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EFFECTS OF GEOGRID REINFORCEMENT TO MITIGATE EARTHQUAKE HAZARDS OF MEDIUM-RISE BUILDINGS UNDER DIFFERENT EARTHQUAKE MOTIONS

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ABSTRACT
Shallow foundations on the weak soils result in low bearing capacity and/or excessive settlement problems. This can cause structural damage, reduction in the durability, and/or deterioration in the performance level. Some of the soil improvement methods are to replace the weak cohesive soil by a stronger granular fill or to increase the dimensions of the footing, or a combination of two. Recently, the use of reinforced soils under the shallow foundations has received considerable attention. The beneficial effects of reinforcements in foundation applications have been studied by several investigators. In addition, the use of geosynthetics under foundations is an innovative and alternative way of absorbing the seismic energy and mitigate excitations transmitting to upper layers of soils and foundation of overlying structures. This comparative study presents the results of numerical simulations of medium rise buildings on unreinforced and reinforced sand foundation to investigate the effects of earthquake characteristics and reinforcement length to mitigate the earthquake hazards of medium-rise buildings. Various reinforcement lengths in terms of foundation length "B" have been decided. The study has been carried out by using a finite element code, PLAXIS 2D. Numerical results revealed that the geosynthetic-reinforced sand is quite an effective method to mitigate the seismic performance of the mid-rise buildings and earthquake characteristics in addition to the reinforcement zone play a very important role by means of seismic performance.

Keywords: *Earthquake, Geogrid, Medium-rise buildings, Numerical Modelling, Soil reinforcement*

1. INTRODUCTION

The use of geosynthetics for soil reinforcement purposes have been widely used in various geotechnical engineering applications, including bridge approach slabs, bridge abutment, building footings, and embankments. Literature suggests that the inclusion of reinforcement in soil foundations is a cost-effective solution to increase the bearing capacity and to decrease the settlement of footings compared to the conventional methods such as replacing natural soils or increasing the dimensions of the footings. Geogrids are the most commonly used geosynthetic materials to reinforce the foundation soil.

By definition, geosynthetics are synthetic materials that are commonly used to solve civil and geotechnical engineering problems. It is well known that geosynthetics are capable of absorbing dynamic forces and transmitting less dynamic forces to which engineering structure it is implemented. More specifically, the use of geosynthetics under foundations can absorb seismic energy and mitigate excitations transmitting to upper layers of soils and foundation of overlying structures. In addition, tensile strength of the material and the interface between soil and geosynthetic material increases the shear resistance of soil under dynamic conditions. Other important parameters that play an important role in bearing capacity under static and dynamic conditions include the depth to the first layer of reinforcement, vertical spacing of reinforcement layers, and number of reinforcement layers and the properties of the reinforcement.

Literature suggest that the dynamic interface shear properties of geosynthetic materials and geosynthetic reinforced soils is directly related with the proposed energy dissipation along structures and geosynthetic interfaces (Yegian et al.,1995, Kavazanjian et al.,1991, Yegian and Lahlaf, 1992). A study on the bearing capacity of footings on geogrid reinforced sand by Yetimoglu et al. (1994) suggests that the optimum depth would be larger for settlement ratios greater than 6 and the highest bearing capacity occurs at embedment depth of approximately 0.3B. A similar study which investigates the effects of reinforcement parameters of foundations on carrying load and settlements by Adams and Collin (1997) revealed that when the number of reinforcement is N = 3, maximum carrying capacity was obtained and it was determined that soil improvement was not only dependent on number of layers but also varied with total reinforcement depth and vertical space between reinforcements. Another study by Yildiz et al. (2006) investigated the bearing capacity of circular foundations settled on geogrid reinforced sand by using finite element method. During the study, the bearing capacity was increased when the first reinforcement layer was selected as 0.3D and the number of reinforcement layers were selected as N= 4. Alamshahi and Hataf (2009) proved that the inclusion of geogrid layers increases bearing capacity of foundation and decreases the settlement. This statement was declared by a study by Demiroz and Tan (2010) that was performed on design factors affecting the settlement of strip foundation on geogrid-reinforced sand. It is revealed that the settlement increases until the number of reinforcement is N = 3. The amount of settlement increases until 2^{nd} level of reinforcement depth rate (u = 0.5B) and it decreases after this level. Mahboubi and Keyghobadi (2012) investigated the bearing capacity of a strip foundation on geogrid reinforced sand. Results suggest that increasing number of geogrid layers has a positive effect in bearing capacity. Marto et al. (2013) performed a comparative study on the effects of geogrid reinforcement on bearing capacity of a soil under static loading conditions. It is seen that bearing capacity increases and settlement decreases with respect to the increment of reinforcement layers. Edinçliler and Yildiz (2016) investigated the seismic performance of mid-rise buildings overlying the geogrid reinforced sand. Their study revealed that reinforcement depth has an important effect for the seismic performance.

In a study carried out by Edinçliler and Toksoy (2017a), the seismic performance of the building model exposed to two different earthquakes with different characteristics was investigated by using the Plaxis 2D. It was observed that there were significant decreases in the floor displacements and the accelerations on the model which was built on geogrid reinforced sand. By evaluating the effects of geogrid layer number and geogrid layer width on the seismic behavior of the building, an optimally reinforced soil layer model was created to reduce the earthquake damages in the building. In another study, a series of finite element analyzes were performed using PLAXIS 2D to determine the effects of earthquake characteristics on the seismic behavior of the middle-storey buildings built on geogrid-reinforced foundations. The effects of the parameters as the number of geogrid layers, the distance of the first geogrid layer to the building base and the width of the geogrid layer were determined. It was seen that geogrid-reinforced soil improvement method for middle-storey buildings could be an effective method for reducing earthquake damages and proved that the method presented was more effective for strong ground motions (Edinçliler and Toksoy, 2017b). In another study, the seismic performances of low and medium rise buildings on geogrid reinforced foundations were compared for different performance indicators (Edinçliler and Toksoy, 2017c). The aim of this parametric study is to determine the effects of earthquake characteristics and geogrid reinforcement zone to mitigate the earthquake hazards of the mid-rise buildings. A five story building has been modelled over the geogrid-reinforced sand and dynamic response analyses were performed. Obtained results are compared with respect to the earthquake motions and geogrid reinforcement width to the unreinforced case.

