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Research Paper

Seismic Performance of Mat and Grid Foundations on a Soft Fine-Grained Soil Underlying an Eight-Story Building

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ABSTRACT

In cases of large deformations of the ground underlying a structure, mat and grid foundations are two options to reduce probable differential settlements, due to their rigidity in the perpendicular directions and their relatively larger area compared with single spread foundations. A case study of large settlements of an 8-storey structure resting on soft saturated fine-grained soil due to seismic loading is numerically investigated herein. The foundations were matching in plan dimensions (10*18 m), and the grid foundation was 30 cm thicker than the 60-cm-thick mat, reaching nearly similar volume (110 m3 in the case of grid foundation and 108 m3 in the case of mat foundation). To decide on the more economical foundation type between mat and grid, the amount of reinforcing steel bars and the cost of construction, including concrete molding should be considered. Herein, based only on the amount of foundation settlement, it is shown that the performance of a grid foundation is better than or identical to mat foundations, which makes it an alternative with probably a more economical option to be preferred to mats in the design of foundations in areas of high seismicity. It is also shown that assessment of the frequency content of the input motions by applying the white Gaussian noise added to a sine sweep of frequencies to the model and inspecting the results, is useful in understanding the results.

Keywords:
Mat foundation; Grid foundation; Numerical analysis; Seismic loading

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1. Introduction

Mat or grid foundations are ordinarily used when more than half of the ground surface is covered by conventional spread footings (Bowles, 1996). Grid foundations can be alternatives to mat foundations when it is not vital to cover the whole area under construction with footings to provide bearing capacity. Grid foundations are similar in the plan to tied strip footings. However, grids have flexural rigidity in both longitudinal and lateral dimensions, unlike tied strip foundations that do not have significant flexural rigidity along the ties. Settlement of the grid foundation is calculated similar to mats, and its bearing capacity is measured as a strip footing (Fakher, 2021). Jalili et al. (2023) have reviewed the literature regarding numerical investigations on spread footing, which is not repeated herein. They compared the performance of mat foundations with grid foundations under two- and five-story buildings and recommended the grid foundation as an economical alternative to mat foundation in the studied cases. After this recent study on two- to five-story buildings, the question arouses whether the performance of the grid foundation would be better than that of the mat under heavier buildings, or not. In this study, the performance of mat and grid foundations under eight-story buildings was probed to seek the answer to this question. Properties of soft saturated fine-grained soils of coastal areas in northern Iran were considered to calibrate the UBC-PLM constitutive model in PLAXIS 3D. Eight-storey resting on mat and grid foundations were dynamically analyzed by the application of strong ground motions of the area. Some selective properties of the models and the achieved results leading to the conclusion of the study were briefly reported by Jalili et al. (2024) and are explained in subsequent sections with more detail. However, some details of the models and input motions are identical to those of Jalili et al. (2023) and are not repeated herein to observe brevity.

2. Modeling in PLAXIS3D

The structure over mat or grid foundation was modeled with the aid of beam elements as the beam and column and plate element as wall and floor, resting on a 30 m thick layer of soil. Figure (1) shows the geometry of the building compared to the modeled soil strata, along with the mesh dimensions. Boundaries of the model were 60 m away from the structure at each side. Viscose boundaries were also applied at the sides to reduce unwanted reflections.

Modeled mat and grid foundations in PLAXIS3D are shown in Figure (2).

Sensitivity analyses were conducted to arrive at the optimum mesh size and time step for the dynamic analysis in this study. The mesh size was not larger than 0.1 of the shortest wavelength contained in the analysis (Lysmer & Kuhlemeyer, 1969). The UBC-PLM constitutive model

