacement behavior of thermal pile groups in sand, with different parameters for piles' arrangements, pile caps, and soil effects, and concluded thermal piles undergo a notable increase in uplift at the pile head during sequential thermal heating cycles. This effect is particularly substantial for piles situated above rigid rock substrates, as it leads to soil heave near the interface between the pile and soil.

Laloui and Rotta Loria (2020) summarized some important points for energy piles that are attributed to the field of reinforced concrete (RC) as follows: The alterations in stresses and strains caused by thermal effects in energy piles are greatly influenced by the level of pile fixity, potentially reaching critical levels if restraint conditions are not accurately specified. Additionally,



Fig. 2 Two examples of pipe configurations (grey color: inlet, black color: outlet) in energy piles

these changes are influenced by the proportion of mechanical loads imposed on the foundation.

For energy piles many examples of pipe configurations (U-shaped, bent U-shaped, parallel double U-shaped, series double U-shaped, multi U-shaped, indirect double, W-shaped, spiral or helix, coaxial, etc.) are available from e.g., Fadejev *et al.* (2017), Laloui and Rotta Loria (2020), Mohamad *et al.* (2021), etc., and two of them are also presented in Fig. 2. Incorporating thermally enhanced materials into the concrete mix can enhance the concrete thermal performance by up to 40%. For achieving an optimum geometry of heat exchangers in energy piles with U-, W-, or spiral configurations (Fig. 2), it is advised to maintain a 250 mm minimum spacing to avoid thermal interactions between pipe loops. Additionally, attaching the ground heat exchanger (GHE) pipes to the pile reinforcement cage is recommended to minimize the high thermal resistance of the concrete cover. It is suggested to conduct a comprehensive investigation into structural parameters (Mohamad *et al.* 2021).

There is a lack of comprehensive studies on the seismic performance of HRBs founded on energy piled raft foundations. Most of the existing studies focus on single or group energy piles under static or dynamic loading conditions, but they do not consider the effects of building structure, pile configuration, earthquake characteristics, etc. Therefore, there is a need for more research on this topic to understand the complex phenomena involved and to provide design guidelines and recommendations for improving the seismic performance of HRBs on energy piled raft foundations. Using passive TMDs may be a solution to reduce the larger displacements of the HRBs during summer when the buildings are subjected to earthquakes in order to result in displacement values nearby with those of the winter period.

Kontoni and Farghaly (2019a) explored the seismic control of a cable-stayed bridge by using TMDs, including SSI. Kontoni and Farghaly (2019b) investigated the effect of TMDs and base isolation on the seismic response of RC HRBs including SSI. Kontoni and Farghaly (2020) researched the TMD efficiency for steel HRB under earthquake or wind considering SSI. Farghaly and Kontoni (2022) studied the mitigation of seismic pounding between twin RC HRBs with piled raft foundation including SSI. Farghaly and Kontoni (2023) examined the mitigation of the seismic pounding between two L-shape in plan HRBs considering SSI. Kontoni and Farghaly (2023) investigated the improvement of the seismic resistance of RC and steel HRBs with SSI by TMDs, bracings, and shear walls. Faghimejad *et al.* (2024) accomplished performance-based optimization of RC wall-frames using pushover analysis and ABC optimization algorithm to enhance seismic

design performance. Kontoni and Farghaly (2024a) studied the seismic control of T-shape in the plan steel HRBs by utilizing TMDs and including the SSI effect. Ebadi-Jamkhaneh and Kontoni (2024) studied the dynamic response of an offshore wind turbine with a new monopile foundation under different lateral and seismic loadings. Kontoni and Farghaly (2024b) investigated various seismic mitigation schemes of TMDs for a monopile offshore wind turbine considering soil-pile-structure interaction. Kontoni and Farghaly (2024c) studied the seismic control of horizontally and vertically irregular steel HRBs by TMDs including SSI.

Sadeghi and Singh (2023) reviewed the available methods of design and construction of driven precast concrete energy pile foundations. Zhang *et al.* (2024) conducted a critical review of the energy pile technologies with low-carbon considerations and optimization measures.

The effect of energy piles will be studied under earthquake effect for a 15-story reinforced concrete (RC) high-rise building (HRB) with a 15 m piles length piled raft foundation. The building is squared in the plan to avoid torsion and non-symmetrical effect, and this RC HRB will be subjected to an earthquake in two different temperature periods: the first when the piles are subject to cooling period and the second when the piles are subject to heating period to show the effect of these periods on the response of the soil-pile interaction on the seismic behavior of the building.

2. Model description

The 3D HRB model (Figs. 3 and 4) has a height of 15 floors, each floor is of a height of 3 m with a square plan area of 15 m×15 m. The cross-section of the columns is 600 mm×600 mm, and the structural system of the floor slab is a flat slab of thickness 200 mm with upper and lower reinforcement nets 6Ø16 mm/m' as shown in Fig. 3, where all precautions have been taken to reduce the impact of torsion on the model under seismic load. The raft pile cap thickness is 2 m with upper and lower reinforcement mesh 7Ø22 mm/m' and each pile has a diameter of 600 mm with a length of 15 m below the raft thickness, where cross-section and reinforcement details are as shown in Fig. 3.

Fig. 4 shows the 3D model of the 15-story RC building with the soil block (Fig. 4(a)) and the 3D model without the soil block in order to reveal the pile draft foundation (Fig. 4(b)). The dimensions of the soil block are 27×27×25 m (x, y, z). The piles were modeled in the SAP2000 version 25 (2023) program as beam elements and the columns were modeled as frame elements with P-M2-M3 design, all slabs were flat slabs with 200 mm thickness, and the raft foundation (pile cap) with a thickness of 2 m was modeled as shell elements.

All the finite element (FE) models were created in the finite element program SAP2000 version 25 (2023) including both geometrical and material nonlinearity effects. The boundary conditions for the soil block were as follows: the soil block base is provided with fixed supports, and all sides of the soil block were provided by roller supports to allow vertical movement of the soil block in the z -direction only.

3. Soil properties

Table 1 displays the properties of the soil used in the 3D model. The soil below 15 m of the model was modeled as rock. The soil was modeled as a soil block with x, y , and z lengths 27 m, 27

