Effect of Ground Improvement on the SeismicPerformance of Quay Wall

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ABSTRACT: Quay wall failures are mainly attributed to the properties of backfill soil and foun- dation soil. From the research available in the field of earthquake geotechnical engineering, it is evident that the failure of quay walls during Niigata earthquake of 1964, Bhuj Earthquake of 2001, Sumatra earthquake of 2004 and The Great Tohoku earthquake of 2011 are caused due to the failure of foundation soil and / or backfill soil. It has been observed that the improvement in the ground conditions leads to lesser deformation of seismic structures. It therefore becomes essential to strengthen the backfill soil and the foundation soil by suitable improvement methods and mitigate such catastrophic failures. The problem of liquefaction and associated deformation of backfill and foundation soil can be controlled by various ground improvement techniques such as densification of soil, providing drainage at suitable locations, dewatering, and introducing re-inforcements (Kramer and Holtz, 1991).

As an attempt to achieve improved performance, a detailed study is carried out on the effect of ground improvement adopting reinforced earth technique on backfill soil and foundation soil of quay wall systems. For this purpose, GEOSTUDIO, a finite element software has been used. An analytical model is prepared to represent a quay wall system comprising of the wall, the backfill soil and foundation soil and analyzed in 2D plane strain idealization. The influence of ground improvement on the permanent horizontal displacement, vertical settlement and amount of tilting of quay wall subjected to strong ground motion is studied. A comparative study is also made on the influence of strength and stiffness characteristics of foundation soil and backfill soil on the seismic displacement of the quay wall which will contribute towards performance-based design of seismic structures such as quay walls.

Keywords*: Backfill soil; Foundation Soil; Seismic Mitigation; Ground improvement; Per-*
formance of Quay Wall; Performance-based design;

1 Introduction

Quay walls are one of the most important marine retaining structures with utmost in-frastructural significance. The performance of these structures plays a very important role in the progress of a nation. Damage to quay walls due to earthquakes has been witnessed in all major earthquakes around the world. It becomes essential to find meth-ods to minimize these damages and enhance the performance of quay walls. One such technique is reinforcement of backfill soil and foundation soil to improve its strength and stability characteristics. In many earthquakes of the past, namely, the Chile earthquake of 2010, Cephalonia earthquake of 2016, Tohoku earthquake of 2011 and many more, quay wall structures have failed miserably during earthquakes. Performance of these retaining structures with ground improvement under dynamic loads is a topic of present research.

Reinforcement of soil is done using thin sheets of fibers, nets or mats of metal or geosynthetics. The application of reinforcement into quay walls was first introduced by Jones (1985). Reinforcement enhances the ability of the soil to withstand external loads without any major damages. The basic mechanism can further be explained by Rankine's stress theory. The presence of reinforcement can be correlated with the presence of plates which prevent the expansion of the soil. Reinforced earth is a cohesive material (Vidal, 1969) which helps in improving the compaction characteristics, Bearing capacity as well as dilatancy of soil. Dilatancy in soil is restricted by the introduction of reinforcement and shear strength is mobilized (Bassett and Last, 1978). The improvement in these properties reduces the risk of liquefaction of backfill and foundation soil, which in turn helps in the performance-based design of quay walls.

2 Analysis of reinforced backfill quay wall

In order to analyze the performance of reinforced backfill quay wall, a model was developed using the Quake/W module of the finite element software GeoStudio. The model consists of backfill soil, foundation soil and a quay wall. The quay wall is subjected to a horizontal earthquake acceleration of 0.5g with a frequency of 1Hz for a period of 20seconds and a damping ratio of 0.1. The basic parameters involved in the analysis are listed in Table 1.