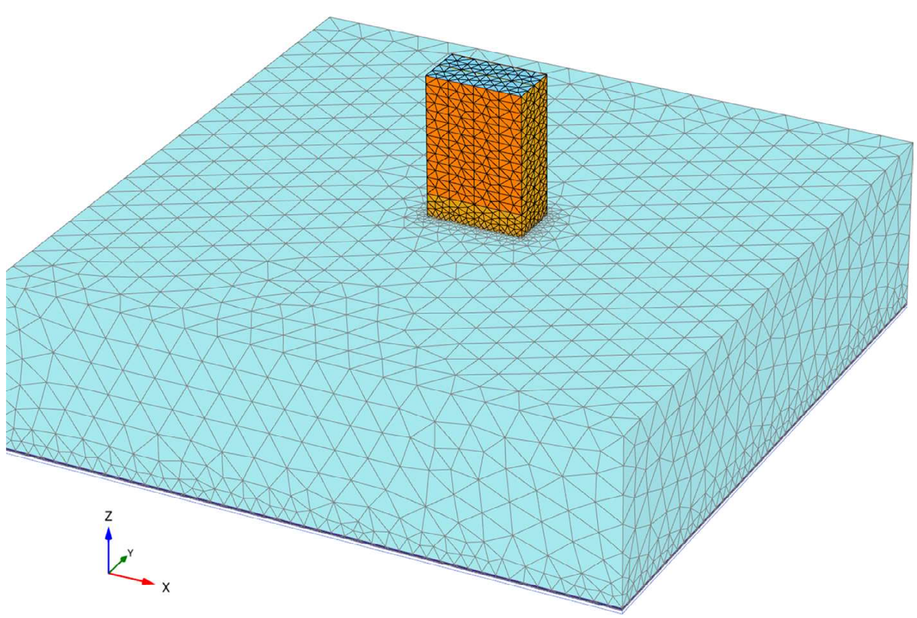
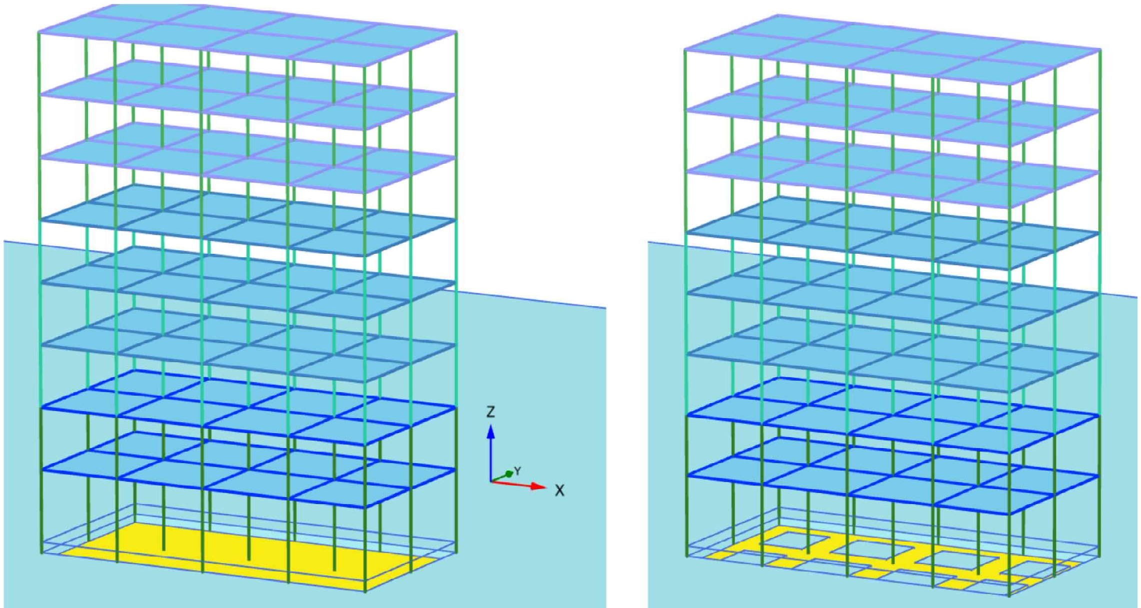


Figure 1. Geometry of the model in PLAXIS3D.



(a) (b)

Figure 2. Modeled 8-storey structures over (a) mat and (b) grid foundations.

(Petalas & Galavi, 2013) was used for the soil modeling, as it is capable of considering degradation due to the increase and repetition of the loading. The parameters of the constitutive models for soil and structural elements were identical to those calibrated by Jalili et al. (2023). The foundations were 18 m long and 10 m wide, with a 60 cm thickness for the mat and a 90 cm thickness for the grid foundations.

Both mat and grid foundations showed uniform settlement under the construction of the building over them in numerical analyses. The static allowable bearing capacity of the foundations in a shear failure by Vesic bearing capacity equations (Bowles, 1996) and considering a safety factor equal to 3, was higher than the surcharge applied by the building construction. Due to the soft soil of the area leading to considerable consolidation settlement ($C_c = 0.1$ and $C_s = 0.01$), the bearing capacity was limited to 80 kPa to satisfy the requirement concerning 10 cm allowable settlement by the Iranian national building code (INBC 7, 2022). That was why the building height was limited to 8 stories in this study.

