IMPROVING SEISMIC RESISTANCE OF HYDRAULIC STRUCTURES USING SOIL IMPROVEMENT TECHNIQUES

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ABSTRACT

Most of the Egyptian irrigation structures were built many decades ago. Most of these structures may be classified as unsafe structures when making an assessment of their resistance to earthquake loads in accordance with the current specifications. This research suggests a technique to increase the ability of these structures to resist seismic loads. The suggested technique depends on using soil improvement methods to improve the most stressed soil bulb zone under the structure. The effect of seismic site soil factor will be decreased by improving this part of soil.
Controlled soil jet grouting technique could be used for the existing structures. Other types of soil improvement techniques such as soil mixing could be used for new structures or other types of earth structures.
Numerical study was performed to investigate the feasibility of the suggested method. Experimental study was carried out to validate the numerical study. The dynamic responses of an improved location and normal location were measured. The two locations were subjected to the same excitation force. The measured responses were compared and evaluated. Based on the results of the suggested technique, a real site condition for an existing barrage structure was numerically analyzed before and after soil improvement to examine the suggested technique.

Keywords: seismic design, barrages, dynamic testing, soil grouting

1. INTRODUCTION

Soil improvement researches dealt with the ability of soil improvement methods to resist the expected soil impacts of earthquakes. Most of these researches have focused only on the soil liquefaction problem. Despite the importance of this problem, the studies have stopped at this point and went mostly to the comparison between the efficiency of each different type of soil improvement methods. Most researches did not address the possibility of using soil improvement techniques to improve the seismic soil factor of the foundation soil as one of the factors affecting the structures seismic design loads.

The main purpose of this research is to increase the earthquake resistance of structures lie on weak soils by using soil improvement methods to improve the most stressed bulb zone under the structure. Controlled soil jet grouting technique could be used for the existing structures. Other types of soil improvement techniques such as soil mixing could be used for new structures or other types of earth structures.

To investigate the effect of these techniques, Finite element model for soil layers consists of poorly graded sand was developed. Non linear dynamic time history was performed using acceleration time history of a real earthquake. The response of the ground surface was obtained. Then, soil grouting with a specific dimensions was added to the model to model the case of improvement soil. Then, the same earthquake was applied to the model. The response of the ground surface in case of soil without grouting and in case of soil with grouting was compared to investigate the effect of grout on the seismic force at the foundation level of the structure. Different grout depths and widths were examined in the research to investigate the suitable grouting depth.

Also, experimental tests were carried out using box filled with sand and exposed to two types of dynamic loading. One of them was cycling loadings applied by shaking table and the other was impulse loading applied by impact hammer. Soil Grouting with specific location and dimensions was done at the sand surface. The site responses due to the applied dynamic loads were measured at the location of normal soil and at the location of improved soil. The two responses were compared to study the effect of soil improvement on soil dynamic behavior. The experimental results obtained from the dynamic tests were used to validate the results of the numerical model.

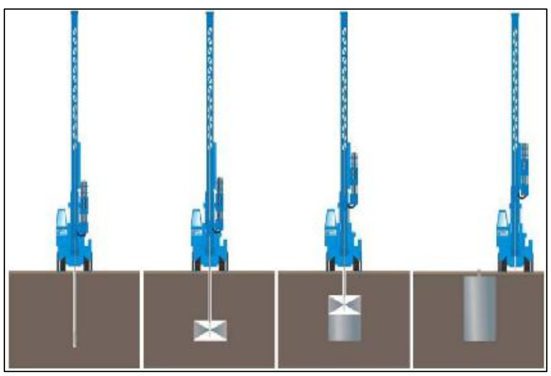
The proposed technique was investigated numerically using real soil strata under a typical old barrage in Delta region in Egypt. This barrage was built on layer of poorly graded sand. Finite element model for the soil layers was developed. Non linear dynamic time history was performed using acceleration time history. Then, soil grouting for the poorly graded sand layer under the foundation of the barrage was added to the model. A comparison between the response of the ground surface for the model with and without soil improvement was carried to evaluate the effect of the soil improvement on the site seismic response.