Table 1: Basic parameters used in the analysis

Soft soil Properties	
Cohesion(kPa)	0
Angle of internal friction (^{0})	30
Unit weight (kN/m^3)	16
Young's Modulus (MPa)	1
Stiff soil Properties	
Cohesion(kPa)	0
Angle of internal friction (^{0})	40
Unit weight (kN/m^3)	18
Young's Modulus (MPa)	100
Retaining Wall properties	
Youngs modulus (GPa)	200
Unit weight(kN/m^3)	24
Reinforcement properties	
Young's modulus (GPa)	200
Spacing	2m c/c
Input motion parameters	
Amplitude	0.5 g
Frequency	1Hz
Period	20s

Consider the quay wall model with reinforcement at the two regions, namely, backfill soil and foundation soil. Four different cases are considered, namely, without reinforce- ment (Case – A), reinforcing only the backfill (Case – B), reinforcing only the founda- tion (Case – C) and reinforcing both the foundation as well as backfill (Case – D) as detailed in Table 2. The amount of reinforcement provided is a major factor which de- cides the stability of the quay wall. Fig.1, Fig.2, Fig.3 and Fig.4 show the quay wall models without reinforcement, with backfill soil reinforcement only, with foundation soil reinforcement only and with backfill soil and foundation soil reinforcement respec- tively. These models were analyzed in the GeoStudio software under Quake/w module.

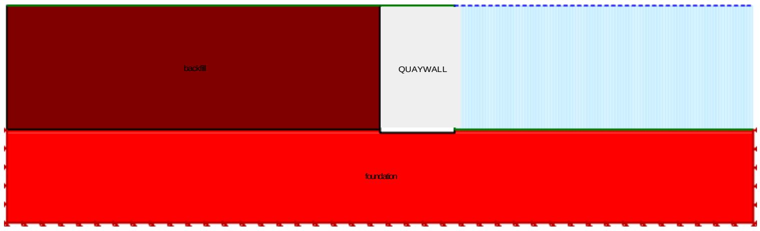


Fig.1 A quay wall model without reinforced backfill and foundation soils (Case A)

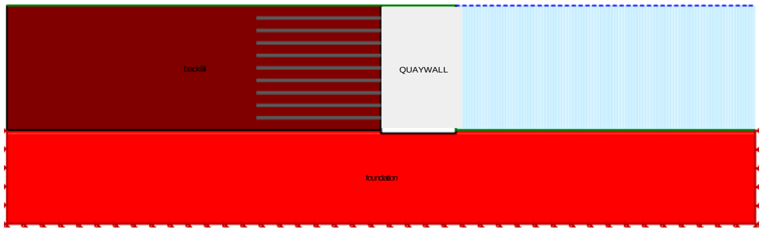


Fig.2 A quay wall model reinforced with backfill soil only (Case B)

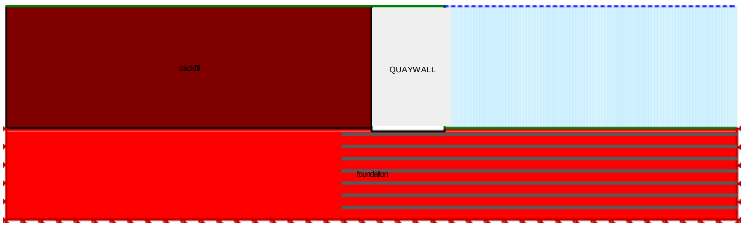


Fig.3 A quay wall model reinforced with foundation soil only (Case C)

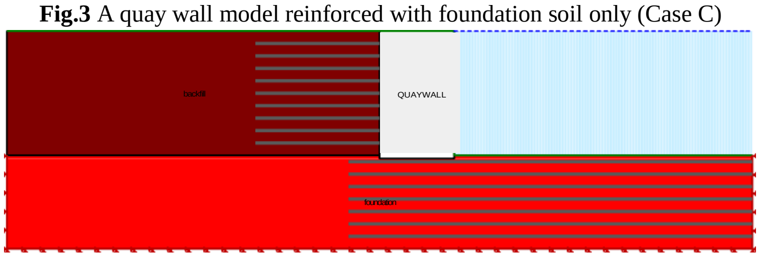


Fig.4 A quay wall model reinforced with both backfill and foundation soils (Case D)

Table 2: Description of the different cases analyzed in the present work

Case Type	Description
Case - A	No reinforcement
Case - B	Reinforcement only in backfill
Case - C	Reinforcement only in foundation soil
Case - D	Reinforcement both in backfill and foundation soil

Table 3 represents the deformation of quay wall along with the state of liquefaction in backfill and foundation soils for the case of soft backfill and soft foundation soil. It can be observed that the maximum horizontal displacement of the quay wall is maximum in Case A and least in Case D. Similar trend has been observed in cases of settlement and quay wall rotation. Further, it can be observed that the performance is better in Case C compared to that in Case B indicating that the improvement of foundation soil is more important than the improvement of backfill soil.