3. Results of the Numerical Analyses

To probe the performance of the mat and grid foundations, four input motions were applied to the model, and the settlements of the center and two opposite corners of the foundations were compared. Figure (3) shows the response spectra of the input motions that were applied to the numerical models in this study.

Figure (4) shows the deformed model of the eight-story building over grid foundation after Aq Qala earthquake. As obvious in the figure, the building punches to the ground with slight tilting.

Figure (5) shows the pattern of the settlement below the foundations after Aq Qala earthquake. As obvious, the counters are larger under the mat foundation, showing higher settlement magnitudes.

Figure (6) shows the variation of the settlement with time at opposite corners and the center of the mat and the grid foundations while the Ahar earthquake was applied to the numerical model. It is obvious in this figure that there is no considerable difference among the settlements of the corners and centers of the foundations, i.e., uniform settlement of the rigid foundations. Notably, there is no considerable difference between settlement of the mat and the grid foundations in Figure (5).

Results of the numerical analyses in this study are summarized in Tables (1) and (2). In line with findings of Jalili et al. (2023) for two- and five-story buildings, grid foundations under eight-story buildings have a better performance than the mat foundations. Based on the achieved results, the total residual settlements of the grids are less than those of the mats.

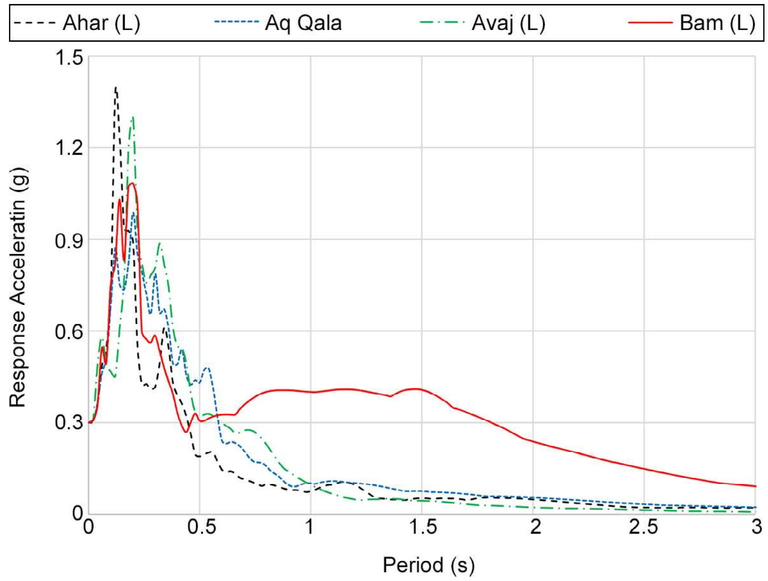


Figure 3. Response spectra of the input motions applied to the numerical models in this study.

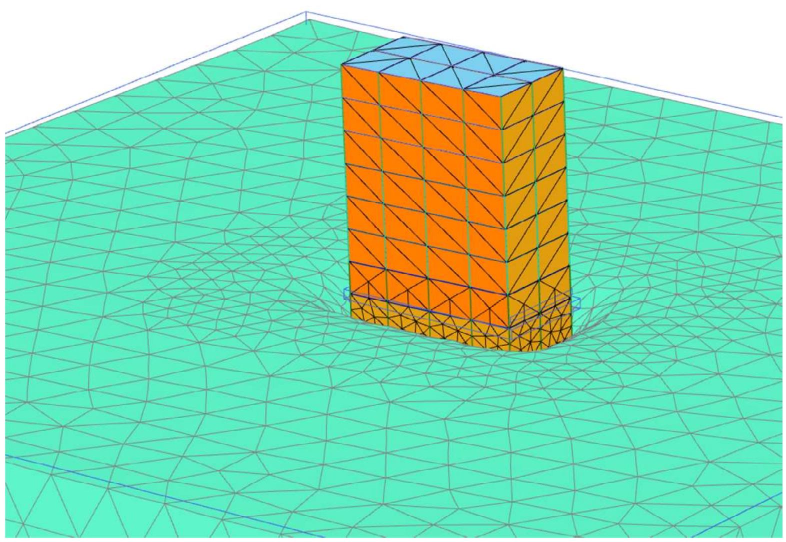


Figure 4. Exaggerated deformed geometry of the building over grid foundation after Aq Qala earthquake.