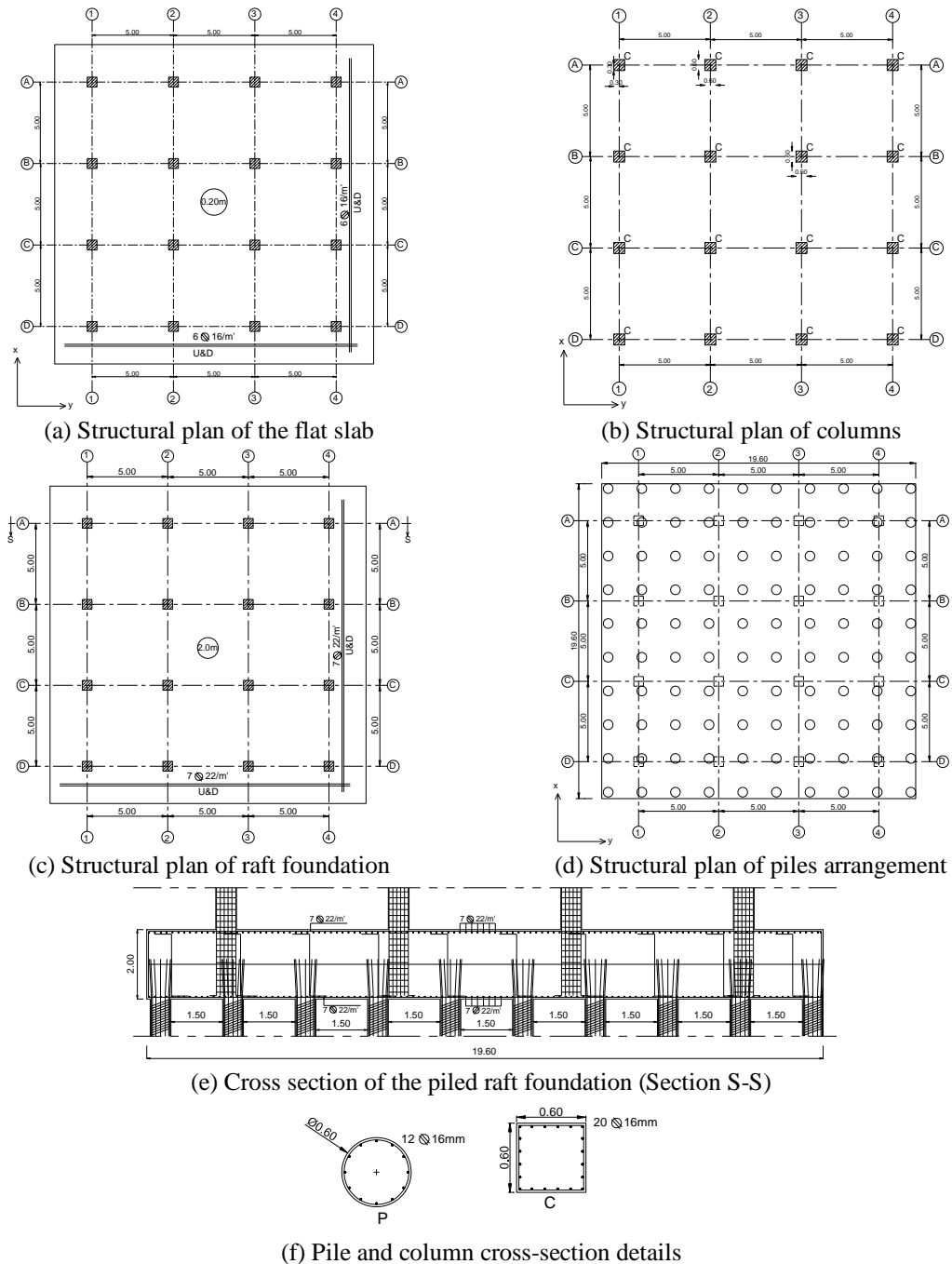


Fig. 3 Model description of the HRB

m, and 25 m respectively. The soil was modeled as solid elements to ensure the contact effect between piles and soil to give the most realistic soil and piles interaction effect, the boundary conditions for the ends of the soil block were at base fixed supports and at all sides of the soil

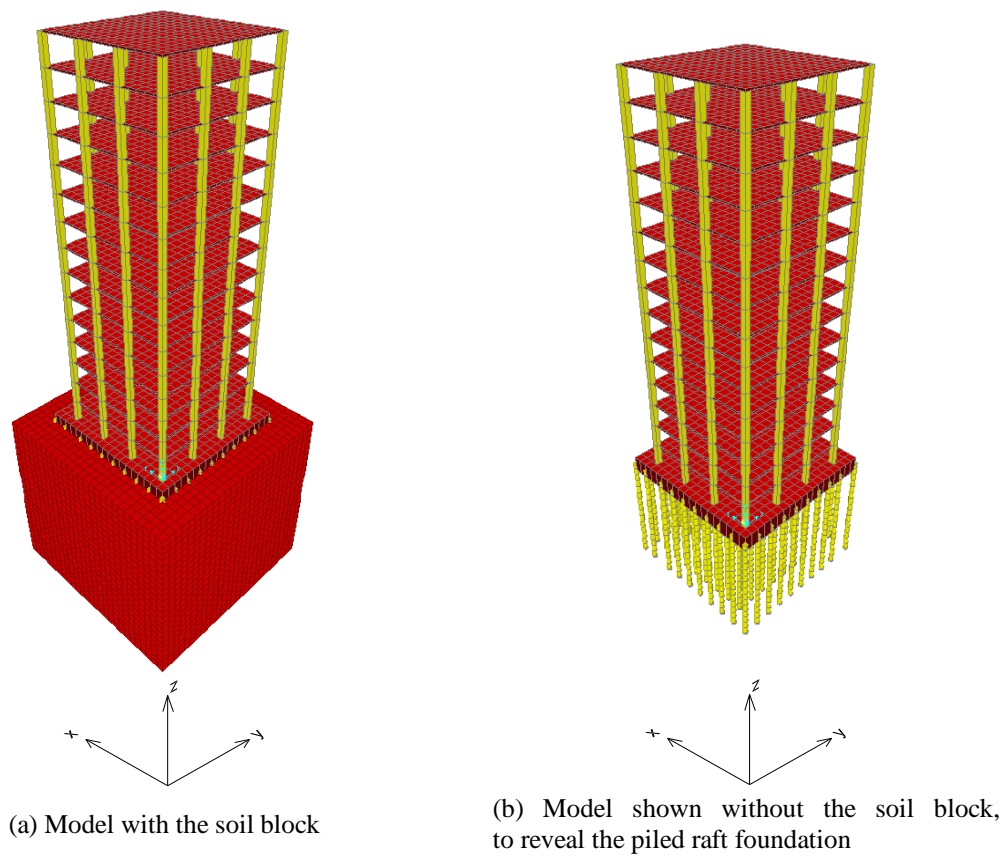


Fig. 4 3D model of the HRB

Table 1 Soil properties

Depth from Ground Level (G.L.) (m)	Soil type	Unit weight (kN/m ³)	Shear modulus (kPa)	Shear strength (kPa)
0-6	Clay	15.70	20.40	33
6-15	Sand	18.60	154.30	140

block were roller supports to ensure the vertical movements without effect on the soil block behavior during the heating or cooling cycles and the earthquake effect. The effect of heating or cooling of piles affected the soil around the piles by piles surfaces in the soil around the piles only.

4. Loads

The 3D 15-floor building with piled raft foundation was subjected to vertical live load (200 kg/m²) in addition to dead loads (weight of the structural elements and brick walls).

The dynamic load was applied as an earthquake wave from the El Centro earthquake of magnitude 6.9 M_w , the Loma Prieta earthquake of magnitude 6.9 M_w , the Northridge earthquake of magnitude 6.7 M_w , and the Kobe earthquake of magnitude 6.9 M_w (Fig. 5).