2. BACKGROUND

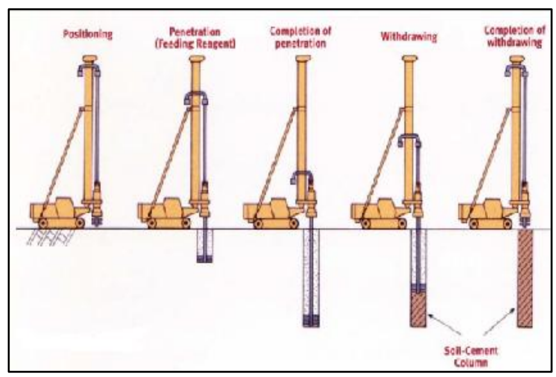
Many researchers studied the effect of soil grouting of loose layers to decrease the liquefaction potential or to increase the bearing capacity. **Paul et al., [1]** studied the increase in shear modulus by soil mix and jet grout methods to determine the decrease in liquefaction potential and earthquake-induced permanent deformations. **Saravut J. [2]** presented an innovative use of soil-cement mixing method using jet grouting technique to improve the bearing capacity of sub-base foundation for road construction. **Jafarzade et al., [3]** Compared the experimental results obtained from dynamic tests carried out by shaking table on loose and dense sand models using cyclic loads with the numerical simulation results.

ALKAYA et al., [4] studied the performance of stone columns and jet-grouting practices carried out in the location of railway which is dominated by poor soil conditions. The soil conditions obtained with jet grouting practices are higher than those of stone column practices. These results were checked by both seismic refraction and on-site tests. The results shown the grouting jet technique update the soil site condition from class D to class C according to Euro code. **Barron et al., [5]** concluded that the use of proper Cement Deep Soil Mix (CDSM) construction method could result in significant strength increases and relatively uniform ground improvement from loose to medium dense sands. The design of the CDSM treatment to improve the weak foundation was able to meet the seismic performance objectives that were established for a project. To increase the ability of soft soils at shallow depth to resist seismic horizontal loads **Mseda** et al., **[6]** proposed a methodology depends on forming a cement soil mass composed of steel piles and soft soil improved by cement mixing method.

This research studies the effect of soil improvement methods (see figure 1) on the dynamic response of the soil at the contact surface with the superstructure. The expected improvement on the soil properties will affect the amount of response of the improved soil to the earthquake movement. This improvement may be used to increase the structure capacity to resistance earthquake loads. This technique may be used in the case of re-rehabilitation of hydraulic structures to upgrade its seismic loads capacity. In other words, the proposed technique can be applied when the need to increase the structures resistance to earthquake loads is required.

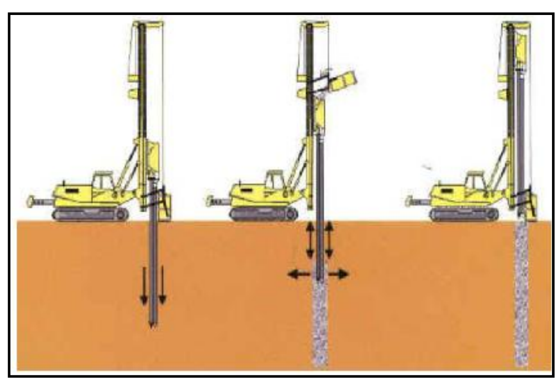


a) jet-grouting technique



b) Cement deep soil mixing

c) Soil mixing machine



d) Stone column technique

Figure1. Soil Improvement Techniques

3. NUMERICAL MODEL

Soil strata consists of one layer of loose sand with 20.0 m depth and 100.0 m width rested one bed rock layer was subjected to seismic wave. A finite element numerical analysis using nonlinear time history dynamic analysis was performed using Plaxis 8 professional version **[7].** For avoiding reflect of waves from side boundaries into the model, an absorbent boundaries were used and the breadth of soil was chosen relatively far from the region of interest (100.0 m). Figure 2 shows the Finite element model of the soil strata.

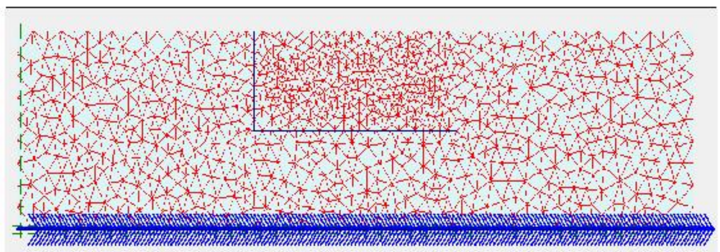


Figure 2. Finite element model.

in the study The soil strata subjected to real earthquake waves (upland earthquake) which occurred in 1990. Figure 3 shows the acceleration time history for Upland earthquake. The peak acceleration of this earthquake was 2.34 m/s^2.