Table 3: Results for quay wall with Soft backfill and soft foundation soil

Description	Without Reinforce-ment (Case A)	Backfill Reinforced (Case B)	Foundation Reinforced (Case C)	Both backfill & foundation Reinforced (Case D)
Horizontal Displacement (m)	0.180	0.140	0.05	0.012
Settlement (m)	0.082	0.037	0.02	0.019
Rotation (rad)	0.005	0.0003	0.0009	.000009
Liquefaction	Backfill and foundation liquefied	Liquefaction in unrein-forced re-gions	Liquefaction in unrein-forced re-gions	No liquefaction

The graphical representation of these results are shown from Fig.5 to Fig.7. Fig.5 and Fig.6 represent the variations of horizontal and settlements for different case types, while Fig.7 shows the rotation of the quay wall with the proposed input for different case types. It is again very clear that the deformation of quay wall is maximum in Case A where no treatment is provided to either foundation soil or backfill soil and that the performance is best for Case D in which both foundation soil and backfill soil are reinforced. Further, Case C shows better performance than Case B and hence, the overall performance of quay walls depends more on the quality of foundation soil than that of backfill soil.

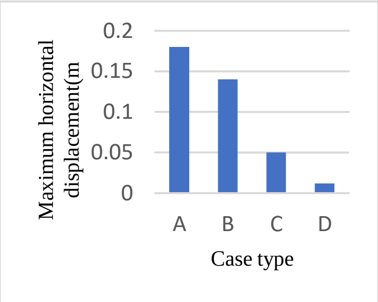


Fig 5: Variation of horizontal displacement of Quay wall with different case types

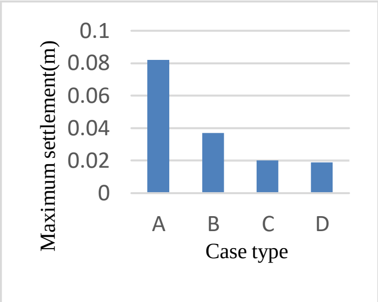


Fig 6: Variation of settlement of Quay wall with different case types

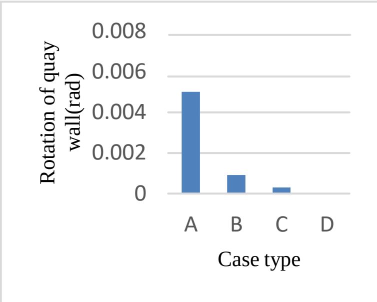


Fig.7: Variation of Rotation of quay wall with different Case types

Table 4 represents the deformation of quay wall along with the state of liquefaction in backfill and foundation for the case of soft backfill and stiff foundation soil. It can be observed that the maximum horizontal displacement, settlement and rotation of quay wall are the highest in Case A and least in Case D.

Table 4: Analysis of Results for Soft backfill and stiff foundation soil

Description	Without Reinforcement (Case A)	Backfill Reinforced (Case B)	Foundation reinforced (Case C)	Both backfill & foundation Reinforced (Case D)
Horizontal Displacement(m)	0.15	0.127	.031	.017
Settlement (m)	.0018	.0003	.00016	.00012
Rotation (rad)	.008	.007	.006	.0004
Liquefaction	Backfill & foundation liquefied	Liquefaction in unreinforced regions	Liquefaction in unreinforced regions	No liquefaction

Fig.8 and Fig.9 represent the variations of horizontal displacement and settlement of quay wall for different case types, while Fig.10 shows the rotation of the quay wall. It can be observed that the horizontal displacement, settlement and rotation of quay wall have reduced with the introduction of reinforcement from unreinforced backfill and foundation soil.