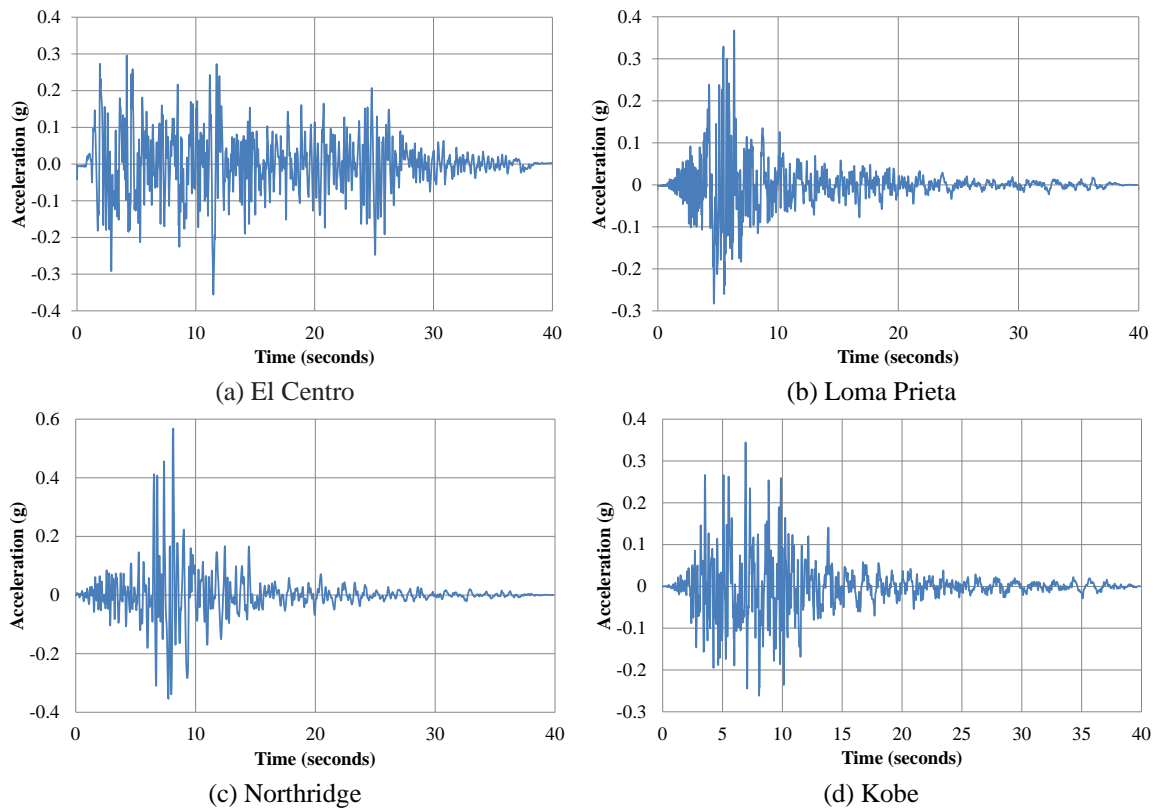


Fig. 5 The acceleration signal of the used earthquakes

The thermal loads on piles were added as constant heating or constant cooling all over the length of the piles under the raft foundation. The heating cycle was in the summer season (when the high-temperature take from the building is scattered through the soil from 37°C to 25°C), and the cooling cycle was in the winter season (when the low-temperature take from the building is scattered through the soil from 22°C to 35°C).

5. Results and discussions

This section presents and discusses the main findings and outcomes of the numerical modeling and simulation of the seismic performance of the RC HRB founded on the energy pile draft foundation. The effects of energy piles (heating and cooling the soil around them) on the soil-pile interaction and the soil-structure interaction are investigated. The results are compared with those of normal case piles without thermal cycles.

To find the effect of energy piles on the seismic response of HRBs, a 3D 15-floor RC building with a 15 m piles length piled raft foundation founded on two layers of soil (clay and sand) was analyzed for different cases. At first, the model is analyzed with energy piles subjected to earthquake without thermal loads (reference case), then the model is analyzed with energy piles cooling cycle subjected to earthquake, and also the model is analyzed with energy piles heating

Table 2 Symbols and definitions

Symbol	Definition
El Centro (C)	The model is under El Centro earthquake and the piles are cooled.
Loma Prieta (C)	The model is under Loma Prieta earthquake and the piles are cooled.
Northridge (C)	The model is under Northridge earthquake and the piles are cooled.
Kobe (C)	The model is under Kobe earthquake and the piles are cooled.
El Centro (H)	The model is under El Centro earthquake and the piles are heated.
Loma Prieta (H)	The model is under Loma Prieta earthquake and the piles are heated.
Northridge (H)	The model is under Northridge earthquake and the piles are heated.
Kobe (H)	The model is under Kobe earthquake and the piles are heated.
El Centro (N)	The model is under El Centro earthquake and the piles are without thermal loads.
Loma Prieta (N)	The model is under Loma Prieta earthquake and the piles are without thermal loads.
Northridge (N)	The model is under Northridge earthquake and the piles are without thermal loads.
Kobe (N)	The model is under Kobe earthquake and the piles are without thermal loads.
El Centro (C) P	Lateral displacement of piles when the model is under El Centro earthquake and the piles are cooled.
Loma Prieta (C) P	Lateral displacement of piles when the model is under Loma Prieta earthquake and the piles are cooled.
Northridge (C) P	Lateral displacement of piles when the model is under Northridge earthquake and the piles are cooled.
Kobe (C) P	Lateral displacement of piles when the model is under Kobe earthquake and the piles are cooled.
El Centro (H) P	Lateral displacement of piles and the model is under El Centro earthquake and the piles are heated.
Loma Prieta (H) P	Lateral displacement of piles when the model is under Loma Prieta earthquake and the piles are heated.
Northridge (H) P	Lateral displacement of piles when the model is under Northridge earthquake and the piles are heated.
Kobe (H) P	Lateral displacement of piles when the model is under Kobe earthquake and the piles are heated.
El Centro (H) TMDs	The model is under El Centro earthquake and the piles are heated using 2 TMDs groups.
Loma Prieta (H) TMDs	The model is under Loma Prieta earthquake and the piles are heated using 2 TMDs groups.
Northridge (H) TMDs	The model is under Northridge earthquake and the piles are heated using 2 TMDs groups.
Kobe (H) TMDs	The model is under Kobe earthquake and the piles are heated using 2 TMDs groups.
El Centro (C) TMDs	The model is under El Centro earthquake and the piles are cooled using 2 TMDs groups.
Loma Prieta (C) TMDs	The model is under Loma Prieta earthquake and the piles are cooled using 2 TMDs groups.
Northridge (C) TMDs	The model is under Northridge earthquake and the piles are cooled using 2 TMDs groups.
Kobe (C) TMDs	The model is under Kobe earthquake and the piles are cooled using 2 TMDs groups.
El Centro (H) TMDs P	Lateral displacement of piles when the model is under El Centro earthquake and the piles are heated using 2 TMDs groups.
Loma Prieta (H) TMDs P	Lateral displacement of piles when the model is under Loma Prieta earthquake and the piles are heated using 2 TMDs groups.