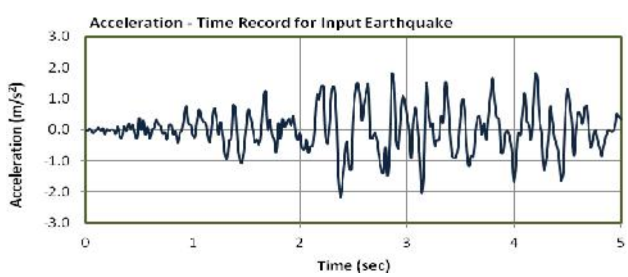


Figure3. Acceleration time history for upland earthquake.

Plane strain elements with 15 nodes and Mohr-Coulomb soil model were used to model the soil as shown in Fig. 2. Tension cut off was used to prevent the tensile stress which is not allowed in the soil element during the analysis. The soil properties were chosen to model poorly graded sand. Modulus of elasticity, angle of internal friction, and density were taken as 20,000 KN/m^2, 20^o, and 17 KN/m^3, respectively.

The location of improved soil was simulated with plane strain elements with 15 nodes and linear elastic model were used to model the grout effect. In this study, the properties of soil-cement (grouted soil) elements are shown in table 1.

The depth of the grout in the finite element mesh was taken as 1m, 5m, 10m, and 15m which represents 0.05, 0.25, 0.5, and 0.75 of the total depth, respectively. The breadth of the grout was taken as 6m, 10m, 20m, and 30m.

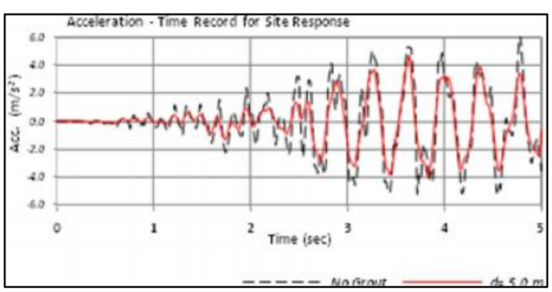
Table 1 properties of grouted soil elements

shear strength(T)	**100 k_{Pa}**
replacement ratio (α)	**35%.**
composite modulus (E_c)	**200,000 k_N/m^2**
Density	**22 K_N/m^3**
Posson's ratio	**0.2**

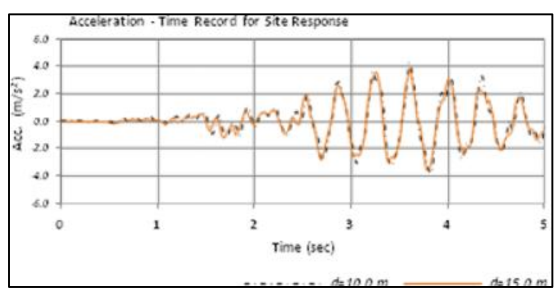
4. NUMERICAL MODEL RESULTS

The effects of grouting depth and breadth on the site dynamic responses were studied. Cases of no grout (normal soil) and cases with the same grout breadth but with different grout depths were performed to study the effect of grout depth only on site dynamic response. Figure 4 displays the analytical acceleration time record for the site responses.

Cases of different grout breadths with the same grout depth were carried out to study the effect of grout breadth only on site dynamic response. Other cases with different grouting depths were solved to study the site dynamic response sensitivity to grouting depth. Figure 5 displays the analytical acceleration time record for site responses.
One of the most important information in the dynamic analyses is the frequency content. The relation between frequency content of excitation seismic waves and frequency content of site response should be considered and studied. Generally it is normal to have some changes in frequency content or frequency shifting between excitation force and site response. The amount of changes depends on soil type and distance between excitation source and the considered site location. The dynamic behavior of the improved soil was studied in terms of frequency content. Figure.6 shows the frequency content of the site responses for cases of no grout (normal soil) and grouting with different depths and breadths.

