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Enhancing the Seismic Stability of Shallow Foundations on Soft Clay with Geogrid-Reinforced Dense Sand Layers

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Research Article

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Posted Date: November 24th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-11745184/v1

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Additional Declarations: No competing interests reported.

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Abstract

When exposed to seismic actions, shallow footings erected on soft clay soils regularly encounter severe stability problems, most remarkably extreme settlement, horizontal displacement, change in stresses and amplified ground acceleration. This is mainly owing to the shaking related thru earthquakes that led to the generated seismic load in horizontal direction then shifted through the soft soil to the footing. For this situation, ground enhancement is compulsory, so this work inspects the shallow square footing response having soft clay bed partially replacement sand, when exposed to the Kahramanmaraş Earthquake with intensity (0.77g) via shakings table device. The upper layer of soft clay replaced with sand in dense state enhanced with geogrid, at thickness primarily with 1B, then with 1.5B (as a percentage of B, where B is a footing width) was, Dynamic response which mainly include acceleration, settlement; and horizontal displacement, has been examined. The settlement and the horizontal displacement, acceleration was measured using rope displacement transducers, and accelerometers. The outcomes displayed amplifies in value of acceleration, when passing through soft clay soil. The settlement and horizontal displacement of footing showed practiced noticeable when exposed to the earthquake load. Alternatively, the technique of the replacement is evidenced to be situated effective in governing the complications interrelated with earthquakes. Tests showed that the increasing of thickness of layer and from (1B to 1.5B) reinforced with geogrid led to reduction in acceleration, settlement, horizontal displacement. The ideal replacement thickness is happened at (1.5B) of reinforced sand, it provided best decrease in the value of acceleration, and the uppermost reduction in the settlement and lateral displacement of footing.

Keywords: Geogrid Reinforcement, Shallow Foundation, Soft Clay, Dense Sand, Kahramanmaraş Earthquake.

1.Introduction

Earthquakes occur daily across the globe, though most minor tremors go unnoticed by people. However, powerful earthquakes can destroy bridges, buildings, and critical infrastructure, and even result in fatalities. Consequently, designers must understand how seismic waves affect structures in order to alleviate damage. Many studies demonstrate that (soil-structure interaction) alters the response of seismic of foundations, and several researchers carried out experimental and mathematical works on same topics, [1-4].

Nevertheless, numerous questions remain regarding soil behavior during shaking and its impact on structural elements. Soils characterized by two condition first moisture content, and the second low shear strength are classified by way of soft soils, which often pose challenges for geotechnical design. Due to their compliance, these soft soils tend to deform under load and are widely distributed along the coasts of many seismically active regions, such as Indonesia, Philippines, Mexico, India, China, and of late Iraq. Furthermore, during seismic, soft clay soils can amplify seismic motion movement, knowingly altering the amplitude, frequency, and duration motion transmitted to the foundations, thereby affecting superstructure dynamic response, [5-7]

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When a footing is exposed to an earthquake load, it hurts from a surge in settlement and lateral movement that to be disadvantageous to the building's upkeep and integrity. The shaky related with seismic can showed in many complications for foundations linking to decline the bearing capacity under earthquake. Wholly these complications product in the predictable letdown of the foundation. This unfavorable countryside of seismic inspires researchers to discover ways to diminish the influences of earthquakes, [8]. Consequently, the seismic response of foundations and surrounding soil must be well understood. This knowledge informs two matters, the first: safe design of foundations and the second is superstructures which support it.

Soil strengthening expertise is specified the greatest reputation in current days to become accustomed soft soil into the experienced unchanging ground for diverse civil engineering requests. It was ongoing and developed familiar thru the inventor effort, and one of the important methods employed in recent decades is the use of geogrid layers to improve the performance of soft soils, in foundations, roads, slope, retaining wall. The reply of footings can be heightened by insertion the geosynthetic layers inside the soft soil resulting soil support matrix. Utmost mutual geosynthetic supplies castoff as strengthening essentials in soft soil namely (geotextile; geocomposite and geogrid), [9-11]. Geogrid material can be defined is a plyometric solid having tensile ribs with an opening to be large enough to permit the interlocking with the close soil .The interlinking amid flanked by geogrid and the soil advances the strong point of the soft soil and this method can be done by engaging the geogrid in diverse arrangement to modified the concert and comportment capacity of soft clay soil. Therefore, to achieve extreme benefit of strengthen of soil and save costs, [12].

2. Literature review

The concert of structure examined as mid-rise on geotextile-enhanced soil by using the (FLAC 3D) program below two types of shaking namely the (1994 Northridge Earthquake) and (1999 Chichi Earthquake). The study mentioned that the reinforcement layers put adjacent foundation ends endure utmost of the stress. In totaling, the structure exhibited fewer settlement, and rocking, as a result of increased number of geogrid layers intensification. This evidenced the important effect of the geotextile location on the dynamic performance structures, [13].

A study via (PLAXIS 2D) program was conducted thru geotechnical seismic separation based on system including two-story building. the results showed that the use of geogrid reinforced is effective in dynamic response and mainly in decreasing settlement, tilting of the foundation, [14].