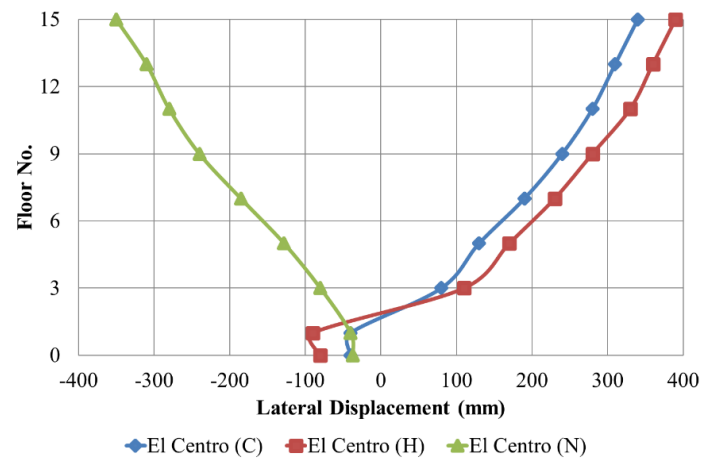
Table 2 Continued

Symbol	Definition
Northridge (H) TMDs P	Lateral displacement of piles when the model is under Northridge earthquake and the piles are heated using 2 TMDs groups.
Kobe (H) TMDs P	Lateral displacement of piles and the model is under Kobe earthquake and the piles are heated using 2 TMDs groups.
El Centro (C) TMDs P	Lateral displacement of piles when the model is under El Centro earthquake and the piles are cooled using 2 TMDs groups.
Loma Prieta (C) TMDs P	Lateral displacement of piles when the model is under Loma Prieta earthquake and the piles are cooled using 2 TMDs groups.
Northridge (C) TMDs P	Lateral displacement of piles when the model is under Northridge earthquake and the piles are cooled using 2 TMDs groups.
Kobe (C) TMDs P	Lateral displacement of piles and the model is under Kobe earthquake and the piles are cooled using 2 TMDs groups.
El Centro (N) P	Lateral displacement of piles when the model is under El Centro earthquake and the piles are without thermal loads.
Loma Prieta (N) P	Lateral displacement of piles when the model is under Loma Prieta earthquake and the piles are without thermal loads.
Northridge (N) P	Lateral displacement of piles when the model is under Northridge earthquake and the piles are without thermal loads.
Kobe (N) P	Lateral displacement of piles when the model is under Kobe earthquake and the piles are without thermal loads.

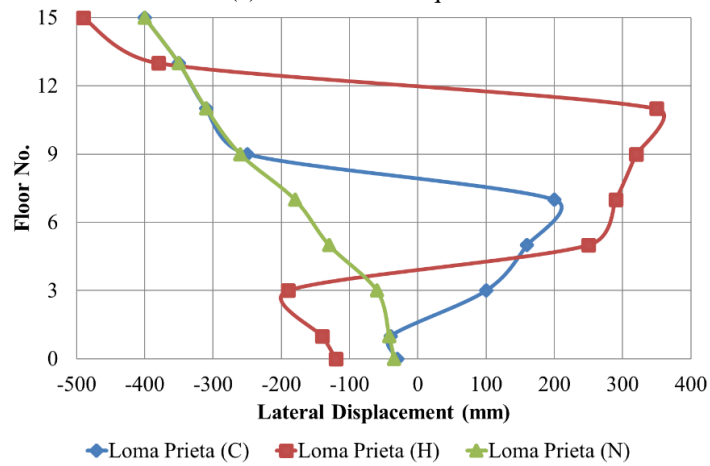
cycle subjected to earthquake. Next, the model is analyzed at cooling and heating cycles with TMDs to control the lateral displacements for both the superstructure and infrastructure. Table 2 shows the symbols used and their definitions.

Fig. 6 represents the comparison between the lateral displacements for the same model with cooling and heating piles under the raft foundation and the normal case without thermal effects. Fig. 6(a) shows the lateral displacements in the x direction, for the model subjected to the El Centro earthquake with cooling piles, heating piles and normal cases, where the difference between the lateral displacement in cooling and heating piles shows that the lateral displacement increases in the heating case of piles by nearly 1.15 times than the cooling piles case, and the lateral displacement of the normal case is nearly as the cooling case. Fig. 6(b) shows the lateral displacements in the x direction, for the model subjected to the Loma Prieta earthquake with cooling piles, heating piles and normal cases, where the heating case of piles increases the lateral displacement by nearly 1.23 times than the cooling piles case. Fig. 6(c) shows the lateral displacements in the x direction, for the model subjected to the Northridge earthquake with cooling piles, heating piles and normal cases, where the heating case of piles increases the lateral displacement by nearly 1.10 times than the cooling piles case and the normal case. Fig. 6(d) shows the lateral displacements in the x direction, for the model subjected to the Kobe earthquake with cooling piles, heating piles and normal cases, where the heating case of piles increases the lateral displacement by approximately 1.32 times than the cooling piles case.

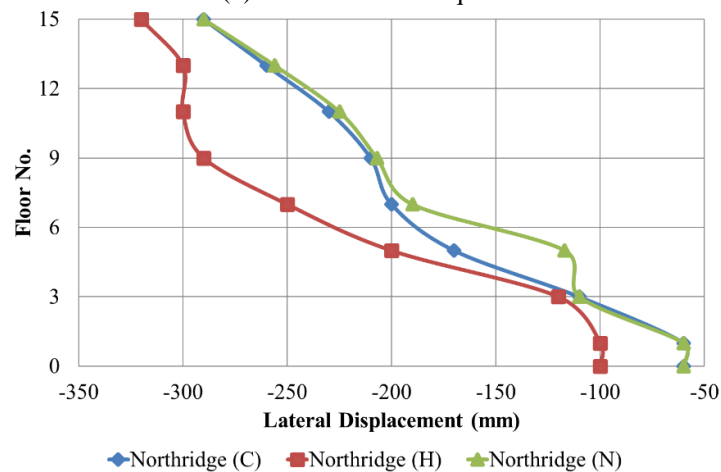
Fig. 7 shows the base shear, where the cooling piles case shows a rise in the values of the base shear than the heating piles case. The base shear in the cooling case increased by 1.27, 1.15, 1.13 and 1.32 times than the heating case in the El Centro, Loma Prieta, Northridge and Kobe earthquakes respectively. The normal case shows an increase in values of 1.22, 0.96, 1.10 and 1.56