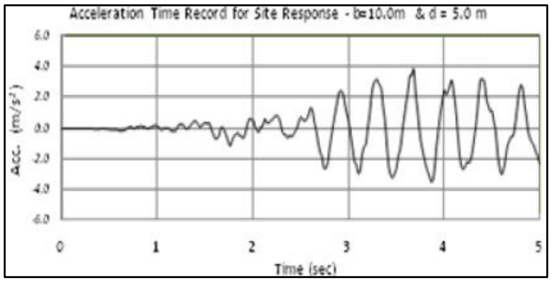


a) Comparison between no grout and grout with depth = 5.0m

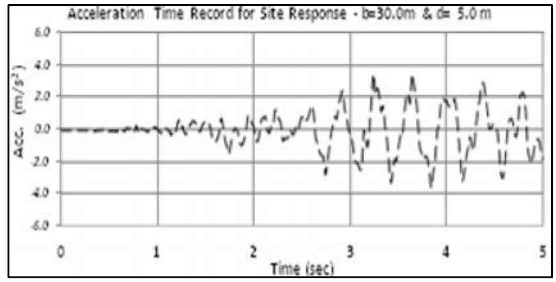


b) Comparison between grout depths= 10.0 m & 15.0 m

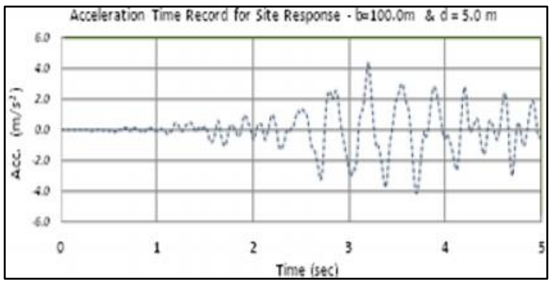
Figure.4 Site Response Acceleration Time Record - Studying grouting depth



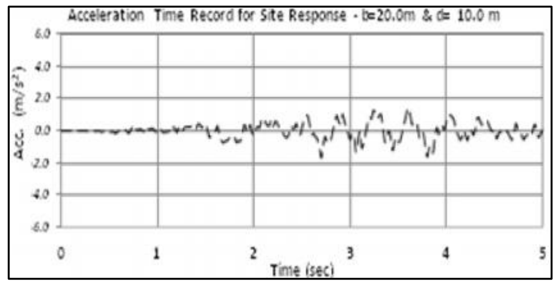
a) Grouting breadth = 10.0m with 5.0m depth



b) Grouting breadth = 30.0m with 5.0m depth

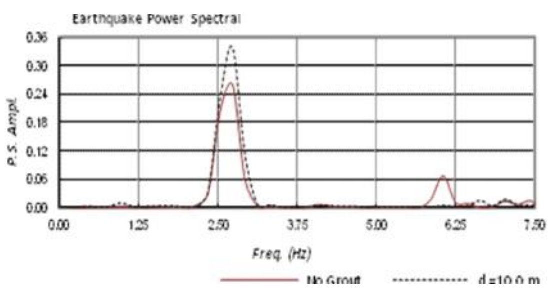


c) Grouting breadth = 100.0m with 5.0m depth

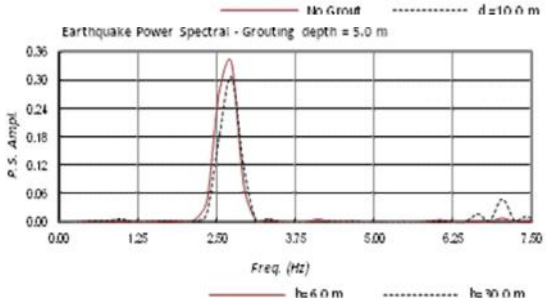


d) Grouting breadth = 20.0m with 10.0m depth

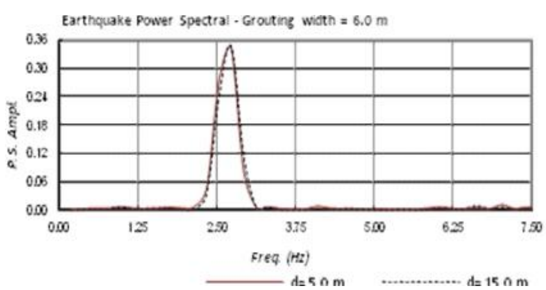
Figure.5 Site Response Acceleration Time Record - Studying grouting breadth