A single fixed pile behavior was investigated in sandy soil with a geogrid, the system exposed to two different seismic types of waves. It was recorded that using geogrid, with pile footing reduced the vertical displacement in the pile by about (50% and 90%) for the (Halabja and Ali Al Gharbi) earthquake forces, correspondingly. The supreme bending moment was also condensed, with the meandering moment percentage at the pile surface for the two earthquakes which mentioned earlier being (70% and 50%) individually. The settlement ratio upsurges as degree of earthquake reductions, [15].

The response of foundation restored on loose sand in saturated condition was inspected, strengthened with reinforced layers in many configurations underneath test via a 1g shaking table device. The outcomes specified the settlement of a footing through a robust seismic happens in two phases, the first phase, is related to the soil movement while, the second phase, includes the vertical displacement of foundation due to decreasing in the bearing capacity of soil, [16].

Experimental study that examined the utilized the geogrid location and the numeral of the layers. The outcomes exhibited that the most effective-depth of reinforcement nearly 2B. these results achieved after many laboratory tests based on bearing capacity and stability of reinforced soil under footing, [17].

The ideal location of the first layer reinforcement deposit was in the range (0.25B - 0.5B), in addition, three reinforcement layers of geogrid was the best number to be used, [18].

The previous studies mentioned that the 3B as geogrid layer length of strip foundations with the extreme advantage of reinforcement was the best based on tests to study the effect of space and length of reinforcement layer, in addition, the depth of reinforcement on the failure mechanism, [19].

Based on previous works, there is rare research who investigating on the performance of footing erected on soft clay when the upper layer partially replacement with sand reinforced with geogrid layers during the earthquake.

3.MATERIALS AND METHOD

To confirm the reliability of the experimental seismic responses, the exactness limits and test repeatability procedures are systematically assessed as outlined below:

- Repeatability and Calibration: the pre-test calibration etiquettes of the shaking table to safeguard harmonic and embattled earthquake histories. To check repeatability, baseline trials were repeated three times, and the variations in peak accelerations and displacements were originate to be within an acceptable error margin of less than (4%).
- Reliability: The stipulations, sampling taxes, and accurateness limits of the LVDTs, accelerometers, and stress transducers have been explicitly exhaustive to confirm measurement dependability.
- specific similarity relationships and scaling laws (λ =10 and 1g law) applied to the soil-foundation-geogrid system based on previous studies which mentioned earlier in this article.

3.1 Shaking Table System

To reproduce earthquake shaking histories and observe their impact on the soil-footing-structure system, the (single-degree-of-freedom shaking) table device constructed and set up at the University of Diyala's, College of Engineering. This apparatus was developed in this work with an advanced data acquisition system to increase the accuracy of the obtained data and fulfilling the study's desires, [20]. Altogether indispensable constituents have been obtained and collected with great carefulness. As depicts in the **Fig 1.**

- Servo Motor
- Digital Data Acquisition (DAQ)
- Sensors Used

- Laminar Soil Container
- Square Foundation Used in the Study

The replicate of propagation wave was created by a device namely the laminar container with dimensions (800 x 700 x500) mm, that occurs during seismic happenings within a restricted soil layer, [21-23]. The laminar shear container, which has individual aluminum laminas. And additional robust nylon layer was installed within the laminar box to prevent the leakage of soil. This configuration has been observed in previous research, [24-27].

A spread footing having a square form with section of (100 x 100) mm with 60 mm thickness was implemented in this research, as comparable to a prototype with the dimension of (1000 * 1000 * 400) mm, meanwhile the agreed scale factor (λ =10). A prototypical foundation weight is 2.4 kg and is manufactured from Aluminum as a rock-hard block. [28-29].

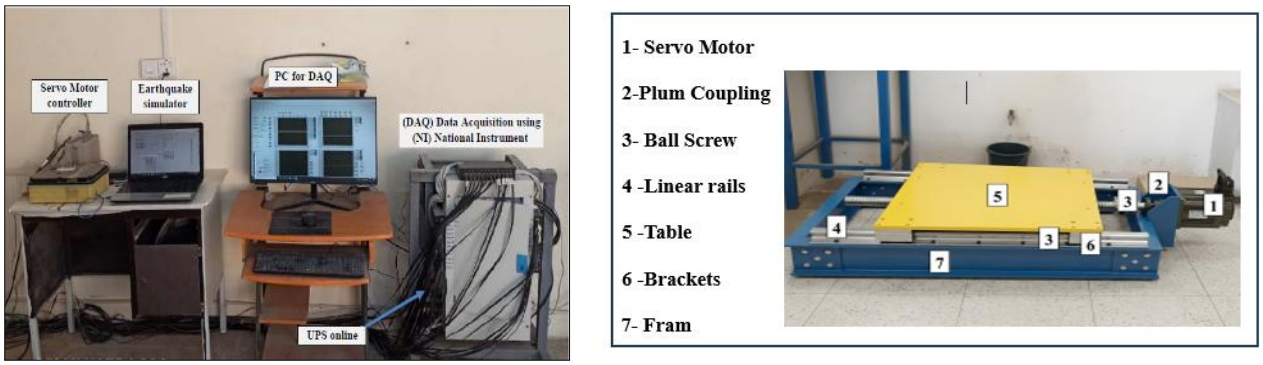


Fig. 1 Test system setup photograph, control of shaking table and DAQ hardware.