2. NUMERICAL STUDY

In this study, a mid-rise (5 storey) building has been modelled and the foundation soil was reinforced with 4 layers of geogrids using the PLAXIS program. As previously investigated by Edinçliler and Yildiz (2016;2017), number of geogrid layers in soil-geogrid reinforcement technique is essential. They stated that the use of 4-layer reinforcements is quite effective to improve the seismic performance of mid-rise structures. For this reason, this study considers a 4 layer geogrid reinforcement. Dimensions are; width of the building B=10m, height of each storey h=3m and depth of the basement is 2m. Mesh of the FEM was chosen as 50m x 100m. The first reinforcement was placed 3m under the footing and the vertical distance between two reinforcement layers is 2m. Total reinforcement depth (d) was calculated with respect to the formulation of d= u + (N-1).h, where h is the vertical distance between two geogrid layers (Patra et al., 2005). Figure 1 represents the both FEM models and dimensions.

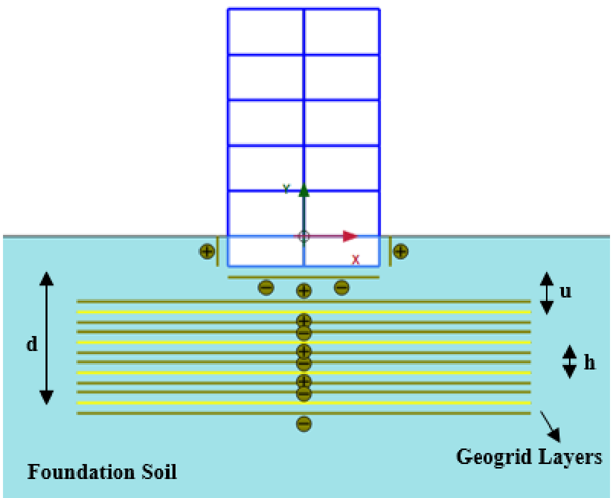

Fig. 1. FEM model

2.1. Material Properties

Sand material was modelled using hardening soil model and the soil parameters are given in Table 1. Structural elements of the model are modelled as plate elements in PLAXIS. Material parameters of the footing and building can be seen in Table 2. Geogrids that are used as reinforcement material are uniaxial type and length of each geogrid layer is model dependent and changes in the range from 10m to 30m (B to 3B). Material properties of geogrid material is given in Table 3.

Table 1. Foundation soil properties

γ_{unsat}	17 kN/m^3
γ_{sat}	17 kN/m^3
c'_{ref}	10 kN/m^2
Ø	30°
ψ	0
E	15.000 kN/m^2

Table 2. Footing and building parameters

	Footing	Building
EA	12E^6 kN/m	9E^6 kN/m
EI	400E^3 kN/m	67.50E^3

Table 3. Geogrid properties

	Geogrid
EA	500000 kN/m

2.2. Dynamic Excitations

Real earthquake records obtained from BU-KOERI have been used for the dynamic response analysis, which are 1999 Kocaeli Earthquake (Yarımca Station) with a PGA of 0.32g and pre-dominant frequency of 0.29Hz (Mw:7.6) in addition to the 2014 Gökçeada Earthquake (Meteoroloji Station) with a PGA value of 0.18g and 2.49Hz of pre-dominant frequency(Mw:6.5). Related accelerogram can be seen in Figure 2 and 3.

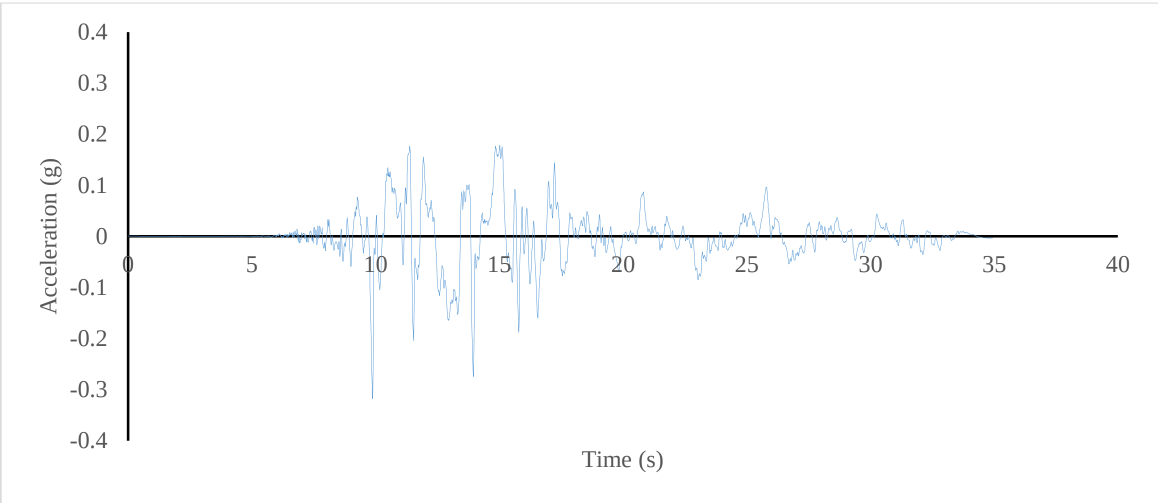

Fig. 2. Kocaeli Earthquake accelerogram (Yarımca Station)

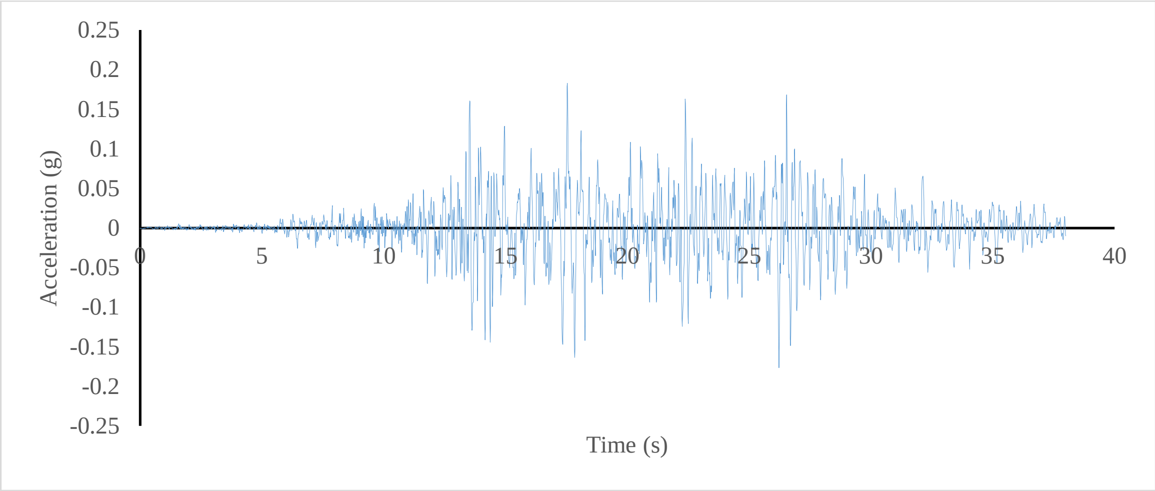

Fig. 3. Gökçeada Earthquake accelerogram (Meteoroloji Station)

3. RESULTS UNDER GOKCEADA EARTHQUAKE MOTIONS

Numerical results are represented in terms of transmitted accelerations and total displacements. Results are given for unreinforced and reinforced cases for the length of geogrid layers as B, 2B and 3B.