a) **Comparison bet. no grout case and 10.0m grouting depth**
Noting that there is some changes in peaks amplitude and some high frequencies disappeared from grouting depth = 10.0 m



b) **Comparison bet. grouting breadth = 10.0m & 30.0m**
Noting that there is some changes in peaks amplitude and some high frequencies disappeared from grouting breadth = 6.0 m



c) **Comparison bet. grouting depth = 5.0m & 15.0m**

Noting that there is negligible changes in peaks amplitude and almost no changes in frequency content.

Figure 6 Acceleration response spectra

Figure 7 shows the relation between the percentage of the decrease in the site response acceleration and the grouting breadth. The relation was calculated at two different grouting depths.

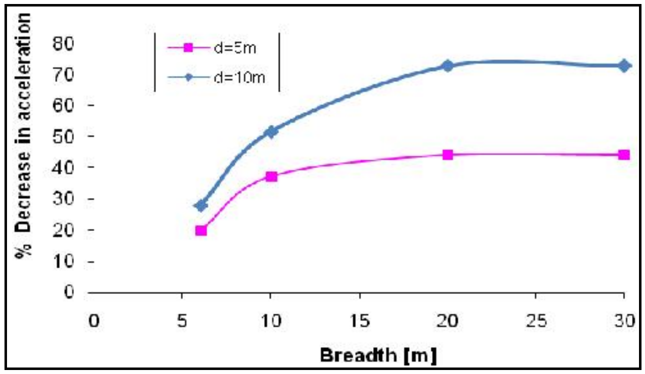


Figure 7. Effect of grout breadth on the acceleration site response

As shown in Figure 7. For grout depth=5m (25% of the layer total depth), the percentage of decrease in the acceleration were 44.16%, and 37.4% for 20m, and 10m grout breadth, respectively. While for grout depth=10m (50% of the layer total depth), the percentage of decrease in the acceleration were 72.93%, and 51.78% for 20m, and 10m grout breadth, respectively. This means that, for the same grout depth and when the grout breadth increases, the percentage of decrease in the acceleration increases until it reaches a breadth to depth ratio = 2. The increase of the breadth above this ratio has a little effect on the results. Figure 8, displays the percentage of the decrease in the site response acceleration and the grouting depth. The relation was calculated at two different grouting breadths. When grout breadth was 10.0m, this decrease reached 51.78 for grout depth=10.0m. Also, when grout breadth was 6.0m, this decrease reached 33.16 for grout depth=15.0m.

This means that, for the same grout breadth and when the grout depth increases, the percentage of decrease in the acceleration increases. The decrease in acceleration site response is limited for grouting depths more than 15.0 m.

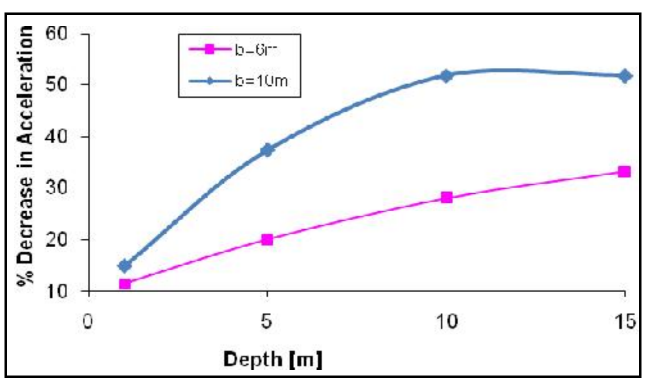


Figure 8. Effect of Grout Depth on the Acceleration Site Response

From the results the seismic forces applied on the structures could be reduced to a considerable amount by improving the local soil area beneath the structure. These results also lead to reduce the cost of new structures and lead to maintain old structures instead of reconstruction solutions when seismic resistance capacity is considered.

5. APPLICATION

A case study was performed using the proposed technique to reduce the seismic force on an existing hydraulic structure. A real soil stratum under a typical old barrage in Delta region in Egypt was used. Finite element model for the barrage site soil layers was developed. Figure 9 shows the soil strata under the barrage site. This strata consists of poorly graded sand layer with 7m depth, Clay layer with 4m depth, and poorly graded dense sand with 14m depth **[8]**. The different properties of soil layers are shown in table 2.