3.2 Geogrid Type

The geogrid supplied by Tensar Company in the UK which used in this study and the model is the InterAx NX750. This geogrid is working across various industrial areas, counting road erection, strengthened soil retaining walls, slopes, footings, and banks **see table 1** and **Fig. 2.**

Table 1. Engineering properties of the geogrid used

Aperture shapes	Hexagonal
Structure	Coextruded and Integrally Formed
Rib shape	Rectangular
Continuous parallel rib mm	75
Rib aspect ratio	≥1.5
Node thickness, mm	3.25
Color identification	White
Mass per unit area (kg/m2)	0.35
Ultimate tensile strength (Mpa)	31
Product EPD* Certification	EN 15804 +A2:2019
Resistance to Chemical Degradation	100%

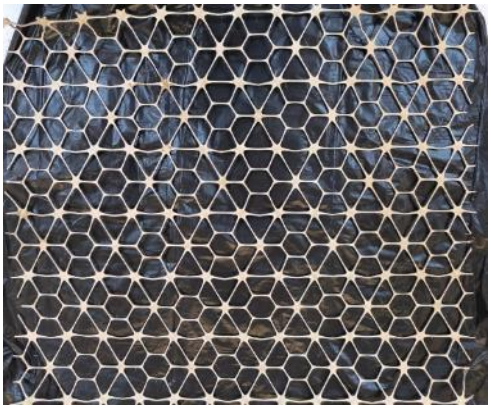


Fig. 2 The geogrid used.

4. Experimental Procedure

It can summarize the subsequent procedures followed to make the soft clay soil then put in the laminar shear box in **Fig 3** after that put sand soil by using the raining technique, so that a model footing organized to achieve tests:



Fig.3 Device mixing and preparation of soft clay soil.

The properties of soft and dense sand can be seen in **table 2** and **table 3**

Table 2 The soft clay soil properties

Soil properties	Shear strength (kN/m^2	Maximum unit weight (kN/m^3)	Minimum unit weight (kN/m^3)	Unit weight (kN/m^3)	Water content	The soil is classified according to the USCS
value	25	17.8	14.8	16	31 %	CL

Table 3 The sand soil properties

Soil properties	Relative density %	Minimum unit weight (kN/m^3)	Maximum unit weight (kN/m^3)	Unit weight (kN/m^3)
value	70	14.3	17.89	16.4

Fig. 4 and **Fig. 5** illustrates the model setup schematic, and model test setup in laboratory

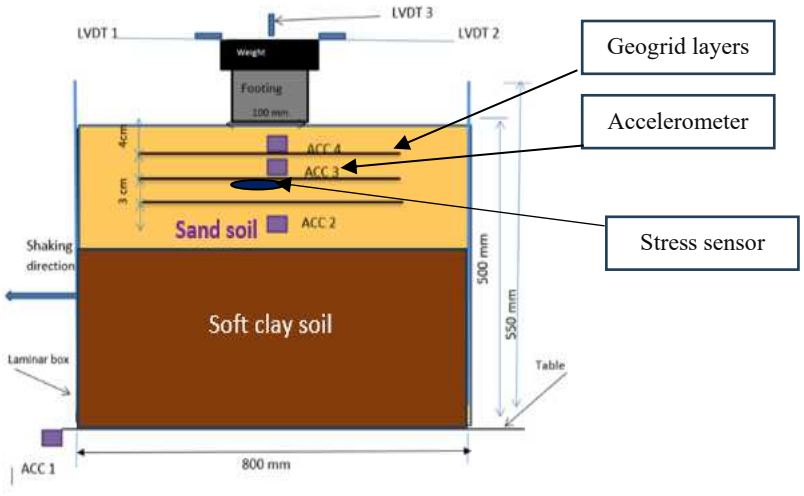


Fig. 4 model test set up schematic.



Fig. 5 model test set up photograph.

5. Experimental Sets

The Kahramanmaraş Earthquake seismic event was selected, with intensity of (0.77g). This earthquake was uploaded in the LabVIEW software program of the shaking table computer by way of Excel sheet files.

A sequence of tests was carried out on square foundation with soft clay soil having shear strength (cu = 25 kN/M^2), subjected to selected seismic ground motions using the shaking table system earlier and after enhancement with geogrid strengthening and as follows:

- shaking time histories selected as the Kahramanmaraş Earthquake with intensity of 0.77g.
- The soft clay soil with shear strength (cu = 25 kN/M^2).
- The dense sand soil with relative density of (70%).
- Geogrid in varying width and different numbers of layers and this number of geogrids was selected based previous research which was mentioned that the optimal number equal 3 layers with width 5B. see **Fig 6.**
- Static loads are instead on the square foundation.and this load carefully chosen based on load settlement curve.

The soil response and footing under the different scenario was observed by measurement the following parameters:

- The settlement of the footing.
- The horizontal displacement of footing.
- The acceleration in diverse points of the soil beneath under footing .
- Stress in soil below the footing.

