

THE BEHAVIOR OF CONCRETE CANTILEVER RETAINING WALLS DURING FAR-FIELD AND NEAR-FAULT EARTHQUAKES

Ayah Hameed MHAWISH^{1,*}, Hussam K. RISAN¹

¹ Department of Civil Engineering, Collage of Engineering, Al-Nahrain University, Baghdad, Iraq.

* corresponding author: Ayah.hameed25@gmail.com

Abstract

The dynamic behavior of retaining walls is a complicated subject and a considerable design challenge, particularly under seismic conditions. Seismologists and investigators have an interest in near-fault earthquakes with significant velocity pulses because it can cause considerable displacements in constructions with respect to far-field earthquakes and consequently rise the hazard of earthquake-caused failure of structures. Despite there are several studies have investigated the seismic behavior of retaining structures, but the researches about retaining walls subjected to the influence of near fault like pulse earthquakes is still not adequate. The current study targets to numerically assess the dynamic performance of concrete cantilever retaining walls during far field ground motions (FFGMs) and near-fault ground motions (NFGMs). The nonlinear analysis of time history is conducted using the finite element method for three cantilever retaining wall models. The results of the analysis gained in terms of top horizontal displacement of the wall, active seismic earth pressure, and acceleration response of the system, which have been considered to recognize the impact of near fault earthquake on retaining structures. Additionally, the influence of different PGA of NF and FF earthquakes has been studied.

Keywords:

Retaining walls;
 Seismic analysis;
 Abaqus software;
 Near-fault like- pulse earthquake;
 Far-field earthquakes.

1 Introduction

Retaining walls are an important system used to stabilize excavations in many infrastructures such as roads and highways, especially in urban regions. The response of retaining walls under earthquakes is a complex soil structure-interaction problem. Many structures have structural elements that directly contact the soil. When earthquakes force these systems, the soil's response affects the structure's motion and vice versa, this phenomenon is known as soil-structure interaction (SSI) [1].

Characteristics of an earthquake ground motions near a ruptured fault could be considerably different from those recorded far away from the seismic source. The near-fault region is often thought to be limited to a distance of roughly 20 kilometers from the ruptured fault. Two major characteristics of near-fault earthquakes that seismologists have identified, which are the directivity feature and fling step. The first one is the effect of forward-directivity, it is considered as the most important phenomenon in which pulses happen toward the propagation of the rupture where the velocity of the rupture and the velocity of shear wave is close together [2].

Another phenomenon that is commonly used when explaining the difference between far and pulse-like ground motions is the fling step. Pulses of fling-step are recognized with characteristics different from those of forward-directivity pulses. Fling-step has in the velocity time history a one-sided pulse and thus produces in the ground a permanent static movement. While forward-directivity does not generate residual ground displacements and has velocity pulses with two sides [3]. It has noticed that the forward directivity effect causes higher input energy, acceleration, and base shear in the structure [4]. A comparison between far-fault motion earthquake (Taft station of Kern County event earthquake 1952) and the forward-directivity effect (Rinaldi record of Northridge event earthquake 1994) and fling step effect (Sakarya-SKR station of 1999 Kocaeli event earthquake) respectively is illustrated in Fig. 1 [5].

The above explanation shows the variance between far-field and near-fault like-pulse earthquakes. Consequently, special consideration is required when designing retaining structures exposed to such earthquakes. It is important to mention one of the greatest initial estimations among other complicated numerical techniques and theoretical models which is Mononobe-Okabe method (M-O). It is a seismic form of coulomb theory for granular soils, it was suggested accordingly to pseudo-static ground motion loading. M-O theory is still one of the best approximations for designing retaining structures. However, some drawbacks make it unable to model structures. Therefore, many studies have investigated the behavior of retaining walls by experimental, analytical, and numerical analysis under earthquakes. Some of these studies are briefly summarized as follows.