3.1. Results in Terms of Total Displacements

Total displacement values are determined for the bottom of the structure, the basement, 1st, 2nd, 3rd, 4th and 5th floors. Displacement-time histories for unreinforced case is given in Figure 4.

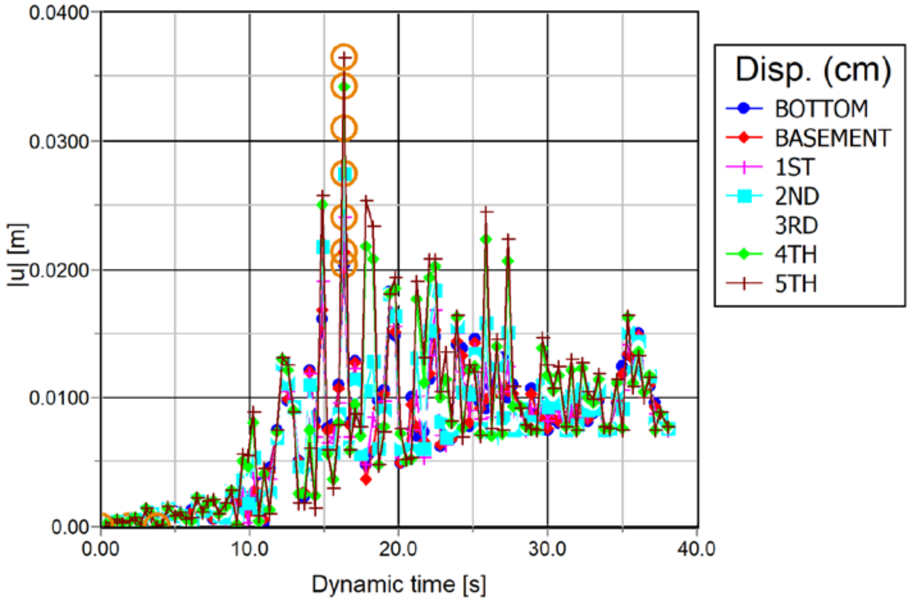

Fig. 4. Displacement-Time Histories in unreinforced case

In the unreinforced case, bottom of the structure displaces 2cm whereas basement, the 1st, 2nd, 3rd, 4th and 5th floors displaces 2.1cm, 2.4cm, 2.7cm, 3.1cm, 3.4cm and 3.6cm, respectively. Displacement-time histories of the pre-defined points of the structure which was constructed on the foundation soil reinforced with B length geogrid layers are represented in Figure 5.

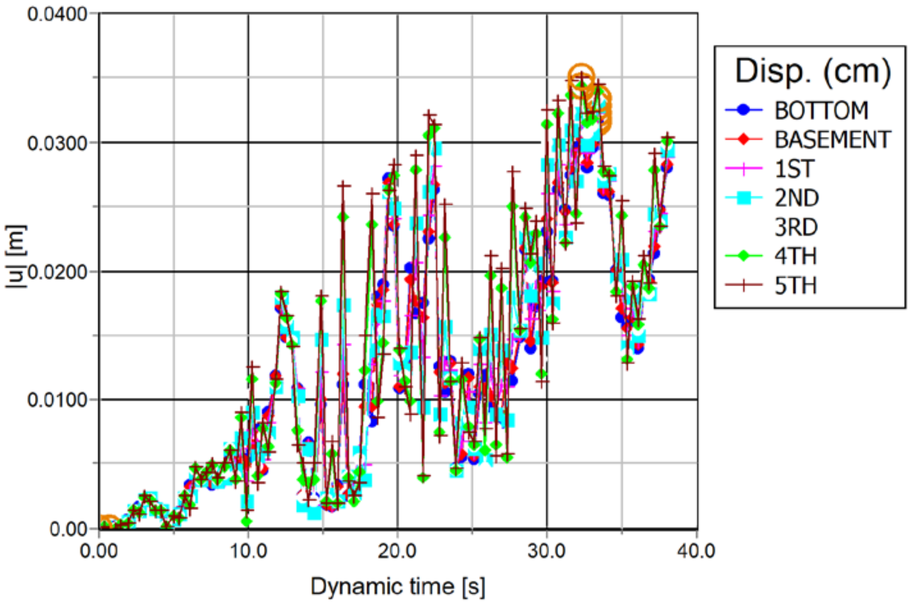

Fig. 5. Displacement-Time Histories in B length case

As the unreinforced case, total displacements increase with the structural height in geogrid reinforced cases. The bottom, basement and the 1st floor over the B length geogrid layers displace 3.2cm. Displacements increase a bit to 3.3cm on the 2nd and 3rd floors as 3.4cm and 3.5cm of displacement values were obtained from the 4th and the 5th floors. Displacement-time histories of the pre-defined points of the structure which was modelled on the foundation soil reinforced with 2B length geogrid layers are represented in Figure 6.