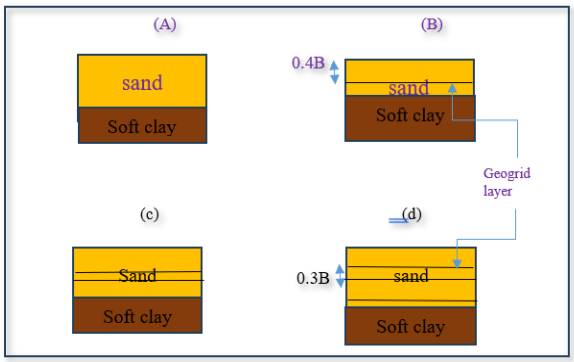


Fig. 6 model test set up photograph.

6.RESULTS AND DESCUSSION

6.1 Acceleration Response of Footing

Fig. 7 illustrate the acceleration response at soil surface versus time for soft clay and replacement unreinforced sand soil, the experimental outcomes for the unreinforced soft soil, recorded a slight damping of seismic acceleration at soil surface by about (8%) comparison with acceleration base with intensity of (0.77g). this behavior associated with the inherent damping characteristics and nonlinear dynamic response of soil, which can contribute to the dissipation of seismic energy during strong wave propagation, then the reduction in surface acceleration value due to replacement the upper layer of soft clay with dense sand with thickness equal to 1B then 1.5B, (where B is the width of footing and equal to 10 cm), in the other word, (10 cm , 15 cm), by about (7%, 10%) respectively, the replacement of the soft clay layer with a dense sand, meaningfully mitigates seismic motion amplification concluded stiffness optimization and energy degeneracy. Soft clay has a low shear wave velocity, creating a high impedance contrast that magnifies seismic wave amplitudes upon attainment the surface. Take the place of this zone with dense sand bonds the stiffness gap, overpowering this contrast. Alongside, under sturdy cyclic loading, the

basic soft clay acts as a nonlinear damping strainer, showing out high frequency accelerations owing to its incapability to diffuse high shear stresses.

Growing the thickness of the replaced dense sand layer from 1B to 1.5B (10 cm to 15cm), supplementary enhances this decrease. A profuse sand stratum encompasses the wave propagation pathway through a high damping medium capitalize on energy dissipation thru inter granular friction, while simultaneously collective constrictive pressures underneath, enriching the inclusive dynamic shear modulus of the spot contour and ever-changing it left from structural resonance.

Fig 8 illustrates the acceleration response at soil surface versus time for soil condition, when inserted the geogrid layer (3G – three layers) in sand soil, the acceleration exhibit decreasing in its value comparison with unreinforced sand soil, this is mainly attributed to the heightened dynamic damping ability and shear stiffness of the amalgamated soil-geogrid mass. When numerous geogrid layers are presented, the sand soil particles interlock within the geogrid openings (the interlocking mechanism) so it can be seen the value of acceleration decreased by about 12% for (10 cm), and 17% for (15cm) when compared between reinforced and unreinforced sand soil. This structural confinement meaningfully elevates the dynamic shear modulus (G) and upsurges the structural damping ratio (D%) of the footings bed.

Consequently, a considerable portion of the seismic energy by the (0.77g), acceleration is engrossed and dissipated within the strengthened zone, acting as an isolation mechanism that reduces the response before it influences the ground surface. These results align with the fundamental principles of Soil-Structure Interaction (SSI) under seismic loading established by Shin and Das [30]. Furthermore, shaking table investigations conducted by Das [31], confirmed that multi-layer geogrid configurations significantly alter the natural frequency of the soil bed, transforming it from a soft amplifying medium into a rigid, energy-dissipating coherent block.

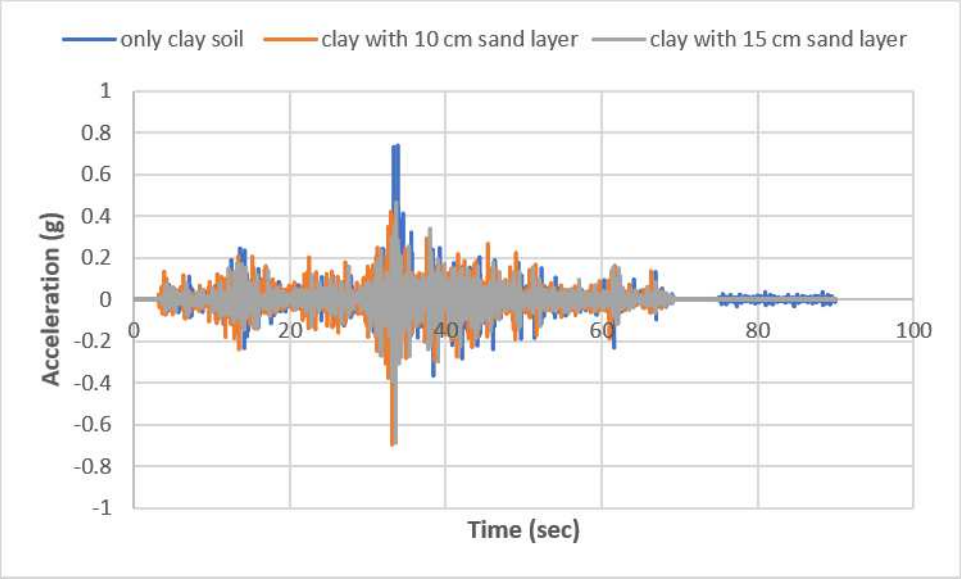


Fig. 7 The acceleration response at soil surface versus time.