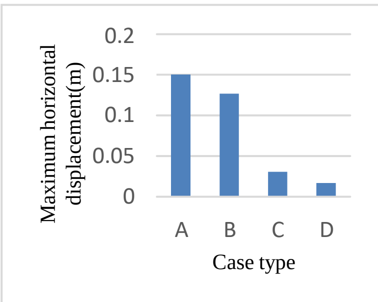


Fig 8: Variation of maximum horizontal displacement of Quay wall with different case types

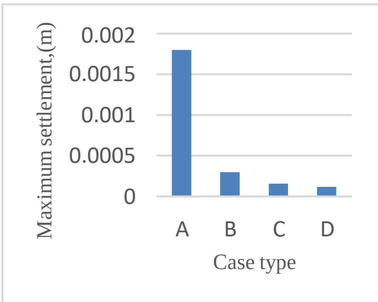


Fig.9: Variation of maximum settlement of Quay wall with different case types

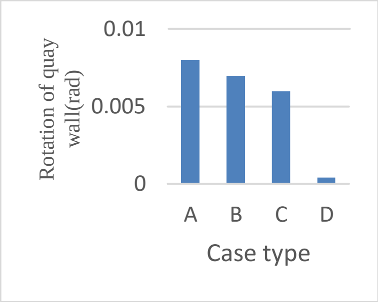


Fig 10: Variation of rotation of quay wall with different case types

Table 5 represents the deformation of quay wall along with the state of liquefaction in backfill and foundation for the case of stiff backfill and soft foundation soil. It can be observed that the maximum horizontal displacement, settlement and rotation of quay wall are the highest in Case A and least in Case D.

Table 5: Analysis of Results for Stiff backfill and soft foundation soil

Description	Without Reinforcement (Case A)	Backfill Reinforced (Case B)	Foundation re-inforced (Case C)	Both backfill & foundation Reinforced (Case D)
Horizontal Displacement (m)	.06	0.057	.056	.049
Settlement(m)	0.082	.002	.0009	.0002
Rotation(rad)	.0003	0.00027	.000045	.00001
Liquefaction	Backfill and foundation liq-uefied	Liquefaction in unrein-forced regions	Liquefaction in unreinforced re-gions	No liquefaction

Fig.11 and Fig.12 represent the variations of horizontal displacement and settlement of quay wall for different case types, while Fig.13 shows the rotation of the quay wall. It can be observed that the horizontal displacement, settlement and rotation of quay wall have reduced with the introduction of reinforcement from unreinforced backfill and foundation soil.

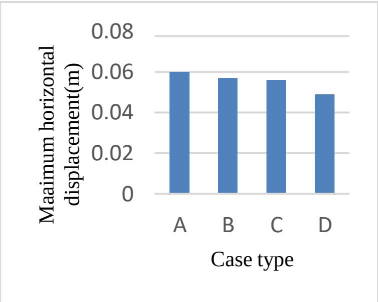


Fig 11: Variation of horizontal displacement of quay wall with different case types

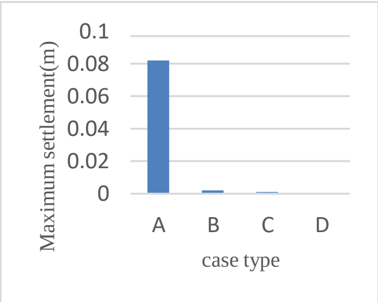


Fig 12: Variation of settlement of quay wall with different case types

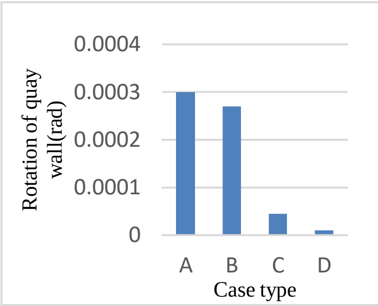


Fig 13: Variation of rotation of quay wall with different case types

Table 6 represents the deformation of quay wall along with the state of liquefaction in backfill and foundation for the case of stiff backfill and soft foundation soil. It can be observed that the maximum horizontal displacement, settlement and rotation of quay wall are the highest in Case A and least in Case D.