Table 1. Displacement of the mat foundation in dynamic numerical analyses of this study.

Earthquake	Max Relative Displacement (cm)	Residual Relative Displacement (cm)	Average Total Displacement (cm)
Bam	3.61	1.35	12.11
Avaj	1.63	0.20	6.00
Aq Qala	7.84	4.73	20.24
Ahar	3.27	2.13	7.50
Average	**4.09**	**2.10**	**11.46**

Table 2. Displacement of the grid foundation in dynamic numerical analyses of this study.

Earthquake	Max Relative Displacement (cm)	Residual Relative Displacement (cm)	Average Total Displacement (cm)
Bam	3.04	0.68	11.34
Avaj	1.31	0.19	5.52
Aq Qala	5.93	2.45	19.11
Ahar	2.99	1.87	6.79
Average	**3.32**	**1.30**	**10.69**

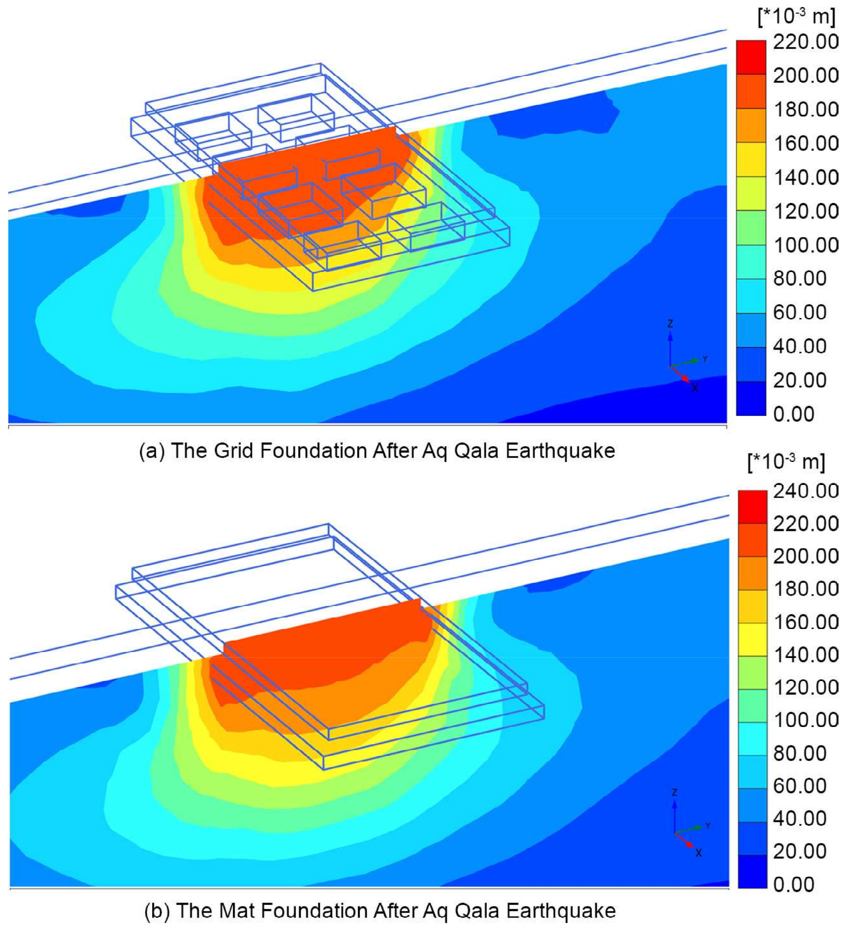


Figure 5. Settlement below (a) the grid foundation and (b) the mat foundation after Aq Qala earthquake.