(a) El Centro earthquake

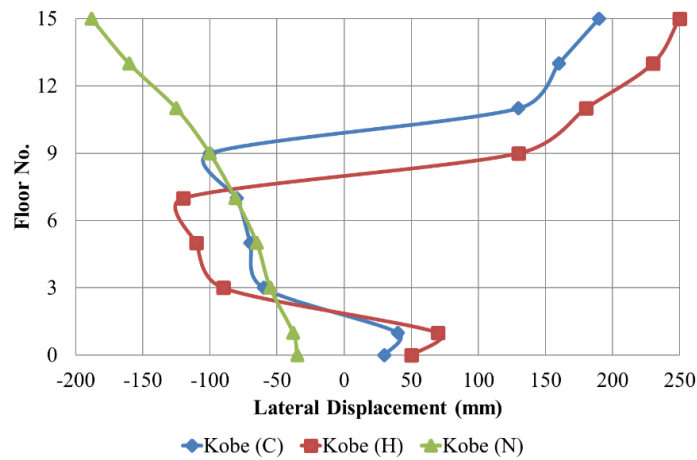


(b) Loma Prieta earthquake



(c) Northridge earthquake

Fig. 6 Lateral displacements of the superstructure under four different earthquakes for cooling (C), heating (H), and normal (N) piles cases



(d) Kobe earthquake

Fig. 6 Continued

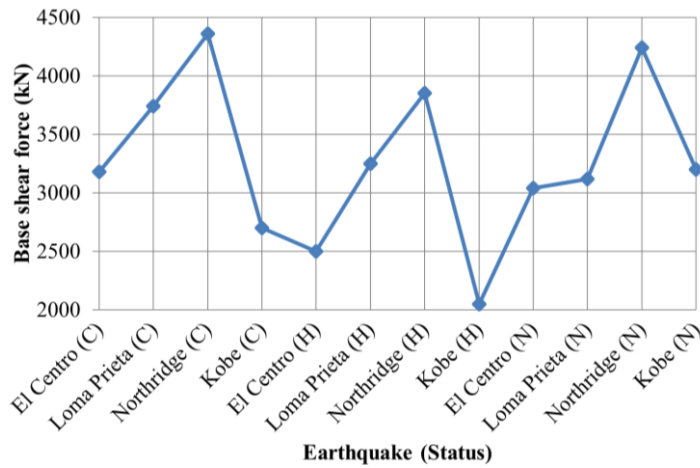


Fig. 7 Base shear force under four different earthquakes for cooling (C), heating (H), and normal (N) piles cases

times than the heating case in the El Centro, Loma Prieta, Northridge and Kobe earthquakes respectively.

Fig. 8 shows the base moment, where the cooling piles' case shows a rise in the values of the base moment by 1.22, 1.02, 1.03 and 1.11 times than the heating piles case in the El Centro, Loma Prieta, Northridge and Kobe earthquakes respectively. The normal case base moment rose by 1.28, 0.89, 1.04 and 1.4 times than the heating case in the El Centro, Loma Prieta, Northridge and Kobe earthquakes respectively. The results of the cooling and normal cases are similar in their effect with respect to the heating case.

The increase of heat around the piles in the heating season (summer season) reduces the capacity of soil so, when the model is subjected to earthquakes, the ability of piles to transfer loads and the resistance to the large lateral displacements is reduced. This is noticed when comparing the results of lateral displacements, base shear forces and base moments of the heating and cooling

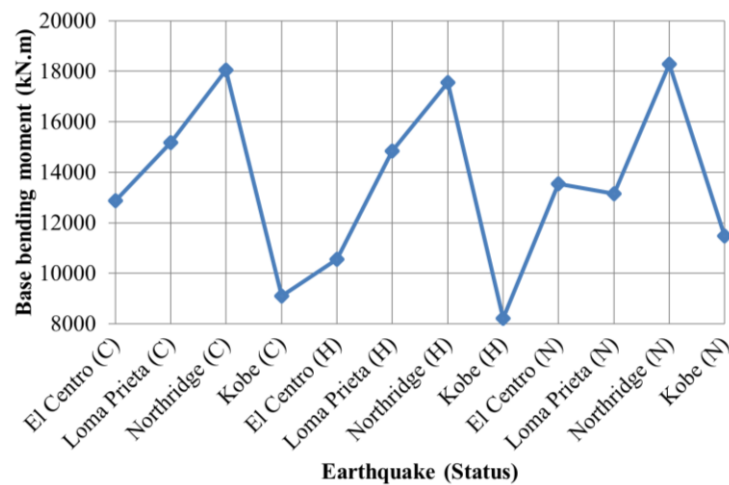


Fig. 8 Base moment under four different earthquakes for cooling (C), heating (H), and normal (N) piles cases

piles cases and also the normal case, where in the cooling piles case the lateral displacements decrease and the base shear and base moment increase. To mitigate the large lateral displacements of the model in the heating piles case, tuned mass dampers (TMDs) are used as two groups of 4 TMDs each (at the corners of the model) in the top and the mid-height of the model to reduce the lateral displacements under earthquakes. Fig. 9 shows the elevation and plan of the model showing the configuration of the two TMDs groups installation (each group of 4 TMDs at corners of the model plan) with one group at the top (at level 45 m) and the second group at about mid-height (at level 24 m) of the model.

Fig. 10 shows the comparison between the lateral displacements for the same model with cooling, heating, and normal piles under the raft foundation with two groups of TMDs (each group with 4 TMDs at the corners of the model), at the top and mid-height of the model, where the application of TMDs on the model in both cases (heating and cooling) reduce the displacements in both cases, as the most important thing is that the values of the displacements are close in both cases, which maintains the values of the displacements within certain limits (rather small) between the winter and summer seasons to keep the structure from increasing the lateral displacements in one season than the other. Fig. 10(a) shows the lateral displacements in the x direction, for the model subjected to the El Centro earthquake for the model with cooling, heating (with TMDs groups at the top and mid-height of the superstructure), and normal piles cases, where the ratio between the top lateral displacement in winter and summer nearly equals 0.94. Fig. 10(b) shows the lateral displacements in the x direction, for the model subjected to the Loma Prieta earthquake for the cases of cooling and heating piles with 2 TMDs groups and the normal case, where the ratio between the top lateral displacement in winter and summer nearly equals 1.13. Fig. 10(c) shows the lateral displacements in the x direction, for the model subjected to the Northridge earthquake for the cases of cooling and heating piles with 2 TMDs groups and the normal case, where the ratio between the top lateral displacement in winter and summer nearly equals 1.39. Fig. 10(d) shows the lateral displacements in the x direction, for the model subjected to the Kobe earthquake for the cases of cooling and heating piles with 2 TMDs groups and the normal case, where the ratio between the top lateral displacement in winter and summer nearly equals 0.89.