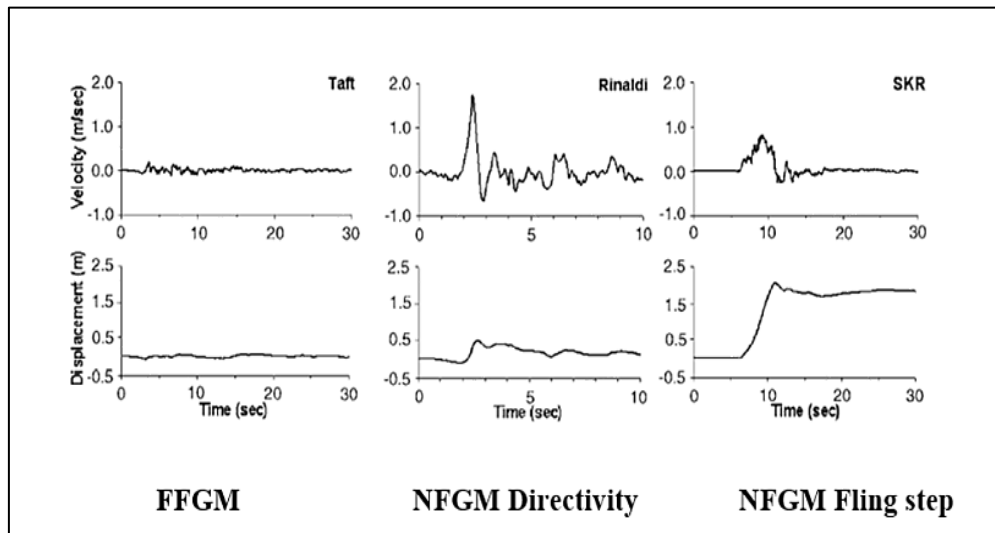


Fig. 1: A comparison between far-fault motion earthquake (Taft station), the forward-directivity effect (Rinaldi station), and fling step effect (Sakarya-SKR station) of Kern County event earthquake, Northridge event earthquake Kocaeli event earthquake respectively [5].

Mohammed and Adnan [6], focused in the research on static and earthquake response analysis of retaining structures influenced by lateral earth pressure. Three retaining wall heights were regarded: (2.9 m, 4.7 m and 6.7 m). The responses obtained using finite element analysis in Abaqus software are compared to those obtained using the Mononobe-Okabe method. For all retaining wall heights, it is observed that the lateral wall responses obtained by using FE were greater than those obtained by the Mononobe-Okabe method. Snehal[1], discussed seismic analysis of cantilever retaining walls-base shear. The effect of different types of soil on the various heights of the wall is examined in his work utilizing numerical 2-D simulation. The soil structure interaction of a cantilever retaining wall is studied using the finite element program SAP2000. It is found that when the soil stiffness rises, the dynamic base shear of the cantilever retaining wall get an increase. Also, it is noticed that there is an increase in the seismic base shear as the seismic region increases.

JUNIED and SYED [7], concluded after analyzing the results, that the Mononobe-Okabe and methods of pseudo-dynamic provided an overestimation of the seismic earth pressure, also found that for an acceleration more than 0.4 g, the retaining wall continued to slide with no increase in the seismic passive earth pressure force. Prajakta and Amit [8], conducted a 2D, plane strain finite element seismic analysis of cantilever retaining walls with various positions of the shear key. Results show that a shear key located at the heel of the cantilever retaining wall reduces the translational displacements by approximately 40%, So it is considered as the appropriate configuration. Milad et al. [9], assessed the dynamic behavior of cantilever retaining walls exposed to near-fault earthquakes, by performing several finite element models. The study found that 'forward-directivity' can cause significant damage to structures. The models were subjected to a variety of peak ground accelerations (PGAs) for near-fault scenarios. So, it is found that the accelerations more than 0.6 g for both near and far-field earthquakes led to wall failure, with a height decrease of more than 5%. Furthermore, for the accelerations greater than 0.4 g, the lateral movement of the wall reached a higher value than the allowed limits. Partha and Maheshreddy [10], attempted to examine the pulse effect on the seismic performance of the retaining wall by establishing a 2D, plane strain finite element model of a concrete cantilever retaining wall and conducting analyses for near-fault and far-field earthquakes. Thus, 10 far-field earthquakes and 70 near-

fault earthquakes have been chosen as a dataset. The obtained analysis results are according to wall displacements to evaluate the influence of NFGMs on retaining walls. The findings show that the displacement of the wall resulting from far field earthquakes are less than that of near fault earthquakes.