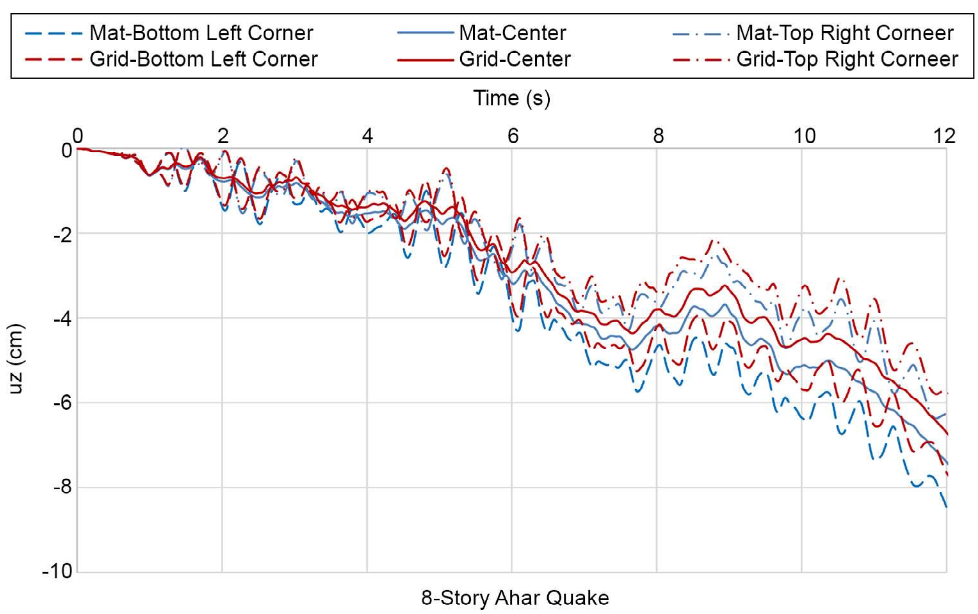


Figure 6. Settlement of the center and two opposite corners of the mat and the grid foundations while applying Ahar earthquake to the model.

4. Discussion on the Results

In Tables (1) and (2), the settlement of the building by the Aq Qala earthquake is considerably different from the remaining ones. In Figure (3), it is obvious that the spectral accelerations of the Aq Qala earthquake are larger than those of the remaining earthquakes in periods of 0.5 to 2 seconds. To probe the natural frequency of the model, a white Gaussian noise was added to a sine sweep of frequencies from 0.1 to 15 Hz (MATLAB, 2020) with an amplitude of 0.2g. The motion was applied to the bottom boundary of the model. The frequencies corresponding to the sharp extremums in the Fourier spectrum were sought, as depicted in Figure (7). It is interesting in this figure that though in the ranges of periods of 0.5 to 1.5 seconds a considerable Fourier amplitude is observed, which interprets the relatively high settlements by the Bam earthquake according to Figure (3), the sharpest maximum belongs to 0.5 seconds, in which the Aq Qala response spectrum has a peak response acceleration in Figure (3). Thus, the resonance of the Aq Qala earthquake with the numerical model of the building and the underlying soil has led to the considerably larger settlements depicted in Tables (1) and (2).

Distribution of normal and shear stress along the cross-section of the foundations is shown in Figures (8) and (9), respectively. Total deviatoric

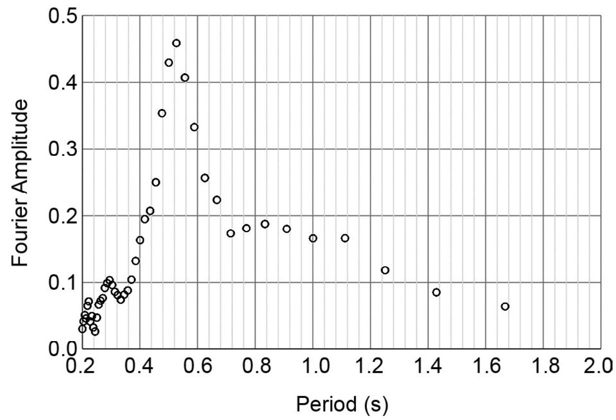


Figure 7. Fourier spectrum of a point on the roof of the 8-story building while a white Gaussian noise was added to a sine sweep of frequencies from 0.1 to 15 Hz was applied to the model.