Table 6: Analysis of Results for Stiff backfill and Stiff foundation soil

Description	Without Reinforcement (Case A)	Backfill Re-inforced (Case B)	Foundation reinforced (Case C)	Both backfill & foundation Rein-forced (Case D)
Horizontal Displacement (m)	.045	0.027	.021	.02
Settlement(m)	0.082	.0035	.003	.00019
Rotation(rad)	.0004	.00039	.0003	.00029
Liquefaction	Backfill and foundation liq-uefied	Liquefaction in unrein-forced re-gions	Liquefaction in unrein-forced regions	No liquefaction

Fig.14 and Fig.15 represent the variations of horizontal displacement and settlement of quay wall for different case types, while Fig.16 shows the rotation of the quay wall. It can be observed that the horizontal displacement, settlement and rotation of quay wall have reduced with the introduction of reinforcement from unreinforced backfill and foundation soil. Table 7 gives the summary of the results.

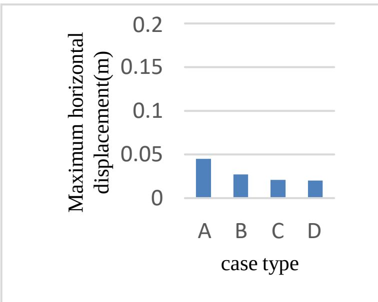


Fig. 14: Variation of maximum horizontal dis-placement of quay wall with different case types

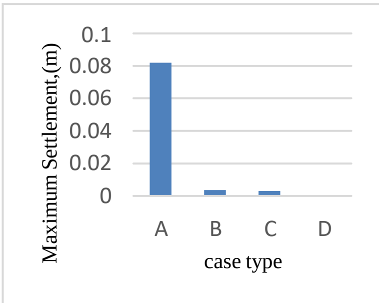


Fig 15: Variation of settlement of quay wall with different case types

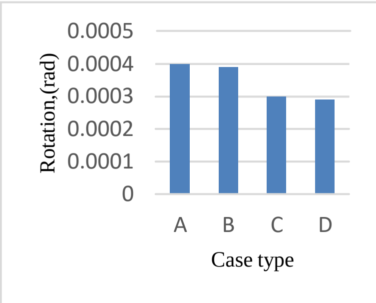
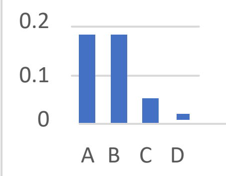
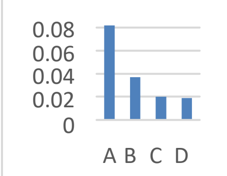
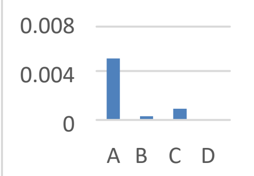
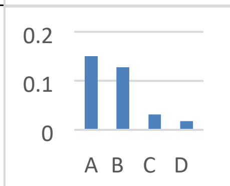
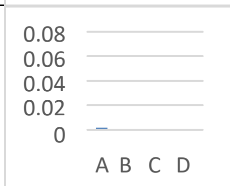
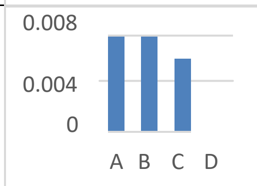
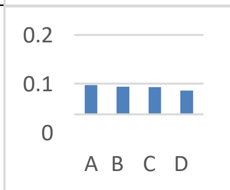
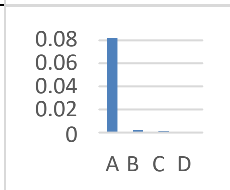
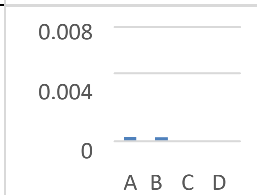
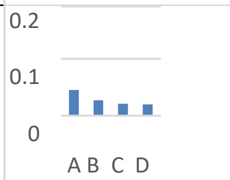
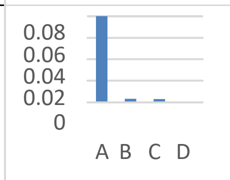
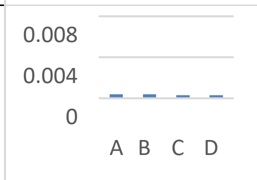


Fig 16: Variation of rotation of quay wall with different case types

Table 7: summary of the results obtained in all the four case types

Condition	Maximum horizontal Displacement(m) for different Case types	Maximum settlement(m) for different Case types	Rotation of quay wall (Radians) for different case types
Soft backfill + soft foundation			
Soft backfill + stiff foundation			
Stiff backfill +soft foundation			
Stiff backfill + soft foundation			

3 Comparison of displacement of model quay wall with that from the present analytical study.

The model test results from shaking table test conducted by Nanjundaswamy P. (2008) as a part of his Doctoral thesis are compared with that obtained from Quake /W module of the finite element software GeoStudio. The model studies were performed at normal gravitational environment. The transparent model container and manual shaking table developed at Earthquake Engineering Laboratory of S. J. College of Engineering; Mysore are shown in Fig. 17.