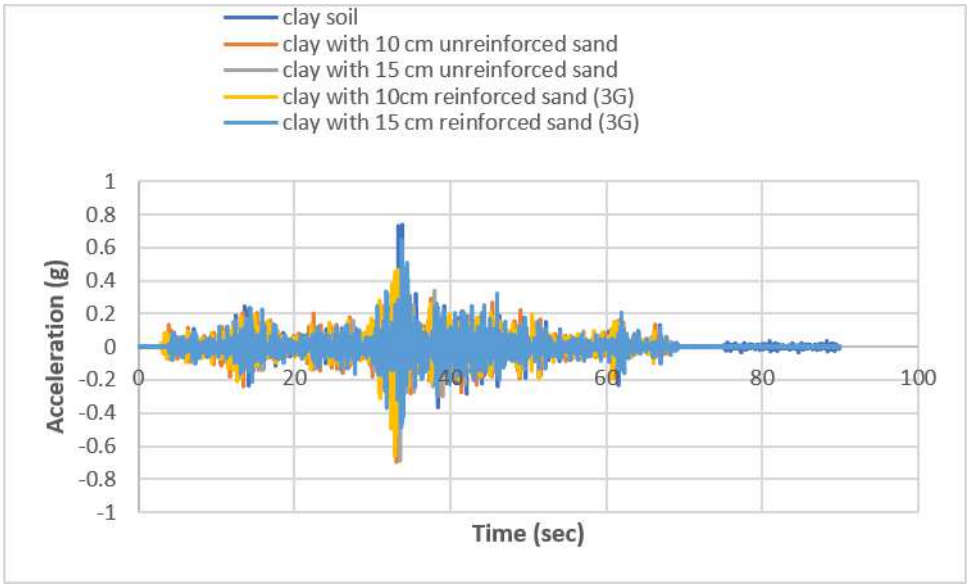


Fig. 8 The acceleration response at soil surface (clay, reinforced and unreinforced sand) versus time at three geogrid layers (3G).

6.2 Settlement of Footing

Fig. 9 illustrate the settlement response of footing versus time for the soft soil and replacement unreinforced sand with different thickness (1B,1.5B). In soft clay, cyclic loading focusses vertical stresses straight beneath the footing, triggering severe plastic distortions and seismic settlement in the soft clay. Changing the upper soft clay with a dense sand layer by about 1B thickness, pointedly reduces the settlements by about (31) % and (39) %, for 10 cm and 15 cm respectively. The dense sand layer performances as a high stiffness load rearrangement dais, dampening and distribution footing stresses completed a wider area, by this means, dropping the net vertical stress augmentation relocated to the underlying squeezable soft clay.

By way of the thickness of the replaced dense sand layer upsurges, the lingering soft clay is effectually pushed to superior depths where the tempted bulb of pressure is highly diminished. This symmetrical formation substantially overturns primary consolidation in the clay medium, while applying the immediate, low degree elastic settlement features of the dense sand, leading to heightened foundation steadiness with augmented replacement depth.

Fig. 10 illustrate the settlement response of footing versus time for the soft soil, replacement unreinforced sand and reinforced sand with different thickness (1B,1.5B). The decay in vertical settlement with the added of (3G) layers is motivated by the stress rearrangement, the (3G) layer of geogrid arrangement performances as a rigid platform that mete out the dynamic vertical loads across a much-varied area, dropping the net vertical stress conducted to the deep of soil column, it can be seen the settlement decreased by 45% and 51% for (10 cm, 15 cm) thickness respectively comparison with unreinforced sand soil. It is important to mentioned that the width of geogrid layer is 5B for all tests, maintaining a reinforcement width of (5B) directly conforms to the optimal geometry suggested by many researchers, such as Moghaddas and Dawson [32], who stated that a width between (4B) and (5B) ensures that the entire failure shear wedge is trapped within the reinforced matrix. Their numerical and experimental findings proved that multi-layer reinforcement maximizes the Dynamic Bearing Capacity Ratio (BCR), leading to a dramatic reduction in permanent seismic settlement.

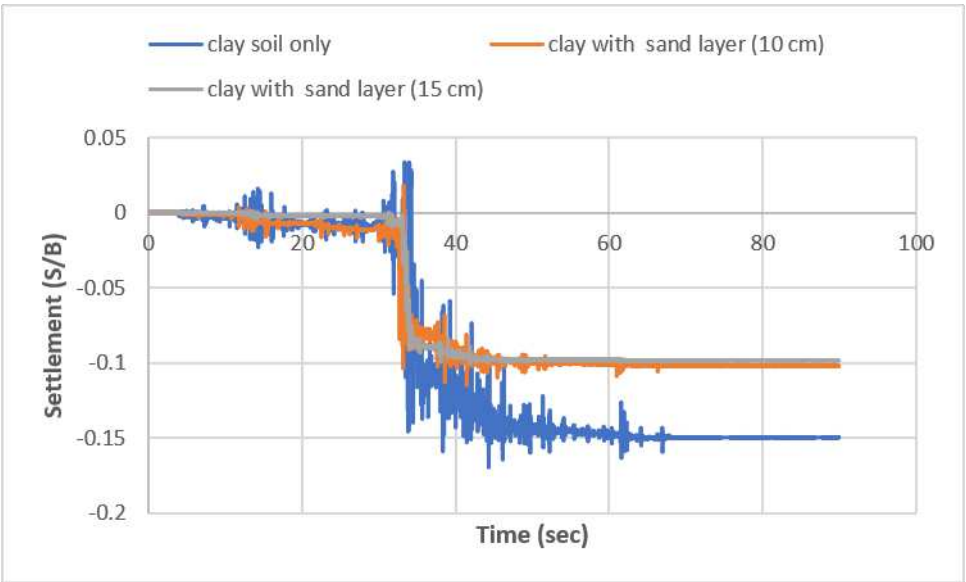


Fig. 9 The settlement of footing versus time during Kahramanmaraş Earthquake.