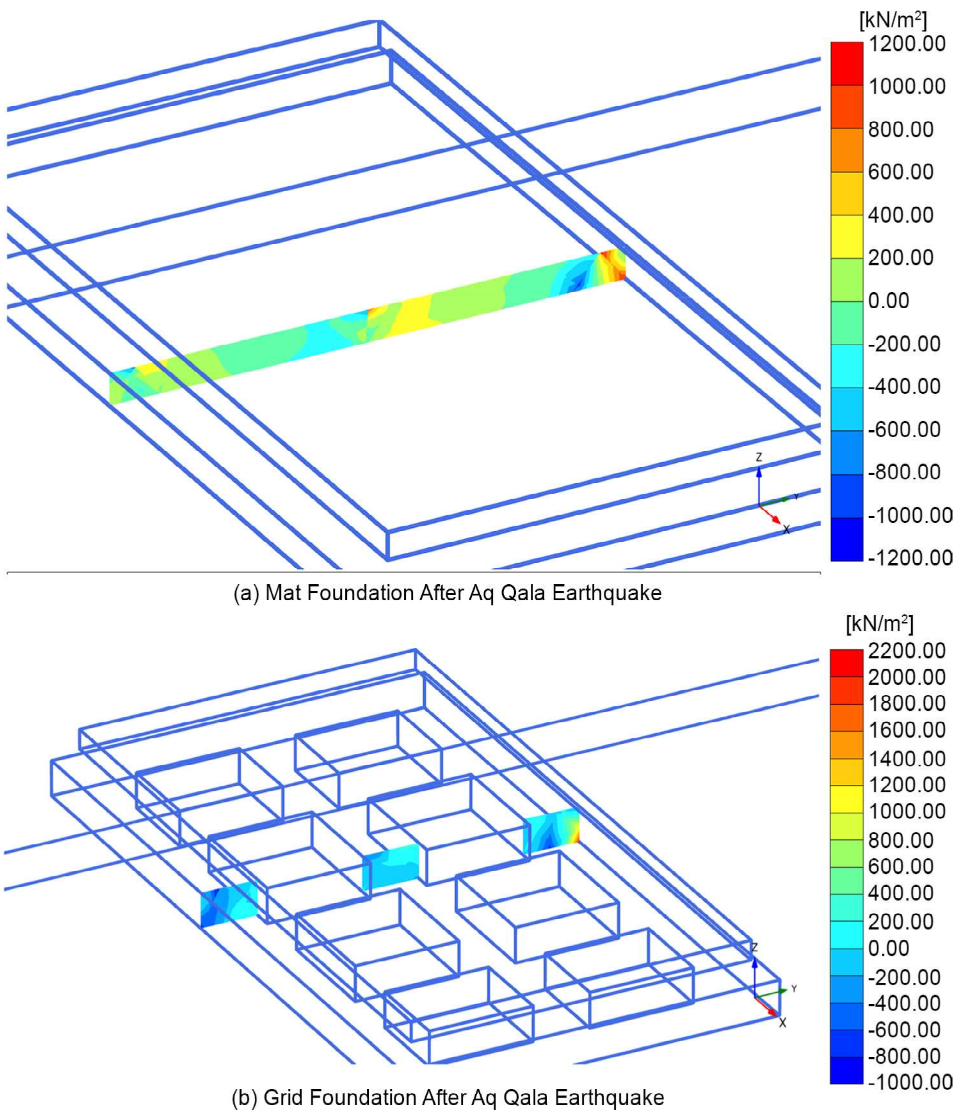


Figure 8. Distribution of shear stress (τ_{yz}) along a cross-section.