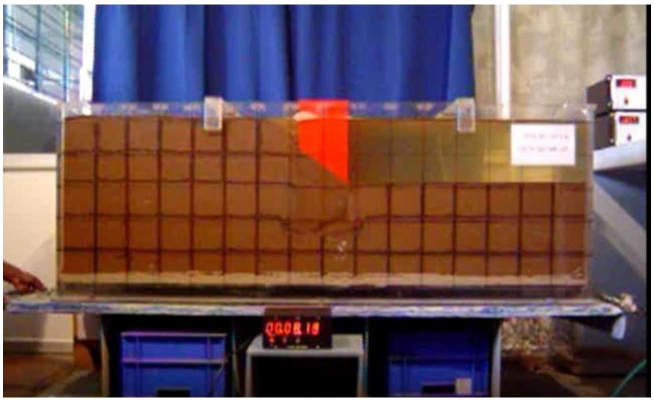


Fig.17: Assembly of quay wall model in manual shaking table with transparent model container (Nanjundaswamy P. (2008))

The materials that are used as well as the size of the shaking table used in the test play a major role in the ground motion study (Nanjundaswamy P. (2008)). The specifications of the shaking table and the transparent container are as below.

- Two panels 600 mm in width, 1800 mm in length and 25 mm in thickness made of wood were used in order that one of these acted as a base and the other a platform.
- Steel plates 350 mm in length, 550 mm in width and 2 mm in thickness provided spring action.
- The connections of wooden panel and plates and were made through steel bolts and angle sections.
- A harmonic sinusoidal input in the longitudinal path was given through the means of a handle.
- 3 mm thick rubber membranes were given between the floor and table and the model container and the table.
- An acceleration level of 0.5g and vibration of 2Hz and a pay load of 7 kN was the shaking table design.
- The cost of fabrication of shaking table was not more than Rs. 10,000/-

Table 8 presents the horizontal displacement, settlement and rotation of quay wall obtained from model shaking table test on quay wall subjected to harmonic vibration and Table 9 gives the results from numerical model test on Quay Wall using Finite Element approach. Further Table 10 gives the finite element analysis results for reinforced backfill and foundation soil condition of the quay wall.

Table 8: Results of Model Shaking Table tests on Quay Wall (Nanjundaswamy P. (2008))

Sl No	Foundation soil type	Backfill soil type	Horizontal sliding displacement (mm)	settlement (mm)	Rotation (deg)
1	Soft	Soft	150	-50	-80
2	Stiff	Soft	95	+10	-10
3	Soft	Stiff	205	+170	+5
4	Stiff	Stiff	90	+55	+7

Table 9: Results from the present Numerical study on Quay Wall using Finite element analysis

Sl No	Foundation soil type	Backfill soil type	Horizontal sliding Displacement (mm)	Settlement (mm)	Rotation (deg)
1	Soft	Soft	162	-58	-38
2	Stiff	Soft	100	+15	-2
3	Soft	Stiff	215	+180	+10
4	Stiff	Stiff	95	+59	+9

Table10: Results from the present Numerical study on Quay Wall using Finite element analysis for reinforced backfill and foundation soil

Sl No	Foundation soil type	Backfill soil type	Horizontal sliding displacement (mm)	Settlement (mm)	Rotation (deg)
1	Soft	Soft	102	-12	-28
2	Stiff	Soft	43	+7	+1
3	Soft	Stiff	127	+105	+2
4	Stiff	Stiff	48	+18	0

The results of performance of quay wall subjected to shaking from numerical model study using Finite element analysis obtained from quake/w (Table 10) indicate that the Horizontal sliding displacement, settlement and rotation of quay wall values are considerably comparable to those from model test (Table 9). Further, the results for numerical model study using Finite element analysis for reinforced backfill and foundation soil indicate that reinforcement is an effective ground improvement technique in improving the deformation characteristics and Fig.18 to Fig. 21 indicate that liquefaction characteristics of backfill and foundation soil have improved with the introduction of reinforcement. Liquefaction is identified by light yellow coloration in the unreinforced regions. Clearly in reinforced regions, the system is found to be free from liquefaction.