Table 2. Zefta Barrage Soil Layers Properties

Layer	γ [KN/m^3]	E[KN/m^2]	C[KN/m^2]	ø	μ
Poorly g. sand	1.6	27000	0	29^o	0.2
Clay	1.8	5300	64	0	0.3
Sand	1.7	60000	0	35^o	0.25

Where: γ is the density, E is the modulus of elasticity,C is the cohesion
ø is the angle of internal friction, μ is Posson's ratio.

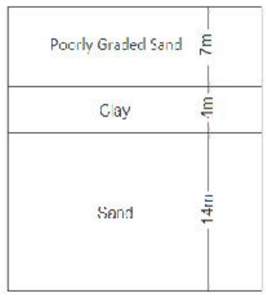


Figure 9. Soil Profile

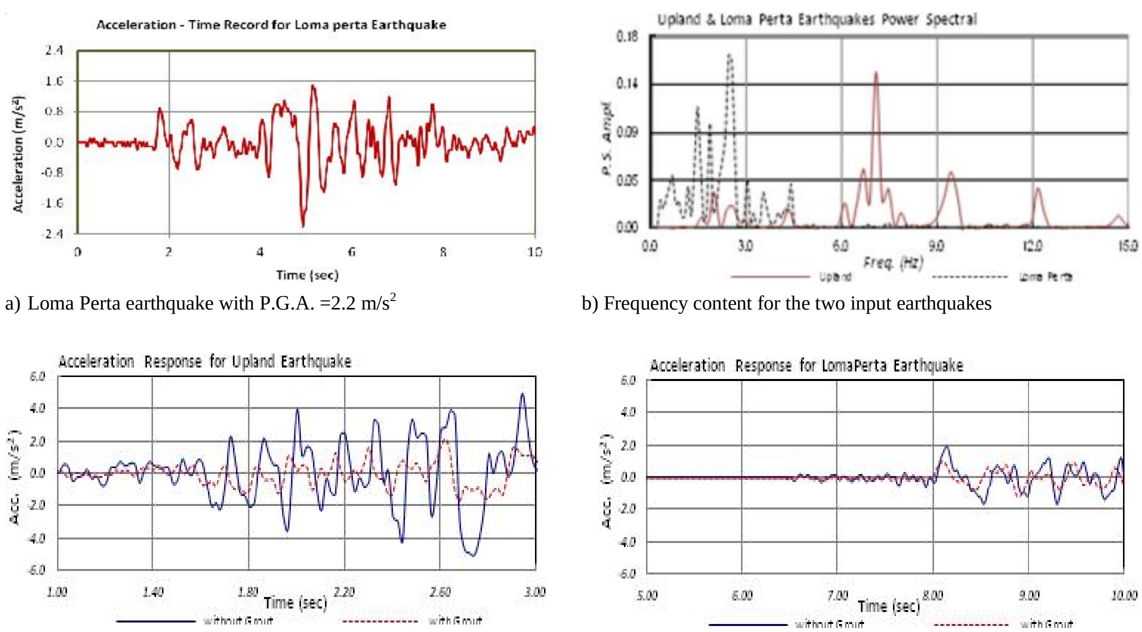
Non linear dynamic time history analysis was performed using normal soil conditions. Then, the effect of soil grouting for the poorly graded sand layer under the barrage foundation was added to the model. Two earthquakes (Upland and Loma Perta earthquakes) were used in the analysis.

The grouted area was 26.0m in breadth and 7.0m depth. The ground water level was taken at the top of the poorly graded sand layer (under the structure). The acceleration response time history at the ground surface for soil with and without grout, also the properties of excitation earthquake used in the analysis are shown in Figure 10.

It was found that the peak ground response acceleration for the soil without improvement = 6.16 m/s^2 and 1.86 m/s^2 under the effect of Upland and Loma Perta earthquakes respectively.

The peak ground response acceleration was 3.17 m/s^2 and 1.12 m/s^2 when using the proposed technique for the soil site improvement.