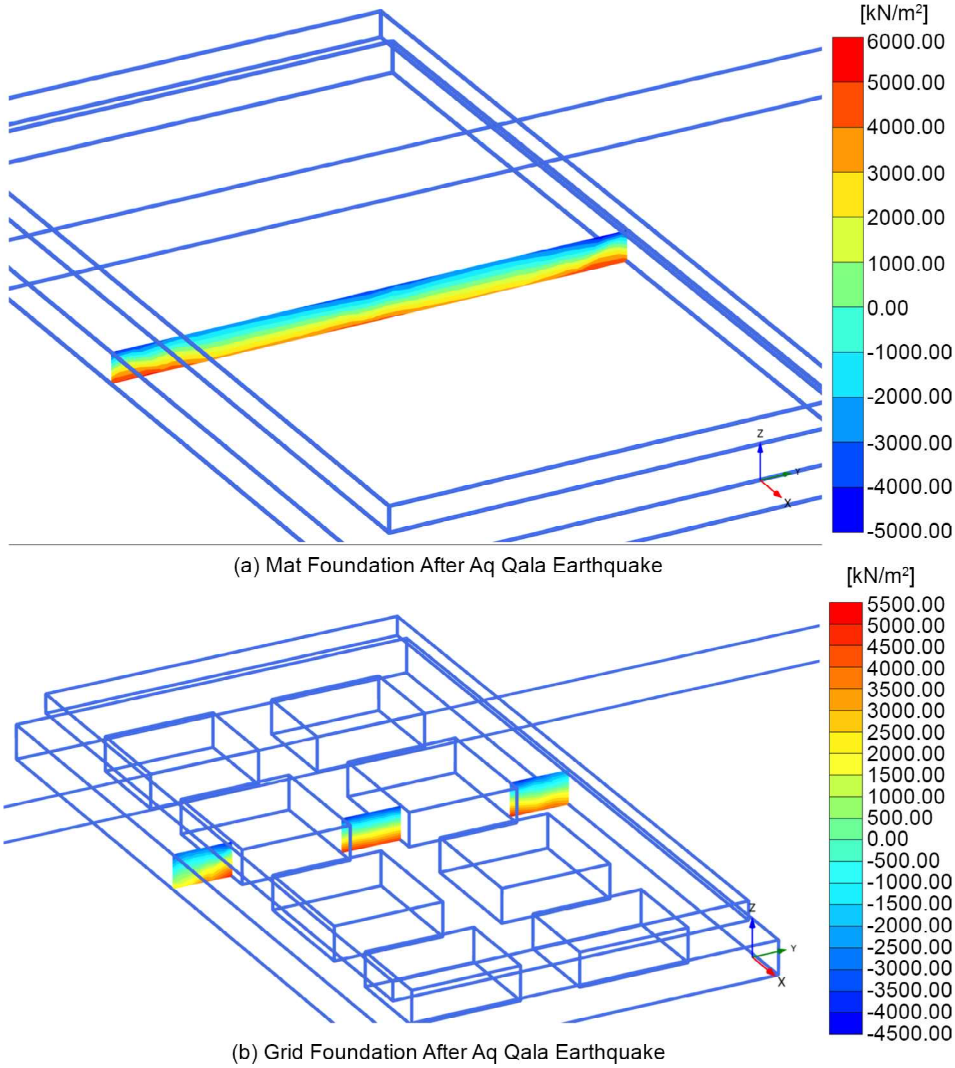


Figure 9. Distribution of normal stress (xx) along a cross-section of the (a) mat and (b) grid foundation after Aq Qala earthquake.

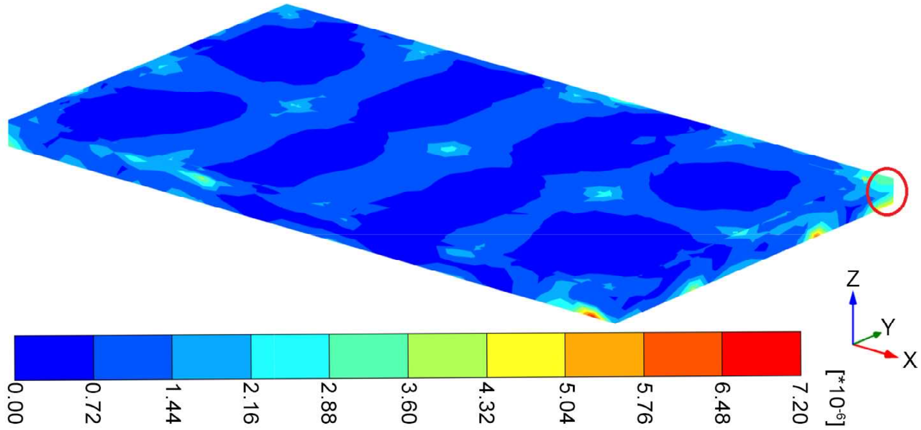
strain $\sqrt{2/3[(\varepsilon_{xx}-\frac{\varepsilon_v}{3})^2+(\varepsilon_{yy}-\frac{\varepsilon_v}{3})^2+(\varepsilon_{zz}-\frac{\varepsilon_v}{3})^2]+}$ $\sqrt{2/3[1/2(y_{xy}^2+y_{yz}^2+y_{zx}^2)^2]}$ distribution is also shown in Figure (10).

Despite some differences in scatter of stress and strain (Total deviatoric strain concentrations, the overall situation of both foundation types is nearly identical in these three figures. The larger deviatoric strains in mat foundations stems from their smaller thickness, compared with the grid foundation. This means that it is the economical issues that determine the better choice among these two types of foundations, as they are almost identical in seismic performance in the case study studied herein.