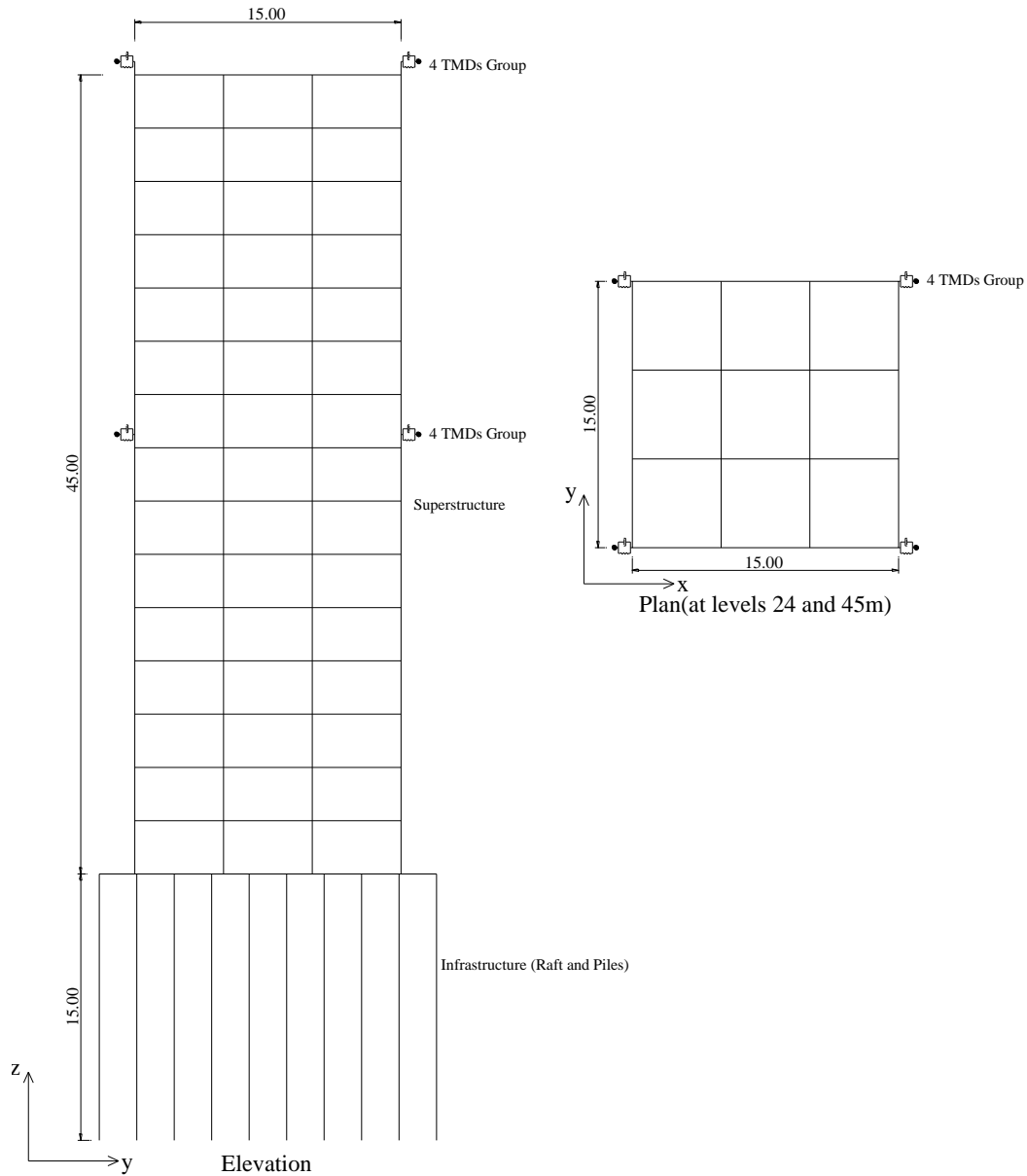


Fig. 9 Elevation and plan of the HRB model with two groups of TMDs

Thus, the 2 groups of TMDs reduce the differences in the top lateral displacements of cooling and heating piles cases to 18 mm for the El Centro, 23 mm for the Loma Prieta, 58 mm for the Northridge, and 17 mm for the Kobe earthquakes.

Fig. 11 shows the lateral displacements of the piles under the raft foundation in heating, cooling and normal cases subjected to earthquakes with the 2 groups of TMDs acting in the top and mid-height of the superstructure, which will affect the lateral displacements of the piles in both heating and cooling cases under the raft foundation. For comparison reasons, results without the 2 groups

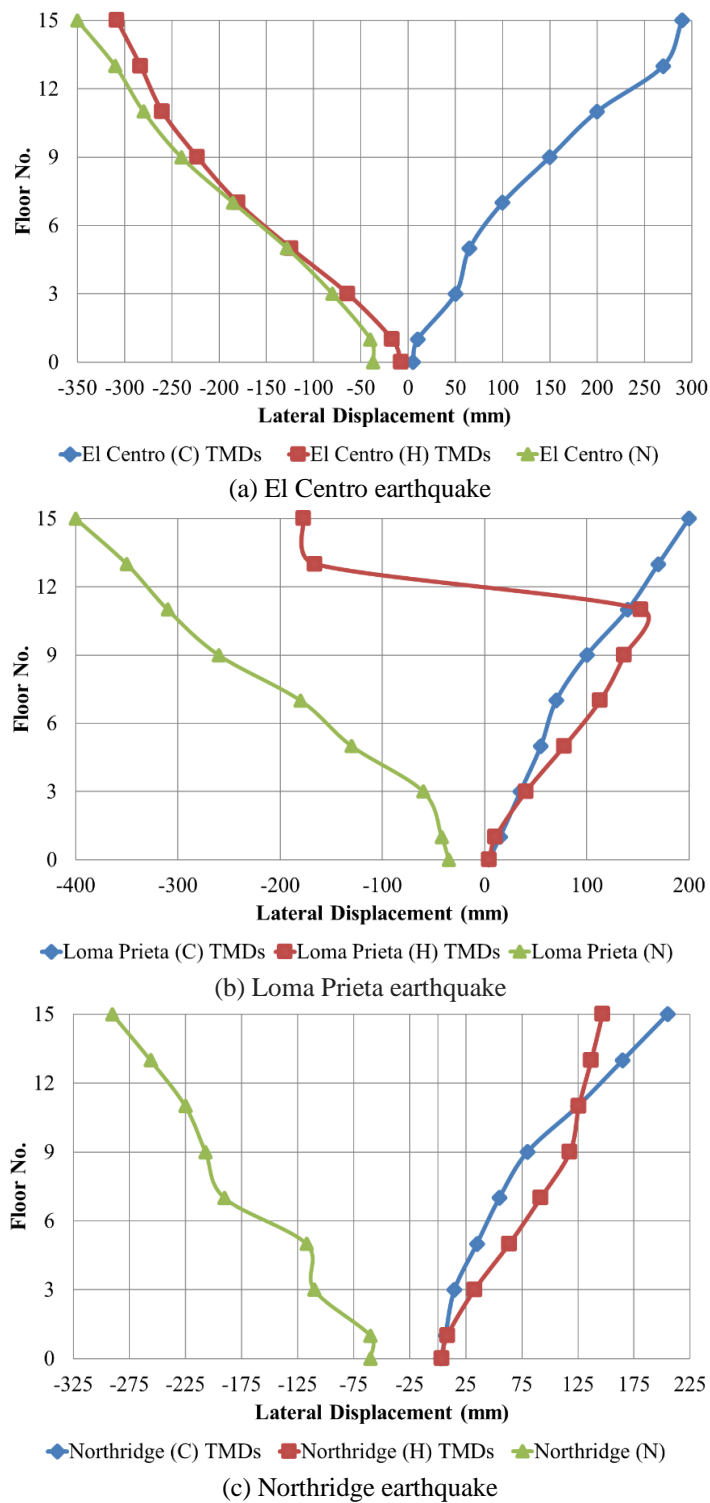
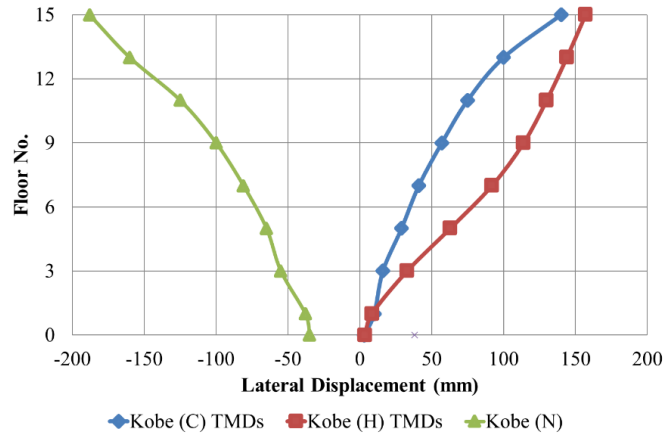
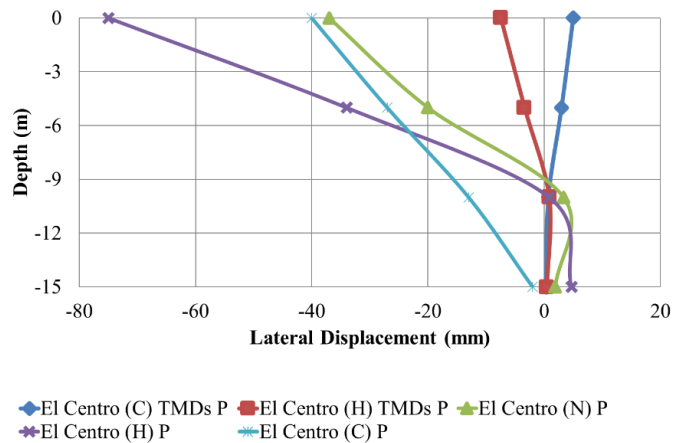