This means that the proposed technique could reduce the peak acceleration by about 40% to 49 %.



a) Loma Perta earthquake with P.G.A. =2.2 m/s^2

b) Frequency content for the two input earthquakes

c) Comparison between with and without grouting for Upland

d) Comparison between with and without grouting for Loma Perta

Figure10. Site excitation earthquake properties and acceleration site responses results

6. EXPERIMENTAL WORK

Experimental work was carried out to verify the previous results. A physical model for sand layer with dimensions of 1×1×1 m was constructed using box container. This box was put on a shaking table and exposed to lateral vibrations with harmonic motion and pulse load by using impact hammer. Two cycling motions with 1.80 Hz and 2.80 Hz were used in the test also impact loads applied at two different points were considered. Soil improvement location was done using grouting mix. The area of the improved location was 0.40×0.40 and with 0.20 m depth. The used grout mixture was made by water to cement ratio = 1.0, grout volume was 40% of the soil volume and the dry cement to soil ratio was 450 kg/m^3. The values of sand properties are summarized in table 3. The grouted soil properties are usually obtained by performing unconfined compressive strength tests of a specific mixture specimen.

Table 3. Tested Sand Properties

Layer	γ [KN/m^3]	E[KN/m^2] Estimated	C[KN/m^2]	Ø	Specific Weight
Tested sand	1.85	27000	0	38.7^o	2.44

The acceleration responses during shaking and during hammering the soil box container were measured. Accelerometers were placed at top surface for normal soil and improved soil in order to measure the behavior of the soil during excitations at the same time. The box, configuration of the instruments and unconfined compression test for grouting specimen is shown in Figure 11.

The accelerometer sensors send the measured signals to a conditioner unit which in turn sends the conditioned signal to a data acquisition card through connecting cables. The acquisition card passes the digital data to a laptop computer for the purpose of data storage and analysis. The logging software controls the measuring process and converts analog signals to digital ones. The data is filtered and analyzed using the signal processing techniques. These techniques were applied on the measured acceleration time record. These techniques such as Cut-off frequency technique filter to be used to remove noises to get signal-to-noise ratio acceptable.

the type of the data acquisition cards is PCD-320A. The software produced by KYOWA is used to control and filter the measurements. The data analysis software used is Seismosignal.

Two harmonic excitation of 20 sec. time length with Peak Acceleration (P.A) = 0.26, 8.00 m/s^2 and with single frequency content of 1.80, 2.80 hz each respectively were applied on the tested soil separately to represent cycling loadings.

Impact load was applied at two points one of them at the center line between improved and unimproved locations and defined as near point. The other point was at box side nearer to the accelerometer at the grout than that at the normal soil. This point is defined as far point. These pulse loads represent the earthquake at base rock applied to the soil layer strata in the box container.

The Max. Void ratio for the sand was 0.307 while the Min. void ratio was 0.235. The sand density varies from Min. density of 1.42 gm/cm^3 to Max. density 1.85 gm/cm^3 . Settlement about 2.50 cm occurred in the sand layer at the end of the two tests.

a) Sand box container

b) Accelerometer fixed at the grouted Area

c) Unconfiened compression test

Figure (11-a) shows sand box container fixed over the shaking table.

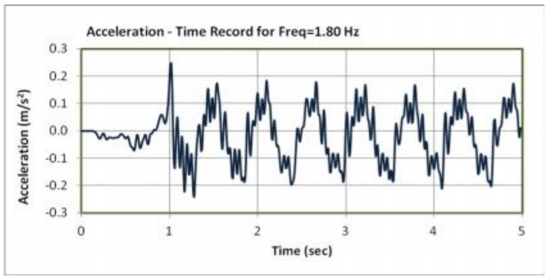
Figure (11-b) shows a photo of one of these accelerometers during installation. The type of accelerometers used is ICP.

Figure (11-c) shows a photo of one of the grouted sand tested specimen after unconfined compression test done.