Mostafa [11], studied the stability and behavior of the mechanically stabilized earth wall system with geogrid (MSE) and the cantilever retaining walls exposed to seismic loads utilizing PLAXIS 3D 2020 program. Results show that, the cantilever retaining wall performance is better than the performance of the MSE wall subjected to ground motions up to 0.35 g PGA level. However, the estimations of the lateral displacement are less in case of the MSE wall.

2 Finite Element Model

The current study aims to assess the effect of the far field and near-fault earthquakes on the cantilever retaining walls' seismic performance by conducting a seismic investigation utilizing Abaqus software. A 2D, plane strain finite element model of a concrete cantilever retaining wall with sandy soil as backfill and subsoil has been established. The proposed system involves three cantilever retaining wall models with heights of 3 m, 5 m, and 7 m. The ratio of B (width of base) to H (height of the wall) is taken as (0.7) and the stem width is assumed ($H/10$) which is kept constant along the wall height and equal to the base height of the retaining wall [12]. The backfill height, the thickness of the foundation soil layer, horizontal distance of soil in front and behind the wall for the numerical model are assumed according to [13] (as shown in Fig. 2). These distances were supposed to be efficient to remove the boundary effects (wave reflection). Four noded, reduced integration plane strain elements are utilized. The wall was modelled as concrete with elastic properties [14]. However, the soil was modelled as an elastic-plastic, frictional model with the Mohr-Coulomb failure criterion. The Mohr-Coulomb model is commonly utilized in researches to evaluate the seismic behavior of the retaining wall during ground motions [15–17]. By using the surface-to-surface interaction module, the wall-soil interaction was modelled with a friction coefficient of 0.55 in a software package and with an angle of friction $\delta = 37^\circ$ between soil and concrete, knowing that the damping ratio assumed 5%. Table 1. illustrates the properties of soil and wall as assumed by [10]. In order to estimate the natural frequencies of the proposed models a free vibration analysis is examined in Abaqus software. Thus, the natural periods for the first two modes of the three models are obtained in addition to their Rayleigh factors (β , α) which are presented in Table 2.

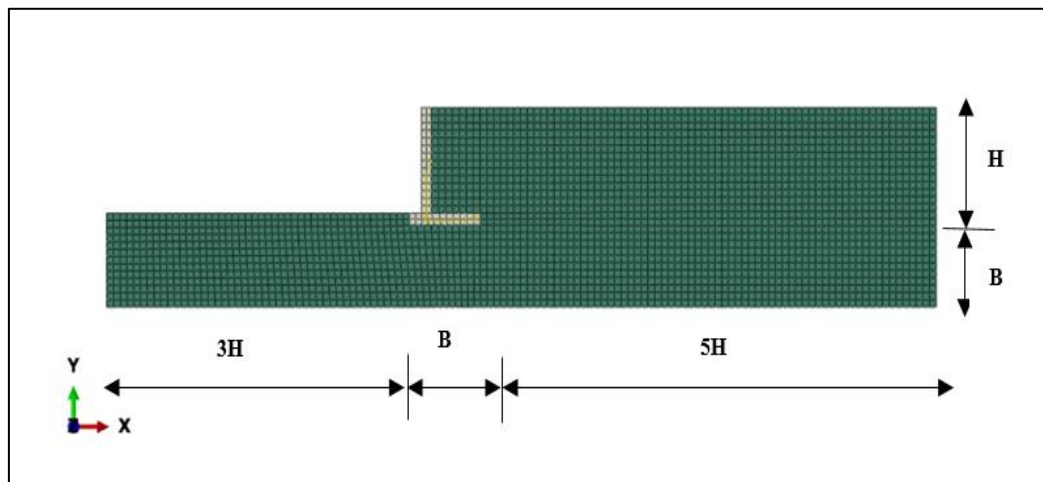


Fig. 2: Finite element mesh.