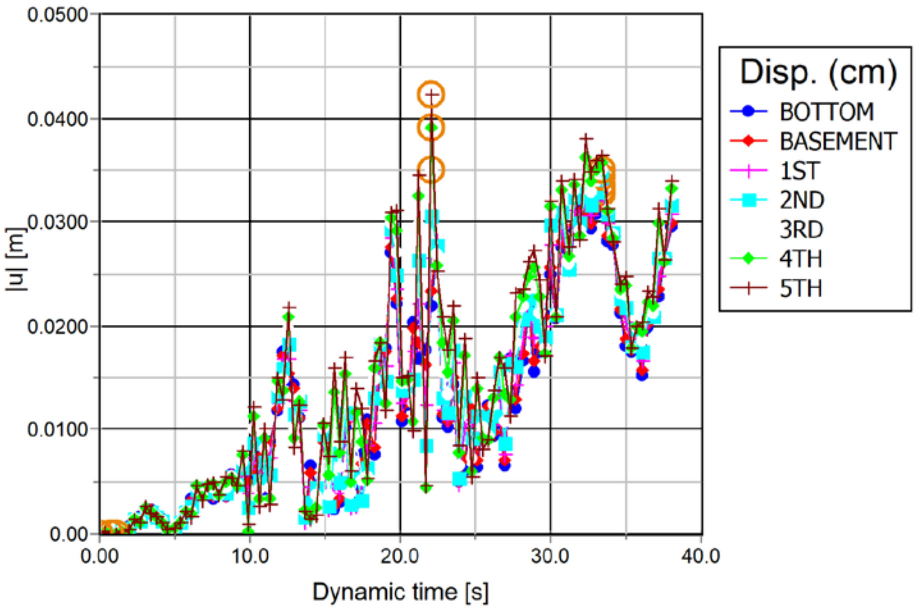

Fig. 6. Displacement-Time Histories in 2B length case

Total displacement values in the 2B length case appear to be 3.3cm at the bottom and the basement of the structure. Measurements increase with respect to the structural height as 4.2cm of displacement value was observed at the 5th floor. Obtained Displacement-time histories in the 3B length case are given in Figure 7.

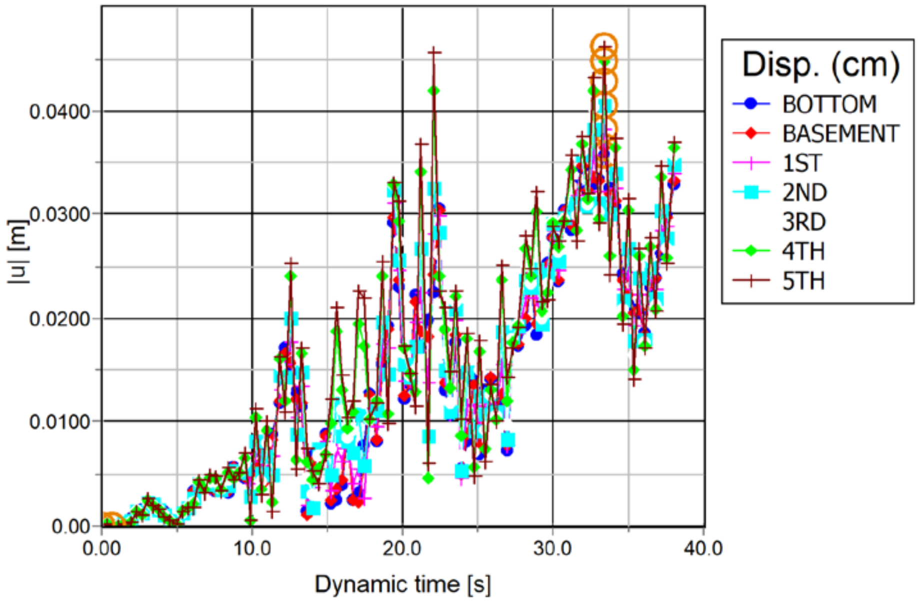

Fig. 7. Displacement-Time Histories in 3B length case

Obtained displacement values in 3B length reinforced case follows the similar trend. Basement of the structure displaces 3.6cm and as the structural height increases obtained displacement values increase as well, up to 4.3cm in the 3rd floor and the 4.6cm at the top.

3.2. Results in Terms of Transmitted Accelerations

Just as it is in section 3.1; Acceleration-Time Histories of those pre-defined locations in unreinforced case is given in Figure 8.

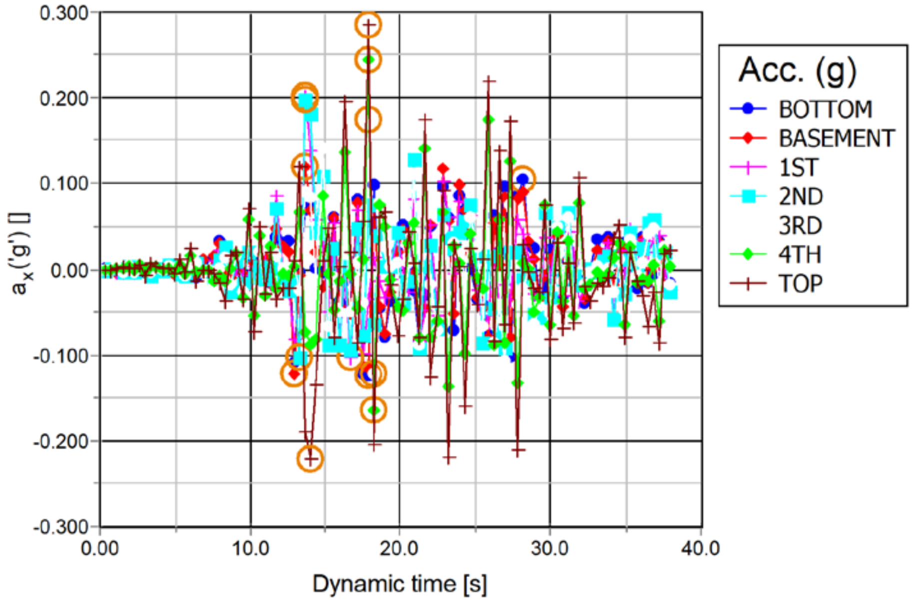

Fig. 8. Acceleration-Time Histories in unreinforced case

In the unreinforced case, obtained transmitted acceleration values are 0.12g at the bottom and the basement and 0.20g on the 1st and the 2nd floors. The transmitted acceleration values on the 3rd, 4th and 5th floors are obtained to be 0.17g, 0.25g and 0.29g; respectively. Acceleration-time histories in B length reinforced case is given in Figure 9.