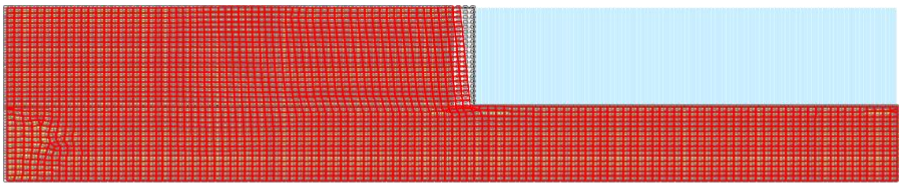


Fig.18 Quake /w model for quay wall system of soft foundation and soft backfill soil with reinforcement subjected to shaking

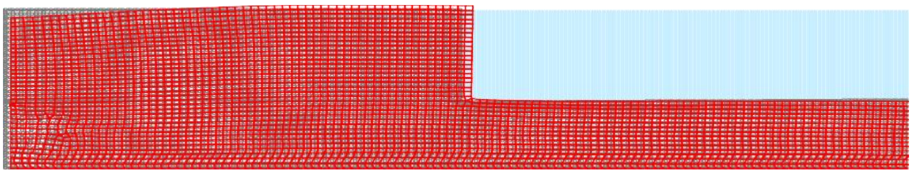


Fig.19 Quake/w model for quay wall system of stiff foundation and soft backfill soil with reinforcement subjected to shaking

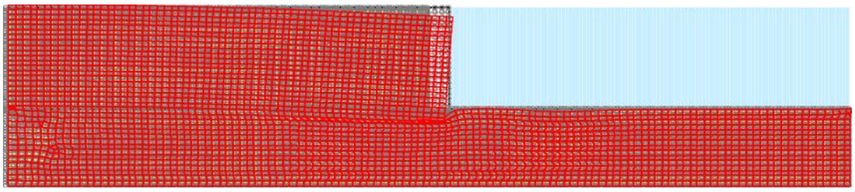


Fig.20 Quake/w model for quay wall system of soft foundation and stiff backfill soil with reinforcement subjected to shaking

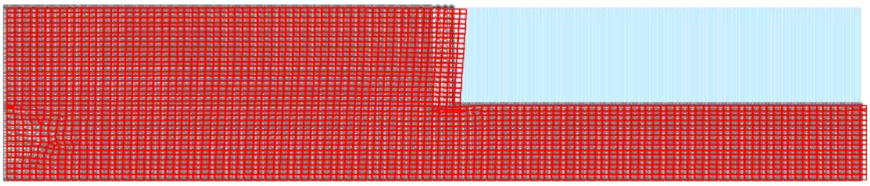


Fig.21 Quake/w model for quay wall system of stiff foundation and stiff backfill soil with reinforcement subjected to shaking

4 Concluding Remarks

The following are a few important inferences from the present study.

- From the laboratory model tests and numerical analysis it has been observed that soft backfill and soft foundation combination for quay wall is the most vulnerable. The vulnerability is assessed based on the maximum horizontal displacement, maximum vertical settlement and rotation of the quay wall in addition to the zone of liquefaction.
- Further, it is observed that the case with stiff foundation soil performed better than the situation with stiff backfill soil. Hence it is essential that the foundation soil should be strong and stable and free from liquefaction susceptibility.
- Provision of reinforcement in backfill and foundation soil has definitely enhanced the performance in terms of reduced horizontal displacement, reduced vertical settlement and decreased rotation of quay wall in addition to the reduction to area of liquefaction. Provision of reinforcement in foundation soil is much more effective.
- There has been an excellent correlation between results from the laboratory model test and numerical analysis using GeoStudio.
- A parametric study of this type will help in understanding the maximum permissible settlement, maximum horizontal displacement and rotation acceptable for good performance of quay wall which is a step towards performance-based design.

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