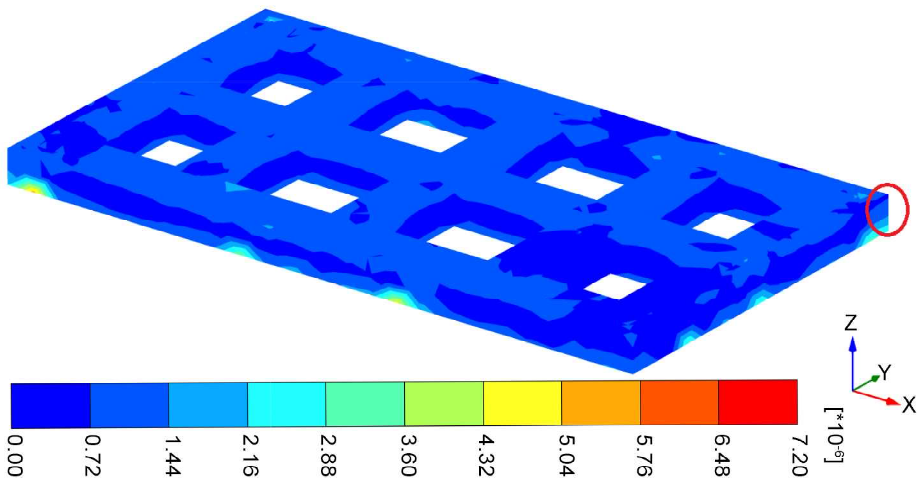
5. Concluding Remarks

In this study, the seismic performance of a mat and a grid foundation underlying an eight-story building was compared with the aid of 3D finite element analyses. The foundations were identical in plan dimensions (10*18 m), and the grid foundation was 30 cm thicker than the 60-cm-thick mat. Although the volume of the grid foundation (110 m^3) is a little bit more than that of the mat (108 m^3), more detailed analyses are required to evaluate the more economical foundation type between mat and grid, considering the amount of reinforcing steel bars and the cost of construction, including concrete molding. This study showed that in terms of foundation settlement under seismic loading, the grid foundation was better than the mat foundation, thus being recommended for consideration in foundation design in areas of high seismicity.

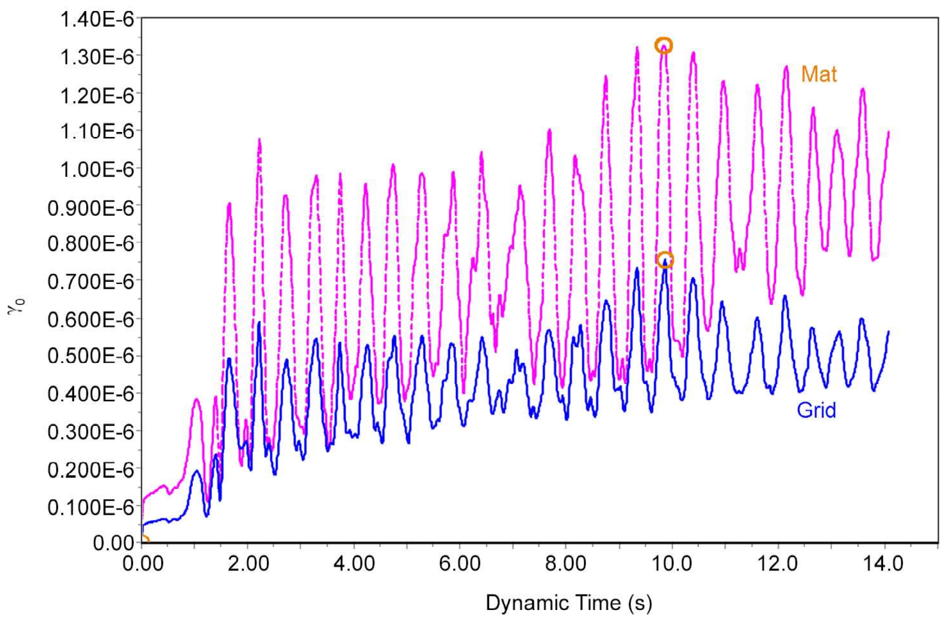
It is also shown that comparison of the frequency



(a) Mat Foundation After Aq Qala Earthquake Z



(b) Grid Foundation After Aq Qala Earthquake,



(c) Its Change with Time during Loading at a Corner Defined by Red Circle

Figure 10. Distribution of total deviatoric strain (s) along a cross-section of the (a) mat, (b) grid foundation after Aq Qala earthquake, and (c) its change with time during loading at a corner defined by red circle.

content of the input motions with that of the model is useful in interpreting the results. To define the frequency content of the models with different constituents, e.g., the building and the underlying soil strata in this study, the application of white Gaussian noise added to a sine sweep of frequencies to the model and inspecting the results was beneficial.

Acknowledgment

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