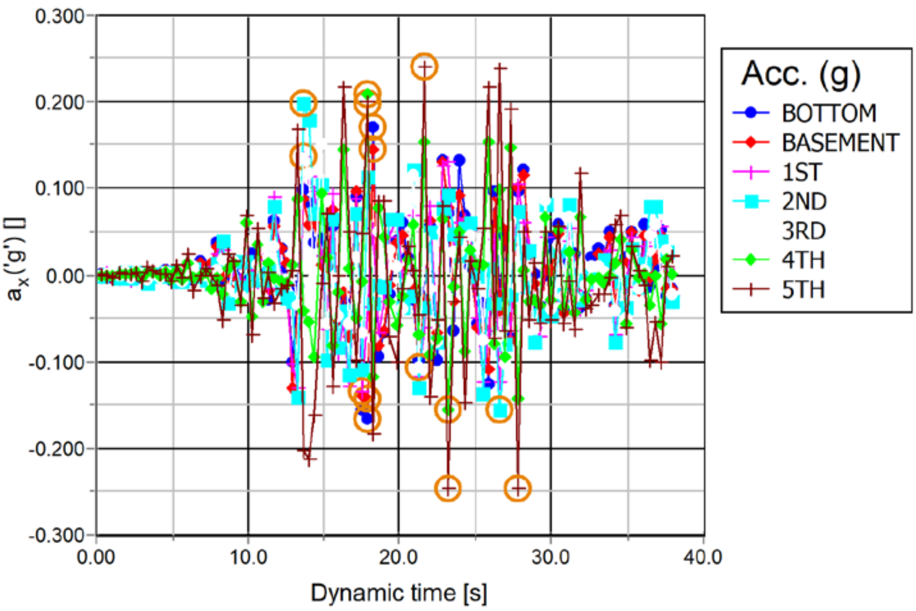

Fig. 9. Acceleration-Time Histories in B length reinforced case

Bottom of the structure experience 0.17g of acceleration under the Gökçeada Earthquake record. Under the given dynamic motions deamplification phenomenon occurs at the basement and on the 1st floor with the 0.14g of acceleration value. Results increase with respect to the height of the structure and 0.25g was measured at the top floor. Acceleration-time histories in 2B length reinforced case is given in Figure 10.

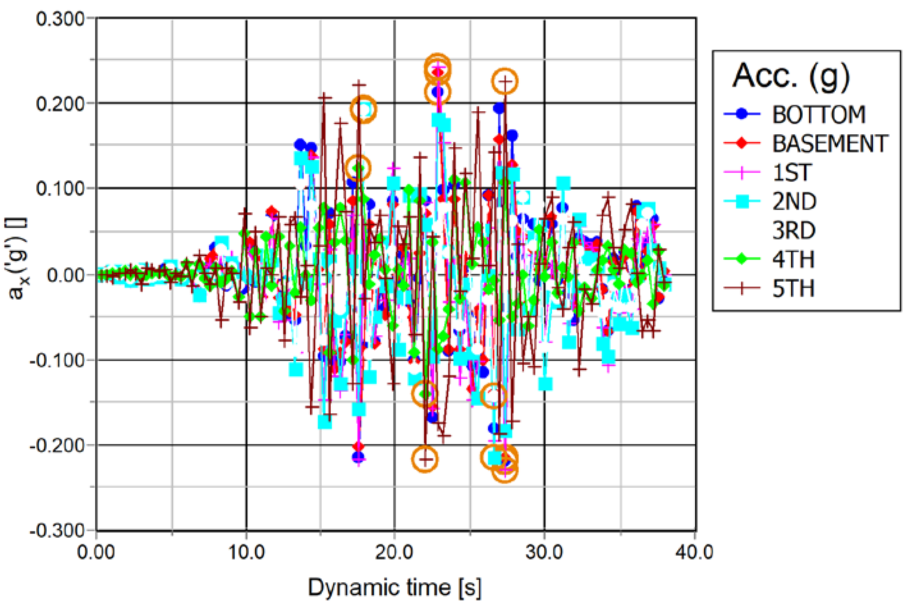

Fig. 10. Acceleration-Time Histories in 2B length reinforced case

Bottom of the structure and the 2nd floor experience 0.22g whereas the basement and the 1st floor experience as 0.24g. De-amplification, due to the inclusion of geogrid layers, takes place as 0.19g and 0.14g on the 3rd and 4th floors, respectively. At the top floor is calculated as 0.23g. Acceleration-time histories in 3B length reinforced case is given in Figure 11.

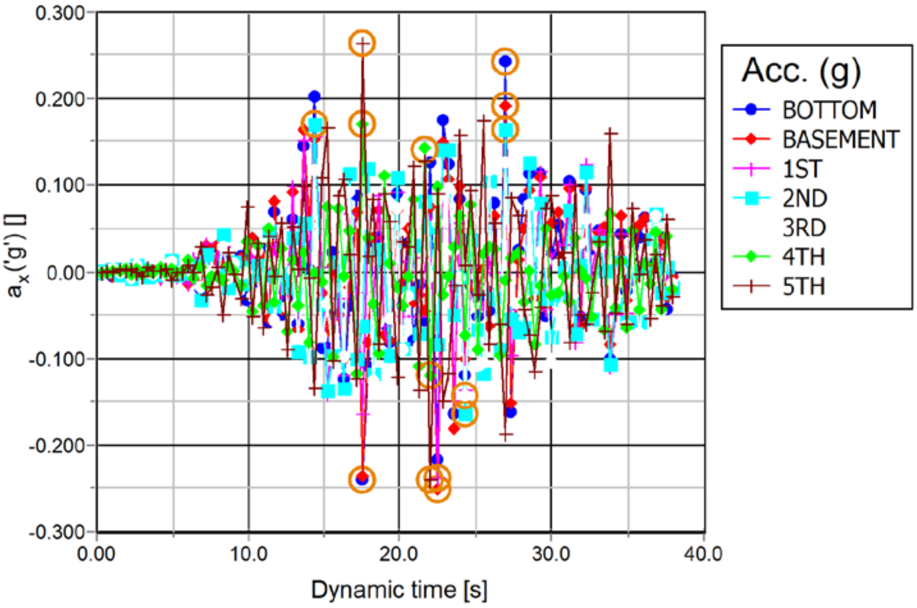

Fig. 11. Acceleration-Time Histories in 3B length reinforced case

In the 3B length reinforced case, the bottom and the 1st floor experience as 0.24g. With the inclusion of geogrids, transmitted acceleration values decrease to 0.17g and to 0.14g on the 2nd and the 3rd floors, respectively. 5th floor is affected by 0.27g of acceleration.

4. RESULTS UNDER KOCAELI EARTHQUAKE MOTIONS

Numerical results are represented in terms of transmitted accelerations and total displacements. Results are given for unreinforced and reinforced cases for the length of geogrid layers as B, 2B and 3B.