Fig. 10 Lateral displacements of the superstructure with two TMDs groups under four different earthquakes for cooling (C), heating (H), and normal (N) piles cases

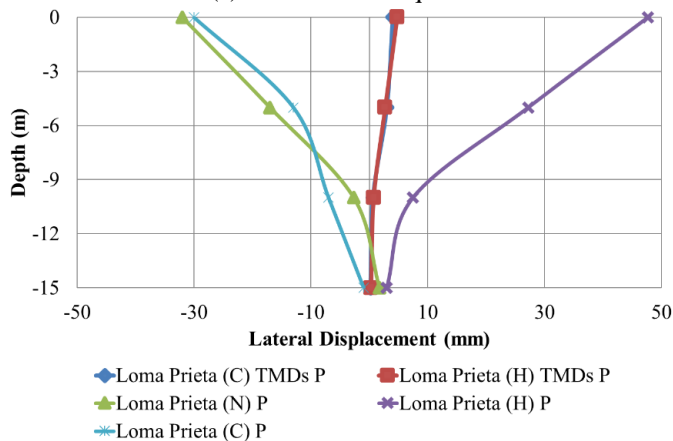


(d) Kobe earthquake

Fig. 10 Continued



(a) El Centro earthquake



(b) Loma Prieta earthquake

Fig. 11 Lateral displacement of piles for superstructure with TMDs under four different earthquakes for cooling (C), heating (H), and normal (N) piles cases

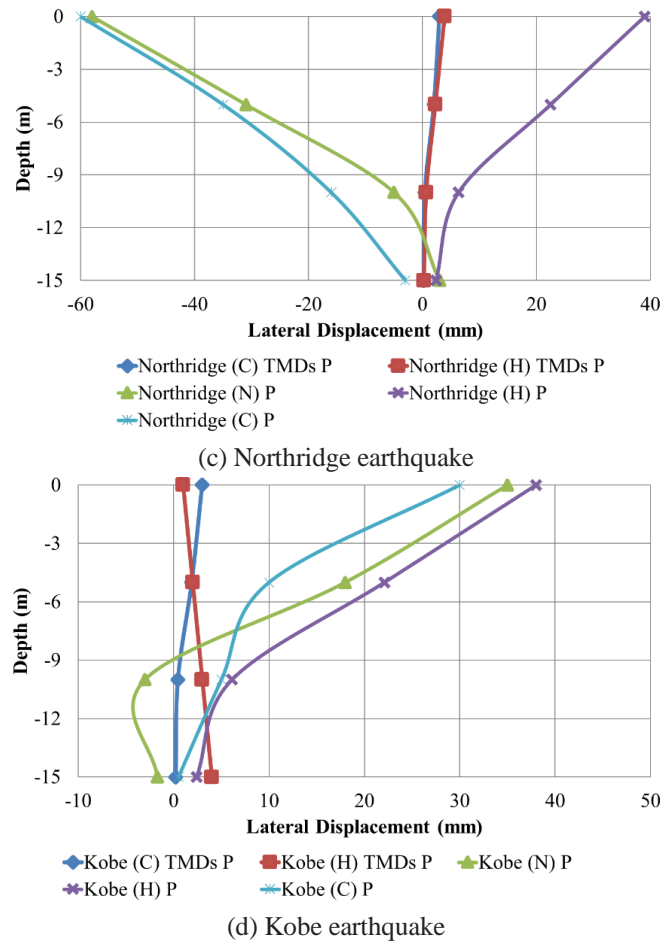


Fig. 11 Continued

of TMDs are also depicted. Fig. 11(a) shows the lateral displacements in the x direction for the piles and the raft foundation subjected to the El Centro earthquake for both cases of cooling and heating piles with 2 TMDs groups, where by applying the TMDs groups on the superstructure the difference between the lateral displacements of piles in cooling and heating cases with TMDs is equal to 2.5 mm, and the TMDs decrease the lateral displacements of piles in cooling and heating cases by 8 and 10 times respectively. Fig. 11(b) shows the lateral displacements in the x direction for the piles and the raft foundation subjected to the Loma Prieta earthquake with both cases of cooling and heating piles with 2 TMDs groups applied on the superstructure (at top and middle height), where by applying the TMDs groups the lateral displacements in both cases are similar, and the ratio between the cooling and heating case lateral displacements without and with TMDs is equal to 6 and 10 times respectively. Fig. 11(c) shows the lateral displacements in the x direction for the piles and the raft foundation subjected to the Northridge earthquake with both cases cooling and heating piles, with 2 TMDs groups applied on the superstructure (at top and middle height), where the lateral displacements with TMDs are similar for cooling and heating cases and the ratio between cooling and heating cases without and with TMDs are 12 and 8 times respectively. Fig.