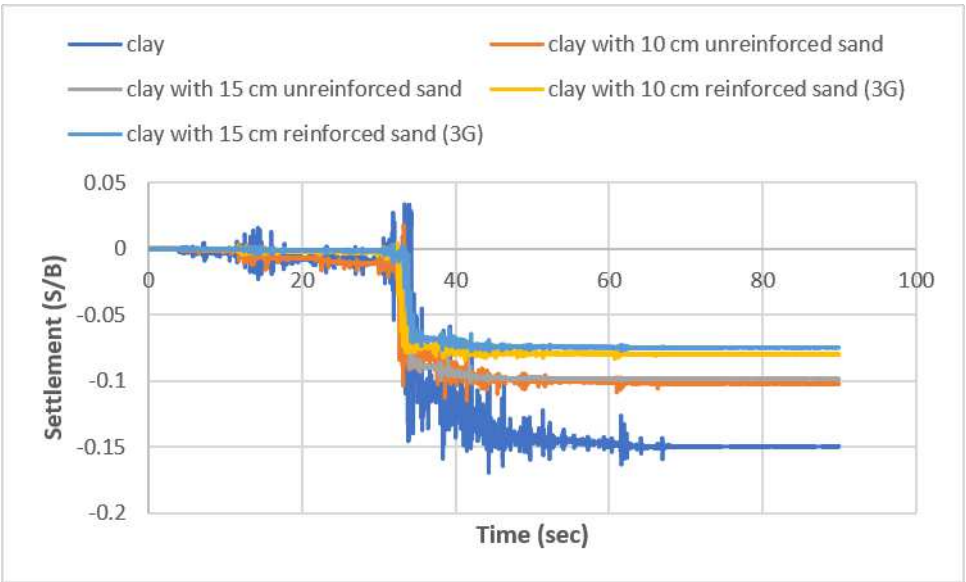


Fig. 10 The settlement of footing versus time during Kahramanmaraş Earthquake.

6.3 Horizontal Displacement Footing

Fig. 11 show the horizontal displacement response of footing versus time, for the soft soil and replacement unreinforced sand with different thickness (1B,1.5B) . The detected mitigation in lateral measure movement is ruled by the lateral limit and confinement effect. Under a seismic excitement of 0.77g, unreinforced soft clay involvements severe repeated shear degradation, persuading a tendency for the soft soil beneath the shallow footing to outflow or spread laterally .

Firstly, replacement the soft clay layer with a (10)cm unreinforced, dense sand layer yields a 6% decrease in horizontal displacement likened to the soft clay bed only. This enhancement is primarily ruled by the higher shear strength and friction angle of the dense sand, which efficiently reallocates and alleviates the driving shear stresses along the shallow sand-clay boundary, contempt the added inertial mass and overburden pressure. Additionally, this lateral movement reductions by about 10 % even more once the thickness of the unreinforced sand layer is enlarged to 15 cm. This further decrease is credited to

the progressive enlistment of the layer's flexural rigidity and passive earth resistance, which meaningfully enhances the inclusive stiffness of the soil and confines lateral spreading.

Fig. 12 show the horizontal displacement response of footing versus time, for the soft soil and replacement unreinforced and reinforced sand with different thickness (1B,1.5B). Presenting a three-layer geogrid formation within the (10 cm) and (15 cm) dense sand layer inductions a thoughtful lateral detention mechanism. This mechanical interlocking among the geogrid apertures and the sand units encourages in height tensile stiffness, and considerable seeming cohesion. This transmutes the dense sand layer into a rigid merged bed or a strengthened diaphragm that effectually intercepts, restructures, and overpowers lateral shear strains, resultant in a noticeable and well decrease in horizontal displacement likened to both the unreinforced sand and the soft clay soil. The insertion of three geogrid layers (3G) creates a highly rigid and the horizontal displacement reducing by about 12% and 18% for (10 cm, 15 cm) respectively, from its value at unreinforced soil.