4.1. Results in Terms of Total Displacements

Total displacement values are determined for the bottom of the structure, the basement, 1st,2nd, 3rd, 4th and 5th floors. Displacement-time histories for unreinforced case is given in Figure 12.

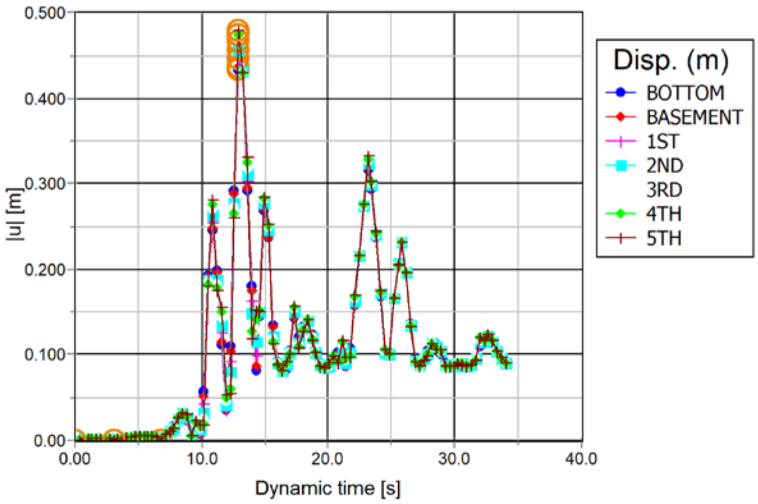

Fig. 12. Displacement-Time Histories in unreinforced case

In the unreinforced case, bottom of the structure displaces 43.2cm whereas basement, the 1st, 2nd, 3rd, 4th and 5th floors displaces 43.6cm, 44.6cm, 45.7cm, 46.6cm, 47.4cm and 47.9cm, respectively. Displacement-time histories of the pre-defined points of the structure which was constructed on the foundation soil reinforced with B length geogrid layers are represented in Figure 13.

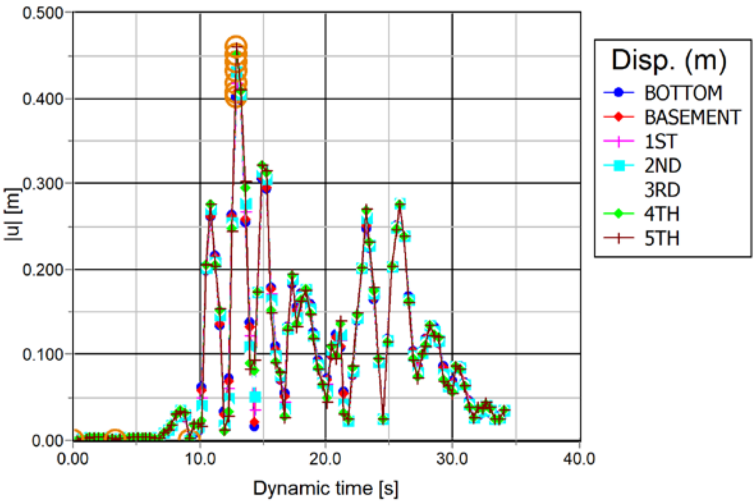

Fig. 13. Displacement-Time Histories in B length case

As the unreinforced case, total displacements increase with the structural height in geogrid reinforced cases. The bottom, basement and the 1st floor over the B length geogrid layers displace 40.1cm, 40.6cm and 41.8cm respectively. Displacements increase a bit to 43cm and 44.2cm on the 2nd and 3rd floors, respectively. Under the defined earthquake record, 45.1cm and 45.9cm of displacement values were obtained from the 4th and the 5th floors, respectively. Displacement-time histories of the pre-defined points of the structure which was modelled on the foundation soil reinforced with 2B length geogrid layers are represented in Figure 14.

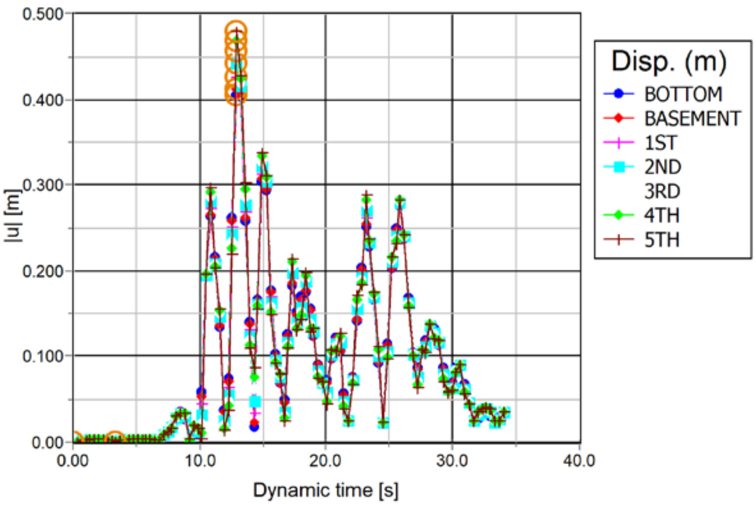

Fig. 14. Displacement-Time Histories in 2B length case

Total displacement values in the 2B length case appear to be 40.5cm at the bottom and the basement of the structure. Measurements increase with respect to the structural height as 47.9cm of displacement value was observed at the 5th floor. Obtained Displacement-time histories in the 3B length case are given in Figure 15.

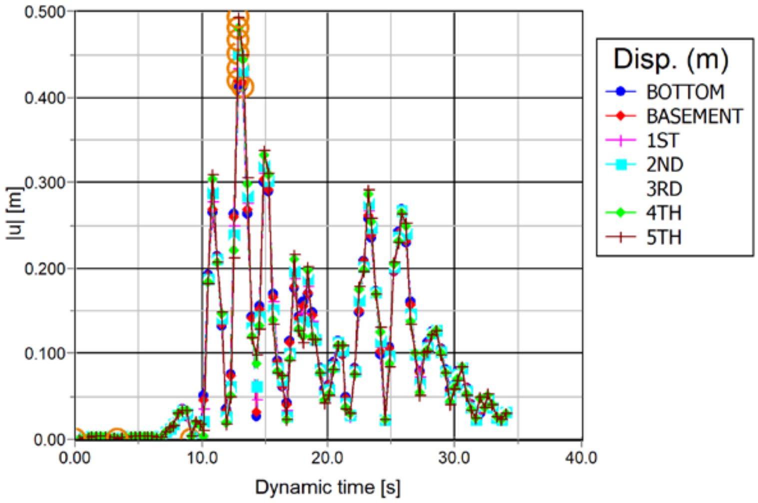

Fig. 15. Displacement-Time Histories in 3B length case

Obtained displacement values in 3B length reinforced case follows the similar trend. Basement of the structure displaces 41.8cm and as the structural height increases obtained displacement values increase as well, up to 46.7cm in the 3rd floor and the 49.3cm at the top.