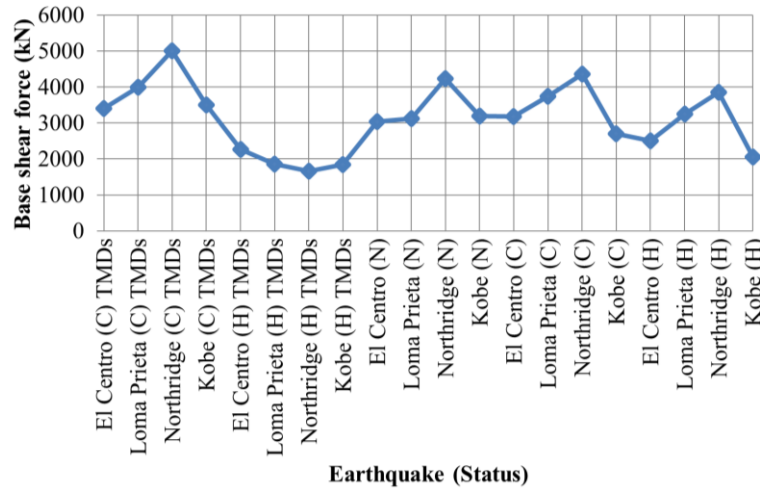


Fig. 12 Base shear force of the HRB superstructure with TMDs under four different earthquakes for cooling (C), heating (H), and normal (N) piles cases

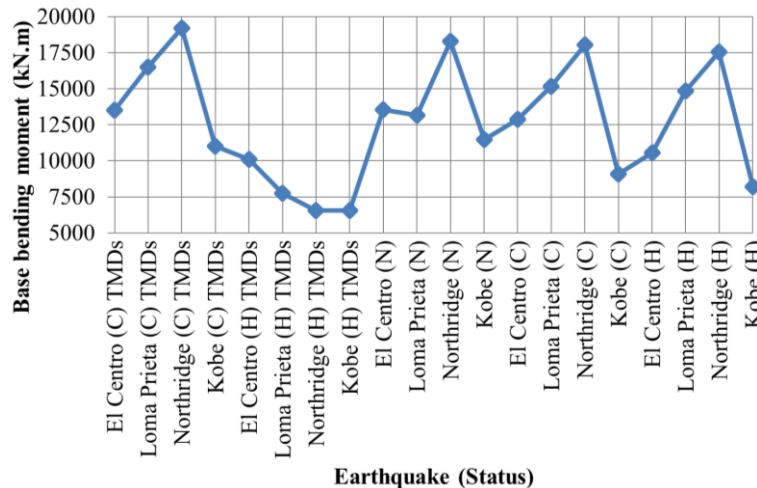


Fig. 13 Base moment of the HRB superstructure with TMDs under four different earthquakes for cooling (C), heating (H) and normal (N) piles cases

11(d) shows the lateral displacements in the x direction for the piles and the raft foundation subjected to the Kobe earthquake with both cases cooling and heating piles, with 2 TMDs groups applied on the superstructure (at the top and middle height), where the difference between cooling and heating cases with TMDs equals to 0.8 mm and the ratio between cooling and heating lateral displacements without and with TMDs equals 10 and 10 times respectively.

Thus, the 2 TMDs groups mitigate the lateral displacements of the piles and reduce the differences between the top lateral displacements of cooling and heating piles to 2.5 mm, 0.8 mm, 0.9 mm and 0.8 mm for the El Centro, Loma Prieta, Northridge and Kobe earthquakes respectively.

Fig. 12 shows the base shear force of the HRB superstructure with TMDs, for both cooling and

heating piles cases, showing a rise in the values of the base shear at the cooling case than in the heating piles case. The ratio between base shear values in the cooling case without and with TMDs are equal to 0.94, 0.94, 0.87 and 0.77 times for the El Centro, Loma Prieta, Northridge and Kobe earthquakes respectively. The ratio between the base shear values in the heating case without and with TMDs are equal to 1.10, 1.74, 2.14 and 1.11 times for El Centro, Loma Prieta, Northridge and Kobe earthquakes respectively.

Fig. 13 shows the base moment of the HRB superstructure with TMDs, where the cooling piles case shows a rise in the values of the base moment than the heating piles case. The ratio between base moments values in the cooling case without and with TMDs is equal to 0.95, 0.92, 0.94 and 0.83 times for El Centro, Loma Prieta, Northridge and Kobe earthquakes respectively. The ratio between base moments values in the heating case without and with TMDs are equal to 1.04, 1.91, 2.68 and 1.25 times for El Centro, Loma Prieta, Northridge and Kobe earthquakes respectively.

6. Conclusions

A 3D HRB model of 15 floors with energy piled raft foundation uses the energy piles as heat exchange with the soil surrounding the piles with a length of 15 m under the raft foundation level. Four different earthquakes were used to obtain results. Energy piles are a type of foundation that can exchange heat with the soil and provide renewable energy for buildings. However, thermal cycles of heating and cooling can affect the mechanical behavior of the piles and the surrounding soil, which may have implications on the seismic performance of a HRB with energy piled raft foundation.

The following conclusions can be drawn about the heating and cooling effect of the energy piles on the seismic performance of a HRB:

- Thermal expansion and contraction of the soil may induce additional stresses and strains in the pile-soil interface.
- Changes in the soil stiffness, strength, and permeability are due to temperature variations.
- The development of thermal gradients in the soil may create uneven settlement or lateral displacement of the pile foundation.
- Energy piles can reduce the seismic demand on HRBs by providing passive cooling during extreme events.
- Energy piles can increase the seismic risk of HRBs by weakening the pile-soil bond or creating differential settlement or buckling of the piles under the heating cycle in the hot season.
- The heating piles case increases the top lateral displacement of the HRB than the cooling piles case and the normal case.
- The cooling piles case shows a rise in the values of the base shear and the base moment than the heating piles case.
- The heating piles case shows a reduction in the values of the base shear and the base moment than the cooling piles case.
- The increase of heat around the piles in the heating season (summer season) reduces the capacity of soil so, when the model is subjected to earthquakes, the ability of piles to transfer loads and their resistance to the large lateral displacements are reduced.
- To mitigate the large lateral displacements under earthquakes of the HRB model in the heating piles case, tuned mass dampers (TMDs) were used as two groups of 4 TMDs each (at

the corners of the model) at the top and the mid-height of the HRB model.

- The use of TMDs contributes to reducing the seismic response of the HRB when the soil is heated in the heat exchange between the piles and the soil in the hot season as the cooling cycle response.
- Using TMDs mitigates the lateral displacements and reduces the differences-between the cooling and heating cases-of the HRB top lateral displacements and also of the displacements of piles.
- The heating piles case with TMDs decreases the base shear and the base moment compared to without using TMDs.
- The cooling piles case with TMDs increases the base shear and base moment compared to without using TMDs.

However, these conclusions are based on limited studies and assumptions, and more research is needed to fully understand and quantify the complex interactions between energy piles, soil, and structures under coupled thermal and seismic loads.

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