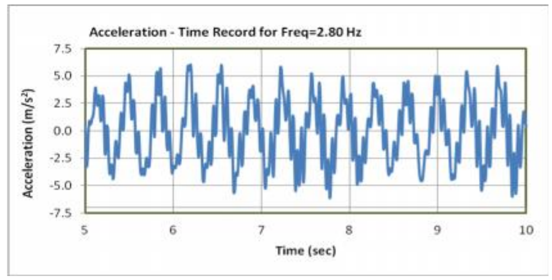
Figure 11. Test configuration

7. EXPERIMENTAL WORK RESULTS

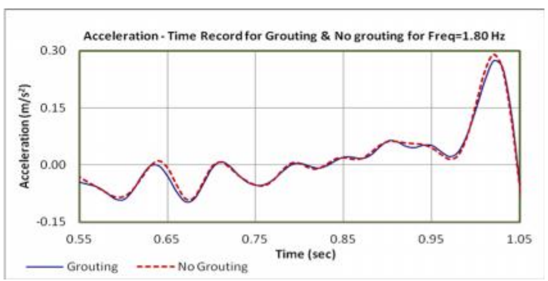
Experimental results obtained from the dynamic tests are compared with numerical analyses performed. The measured results show agreement with the numerical experimental analysis results. Figure 12 (a & b) shows the acceleration time record for the two input motions. Also Figure 12 (c & d) shows comparison between measured time record acceleration response of normal soil and improved one for the two input motions.



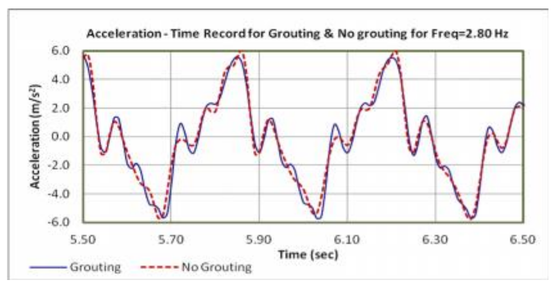
a) Input motion with frequency = 1.80 hz



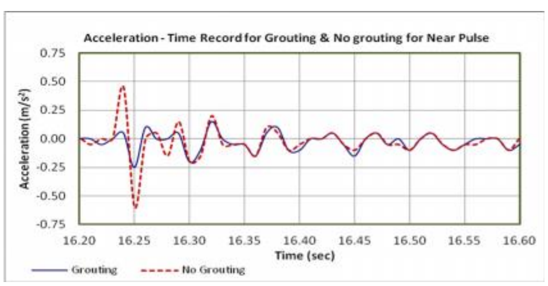
b) Input motion with frequency = 2.80 hz



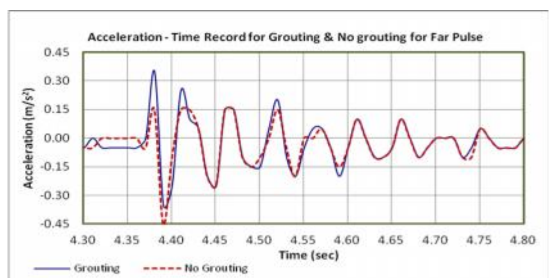
c) Response of grouting and No grouting locations for 1.80 hz. motion



d) Response of grouting and No grouting locations for 2.80 hz. motion



e) Response of grouting and No grouting locations for near pulse



f) Response of grouting and No grouting locations for far pulse

Figure 12. Test results

The percentage of decrease in the acceleration is 4.50% for input motion with P.A=0.26 m/s^2 and single frequency content of 1.80 hz. While The percentage of decrease in the acceleration is 2.80% for input motion with P.A=8.00 m/s^2 and single frequency content of 2.80 hz.

The percentage of decrease in the acceleration is 58% for pulse load at near point. While the percentage of decrease in the acceleration is 22% for pulse load at far point.

Also, to validate the experimental work, a numerical model was developed for the box filled with sand with and without grouted location and exposed to cyclic loading with frequency =1.80hz and amplitude =1.0cm to simulate the experimental work. The results of the numerical model show that the percentage of decrease in the acceleration is 7.5%. These results were matched with the experimental results during the cyclic loads.

8. CONCLUSION

This study leads to the following conclusions:

- The seismic forces applied on the structures could be reduced to a considerable amount by improving the local soil area beneath the structure which leads to reduce the cost of new structures and to maintain old structures instead of reconstruction solutions when seismic resistance capacity is considered.
- For the same grout depth and when the grout breadth increases, the percentage of decrease in the acceleration increases until it reaches a breadth to depth ratio =2. The increase of the breadth above this ratio has a little effect on the results.
- When the grout depth increases, the percentage of decrease in the acceleration increases.

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