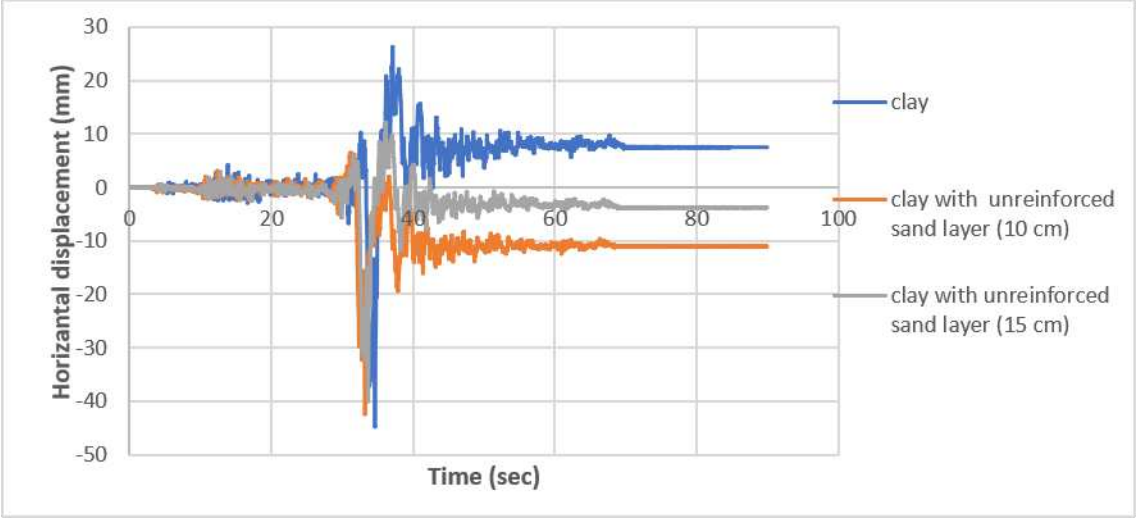


Fig. 11 Horizontal displacement of footing versus time during Kahramanmaraş Earthquake**.**

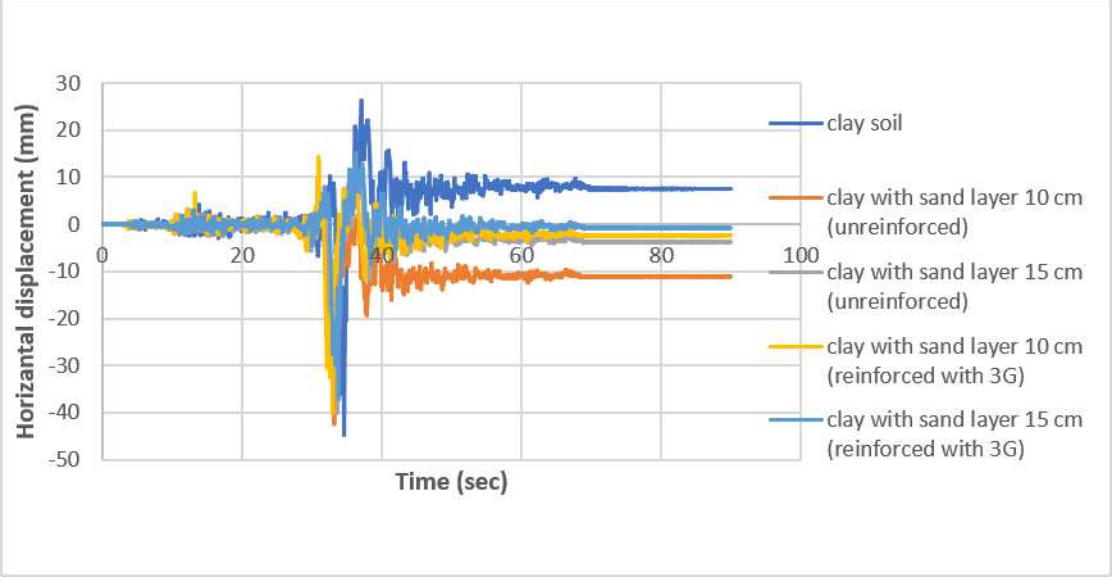


Fig. 12 Horizontal displacement of footing versus time during Kahramanmaraş Earthquake.

This mechanism validates the classical reinforced soil theories founded by Sitharam et al. [33]. It is also strongly supported by the large-scale shaking table trials by El-Emam and Bathurst [34], who demonstrated that growing the number of reinforcement layers yields a proportional reduction in lateral earth displacements under dynamic loads, restricting the lateral deformation of soft subgrades by up to (40 to 60) %.

6.4 Effect of the replacement of clay by reinforced and unreinforced dense sand (with thickness of 1B,1.5B) on stress

Fig 13 showed the stress value for unreinforced soil during Kahramanmaraş Earthquake for different soil conditions at depth of 1.5B (15 cm). The stress analysis exposes that the unreinforced soft clay shows the highest tempted stress amounts within the soil matrix preceding to any soil improvement. When unreinforced dense sand layer of (10) (1B) cm is presented, it induces a restricted vertical and shear stress meditation the shallow (sand-clay) crossing point. At this thickness, the sand layer nonexistence enough structural associating capacity to inductee the stress bulb effect; therefore, a little enriching the driving lateral earth pressures. Though, as the unreinforced sand thickness increases to 15 cm (1.5B), it purposes as an operative load restructuring stand, escalating the stress bulb prediction area and methodically dropping the net vertical stress shifted to the deep soft clay strata. It can be seen that the stress reduced by (9%, 17%) for 10 cm and 15 cm of replacement sand (unreinforced), respectively.