4.2. Results in Terms of Transmitted Accelerations

Acceleration-Time Histories of those pre-defined locations in unreinforced case is given in Figure 16.

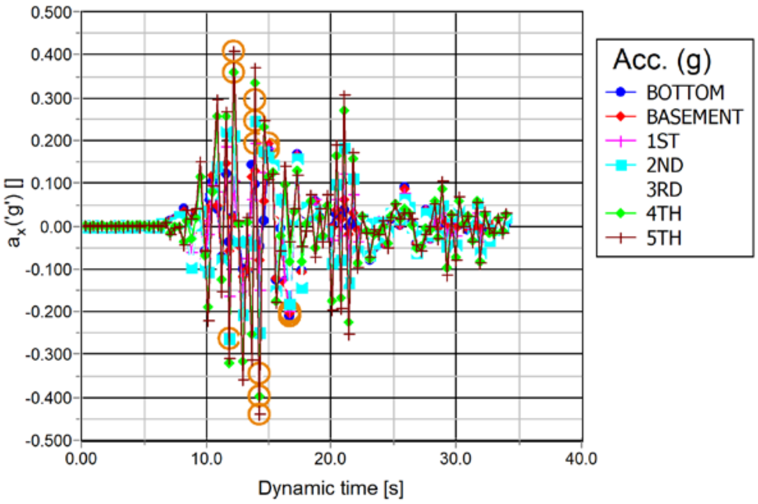

Fig. 16. Acceleration-Time Histories in unreinforced case

Under the pre-defined earthquake record, obtained transmitted acceleration values are 0.21g at the bottom and the basement and 0.20g on the 1st floors in the unreinforced case. The transmitted acceleration values on the 2nd, 3rd, 4th and 5th floors are obtained to be 0.26g, 0.34g, 0.40g and 0.44g; respectively. Acceleration-time histories in B length reinforced case is given in Figure 17.

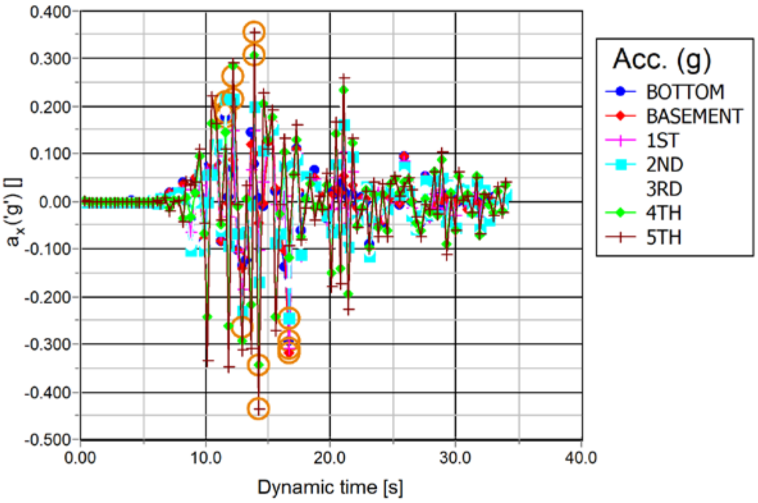

Fig. 17. Acceleration-Time Histories in B length reinforced case

Bottom of the structure experience 0.29g of acceleration under the Kocaeli Earthquake record. Under the given dynamic motions de-amplification phenomenon occurs at the 2nd and 3rd floor with the 0.25g and 0.26g of acceleration value, respectively. Results increase with respect to the height of the structure and 0.44g was measured at the top floor. Acceleration-time histories in 2B length reinforced case is given in Figure 18.

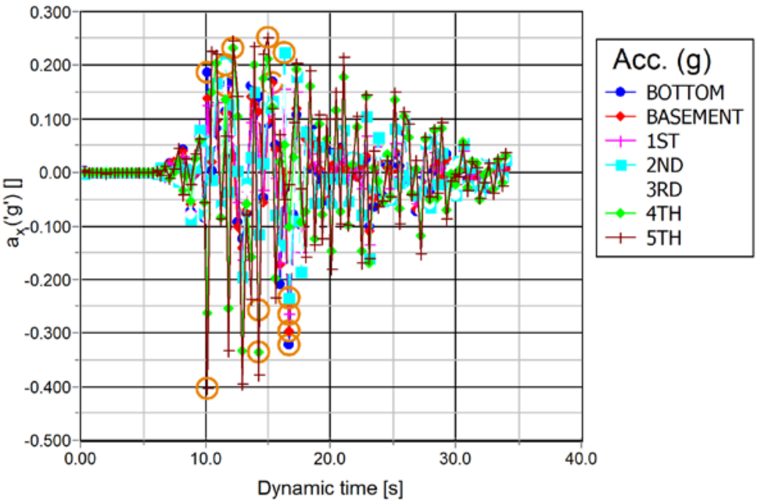

Fig. 18. Acceleration-Time Histories in 2B length reinforced case

Bottom of the structure experience 0.32g of acceleration whereas the 1st floor experience as 0.27g. De-amplification, due to the inclusion of geogrid layers, takes place as 0.24g and 0.26g on the 2nd and 3th floors, respectively. Acceleration-time histories in 3B length reinforced case is given in Figure 19.

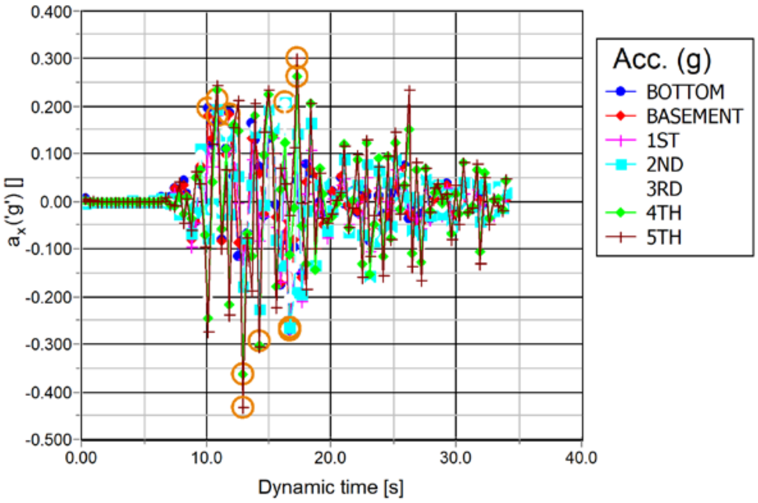

Fig. 19. Acceleration-Time Histories in 3B length reinforced case

In the 3B length reinforced case, the bottom and the 1st floor experience 0.27g of acceleration. Transmitted acceleration values are measured as 0.26g and to 0.29g on the 2nd and the 3rd floors, respectively. 5th floor is affected by 0.43g of acceleration.

5. EVALUATION OF THE RESULTS

For ease of comparison, numerical results obtained from Gökçeada Earthquake in terms of total displacement and transmitted acceleration values are summarized in Table 4 and Table 5.

Table 4. Total displacement values under Gökçeada Earthquake

Disp. (cm)	Bottom	Basement	1ST	2ND	3RD	4TH	5TH
Unreinf.	2.0	2.1	2.4	2.7	3.1	3.4	3.6
B	3.2	3.2	3.2	3.3	3.3	3.4	3.5
2B	3.3	3.3	3.4	3.4	3.5	3.9	4.2
3B	3.6	3.6	3.8	4.1	4.3	4.5	4.6

Table 5. Transmitted acceleration values under Gökçeada Earthquake

Acc. (g)	Bottom	Basement	1ST	2ND	3RD	4TH	5TH
Unreinf.	0.12	0.12	0.20	0.20	0.17	0.25	0.29
B	0.17	0.14	0.14	0.20	0.20	0.21	0.25
2B	0.22	0.24	0.24	0.22	0.19	0.14	0.23
3B	0.24	0.25	0.24	0.17	0.14	0.17	0.27

It is well known that geogrid reinforced soil foundations have a tendency to decrease the vertical displacements but to increase the horizontal ones, which may lead to observe increased total displacements on the structure constructed over it. In Table 4, total displacement values in many of the reinforced cases are higher than the unreinforced case related to increasing the geogrid reinforcement length.

On the other hand, the inclusion of geogrid layers in the foundation soil diminish seismic energy. As seen in Table 5, an important part of the transmitted accelerations is absorbed in different ranges. When the length of geogrid reinforcements equals to the length of the structure (B), 1st floor accelerations can be decreased by more than 30% in comparison with the unreinforced case. In addition, 4th and 5th floor accelerations are approximately 15% less in B length reinforced case. Apparently, 2B length reinforcement in the foundation soil gives the optimum results. Transmitted accelerations at top of the structure successfully reduces by up to 44% compared with the unreinforced case. Similarly, in 3B reinforced case, transmitted accelerations are up to 32% less than the unreinforced case. Total displacement and transmitted acceleration values under Kocaeli Earthquake excitations are given in Table 6 and Table 7, respectively.

Table 6. Total displacement values under Kocaeli Earthquake

Disp. (cm)	Bottom	Basement	1^{ST}	2^{ND}	3^{RD}	4^{TH}	5^{TH}
Unreinforced	43.2	43.6	44.6	45.7	46.6	47.4	47.9
B	40.1	40.6	41.8	43.0	44.2	45.1	45.9
2B	40.5	41.2	42.6	44.2	45.6	46.9	47.9
3B	41.2	41.8	43.4	45.1	46.7	48.1	49.3

Table 7. Transmitted acceleration values under Kocaeli Earthquake

Acc. (g)	Bottom	Basement	1^{ST}	2^{ND}	3^{RD}	4^{TH}	5^{TH}
Unreinforced	0.21	0.21	0.20	0.26	0.34	0.40	0.44
B	0.29	0.32	0.31	0.25	0.26	0.34	0.44
2B	0.32	0.30	0.27	0.24	0.26	0.34	0.41
3B	0.27	0.26	0.27	0.26	0.29	0.36	0.43

Unlike the obtained results from Gökçeada Earthquake, total displacement values are successfully reduced by up to 7% at the bottom of the structure and up to 4% at top of the structure under Kocaeli Earthquake excitations (Table 6).

As can be inferred from Table 7, the inclusion of geogrid layers in the foundation soil diminish seismic energy. When the length of geogrid reinforcements equals to the length of the structure (B), bottom, basement and 1^{st} floor accelerations experience a slight increase in terms of transmitted accelerations in comparison with the unreinforced case. On the other hand, 3^{rd} and 4^{th} floor accelerations are approximately %24 and 15% less in B length reinforced case, respectively. Apparently, 2B length reinforcement in the foundation soil gives the optimum results under Kocaeli Earthquake record too. Transmitted accelerations at top of the structure successfully reduces by up to 8% on the 2^{nd} floor, 24% on the 3^{rd} floor, 15% on the 4^{th} floor and 7% on the 5^{th} floor in terms of transmitted acceleration values compared with the unreinforced case. Similarly, in 3B reinforced case, transmitted accelerations are up to 15% less than the unreinforced case.

6. CONCLUSIONS

In this study, the effects of different parameters as the reinforcement lengths depending on the foundation width, B, and earthquake characteristics to mitigate the earthquake hazards of the medium rise buildings were investigated. Comparative study showed that the inclusion of geogrid layers in the foundation soil may lead to increased total displacement values for the structure depending on the affecting dynamic motion. The displacement values are much higher for the increased lengths of the reinforcement layers. By means of transmitted accelerations along the structure, accelrations are up to 44% less in comparison with the unreinforced case under Gökçeada Earthquake excitations. Highest reduction ratios are observed in 2B length reinforced case. Similar results have been achieved from the dynamic response analyses with Kocaeli Earthquake record. Transmitted acceleration values successfully reduced by up to 24% in 2B length reinforced case which has been determined as the optimal length for this study. It is seen that the reduction ratios lessen as the reinforcement length increases. Numerical results clearly show that earthquake characteristics play a major role on the dynamic response of such structures. In light of the numerical results obtained from this study, it is seen that geogrid-reinforced sand foundations are more successful at reducing total displacement values under stronger ground motions (Kocaeli Earthquake) as well as they are much better at reducing transmitted acceleration values (energy absorption) under weaker ground motions (Gökçeada Earthquake). Comparison of the dynamic responses upon pre-defined performance indicators between unreinforced and reinforced models reveal that the implemented reinforcement technique express a significant difference.

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