Fig 14 showed the stress value for soil at during Kahramanmaraş Earthquake for different soil condition at depth of 1.5B (15 cm). Importantly, the incorporation of a three-layer geogrid (3G) arrangement within the 10 cm and 15 cm dense sand layers basically modifies the stress field thru tensile stress utilization. As per crosswise shear stresses progress under loading, the geogrid interrupts these forces over mechanical interlocking, constrictive the sand soil particles and altering obvious lateral shove into internal tensile struggle. The reduction in stress value by about (27%) for 10 cm reinforced sand and (33%) for 15 cm of reinforced sand replacement. This lateral incarceration generates a rigid compound bed that radically reduces vertical stress transferred to the soft clay beneath while minimalizing tempted lateral stress augmentations, resultant in a noticeable and greater decrease in system deformation associated to both unreinforced replacement sand and soft clay bed.

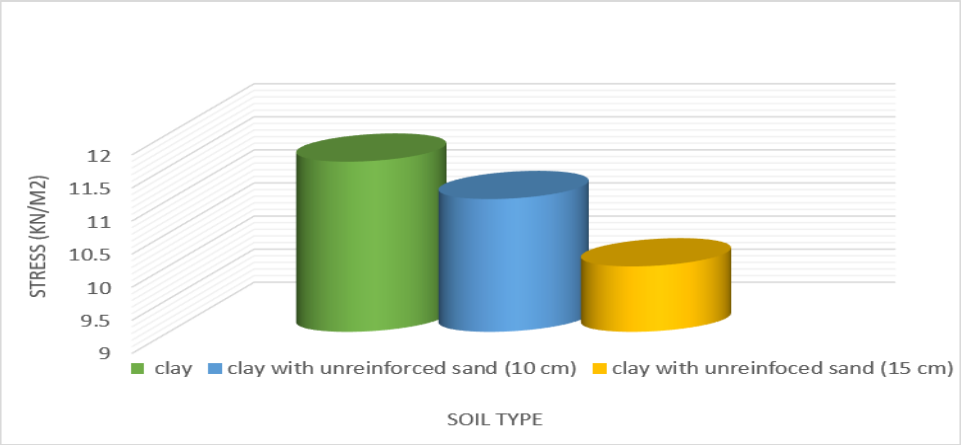


Fig. 13 The stress value below footing at depth of 1.5B (15 cm) for different soil condition during Kahramanmaraş Earthquake.

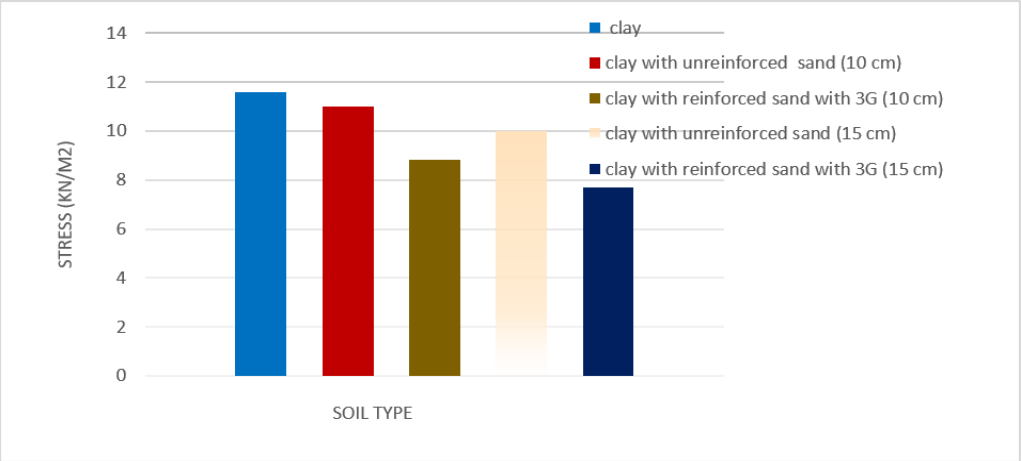


Fig. 14 The stress value below footing at depth of 1.5B (15 cm), for different soil condition during Kahramanmaraş Earthquake.

6. CONCLUSIONS

It can be summarized a main conclusion from this study as follows:

- **The Soil Replacement Effectiveness**: Changing the upper soft clay layer with a dense sand layer evidenced to be a highly operative ground improvement method for attractive the seismic response of shallow footings.
- **Thickness of replacement layer:** The dynamic concert of the footings showed a direct association with the additional depth; growing the sand layer thickness from (1.0B to 1.5B) lead to in an advanced and more noticeable enhancement in soil-structure interface.
- **Surface Amplification Mitigation:** The planned configuration effectively restrained earthquake encouraged inertial forces, resultant to a noteworthy decrease in surface of amplification acceleration, with the lowermost values reached at a thickness of 1.5B.
- **Seismic Deformations Minimization:** The soil footings scheme showed better dimensional steadiness, categorized by a substantial reduction in together vertical settlement and lateral footings displacement by way of the replacement thickness augmented.
- **Reinforcement Performance Dependency:** Although unreinforced condensed sand yielded bordering improvements, the insertion of three layers of geogrid exponentially heightened the dynamic concert across in cooperation examined thicknesses.
- **Mechanism of Geogrids reinforcement:** The geogrid strengthening providing more lateral internment and interlinking mechanisms in the interior the dense sand soil, meaningfully constrictive shear failure and take full advantage of energy degeneracy during seismic conditions.

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