Table 1: Wall-soil properties.

Wall-soil properties	Parameter	Value
Wall	Young's modulus (E)	26267 MPa
	Poisson's ratio (ν)	0.3
	Strength of concrete	31 MPa
	Unit weight (γ)	23.60 kN/m ³
Soil	Young's modulus (E)	150.8 MPa
	Friction angle [ϕ]	34°
	Dilation angle [ψ]	10°
	Poisson's ratio (ν)	0.3
	Unit weight (γ)	15.07 kN/m ³

Table 2: Vibration Periods used to define Rayleigh damping factors.

Model	1st mode [sec]	2nd mode [sec]	α	β
Model-1	0.06712	0.0561	0.811725	0.003055
Model-2	0.11212	0.09346	0.486427	0.005097
Model-3	0.15697	0.13084	0.347452	0.007136

2.1 Validation

The process of verification is considered a vital step to get the reliability of the FE numerical model. Thus, the results of the numerical model is validated with respect to that of the experimental model reported by KENJI et al. [18]. In the experimental model, a shaking table test was performed with a cantilever retaining wall, which was subjected to Kobe record acceleration-time history. The numerical analysis results are certified in terms of the top horizontal residual displacement of the wall. The geometry of the validation model was with a total wall height of 53 cm, a base width of the cantilever retaining wall of 23 cm, a heel width of 15 cm, and a toe width of 5 cm. Furthermore, the stem width was of 3 cm while the height of the base was 8 cm, all dimensions are illustrated in Fig. 3.

The retaining wall is modelled as linear- elastic properties with young's modulus, Poisson's ratio, and unit weight value equal to 25000 MPa, 0.15, and 25 KN/m³ respectively. While the soil was modeled as an elastic-plastic, frictional model with the Mohr-Coulomb failure criterion with poisson's ratio, young's modulus, and unit weight value equal to 0.33, 60 MPa, and 19.5 KN/m³ respectively.

Before applying the earthquake, the model is subjected to surcharge pressure of 1 kPa, and gravity loading which represents its weight. In the following stage, the overall system is exposed to "Kobe-1995" ground motion which is shown in Fig. 4. To maintain static equilibrium, the retaining wall was fixed horizontally using roller support. The sides of the soil were braced with roller support, while the bottom of the soil was fixed with a hinge support [14]. In the seismic step, all supports were released except at the bottom of the soil, which is support with roller, after that the acceleration time history of Kobe1995 record was subjected laterally to overall nodes at the side and bottom boundaries of the soil area. A curve between wall top residual displacement and seismic coefficient [K_h] values, was achieved from the numerical analysis results and experimental model results to make a comparison as shown in Fig. 5. Thus, the Wall top displacement values of the physical model and the numerical model of this study are comparable.

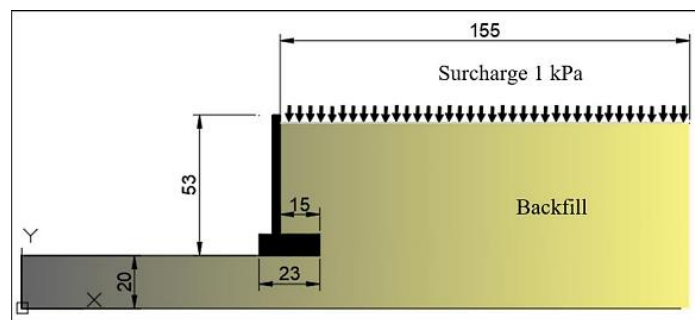


Fig. 3: Finite element dimensions of physical model [18].

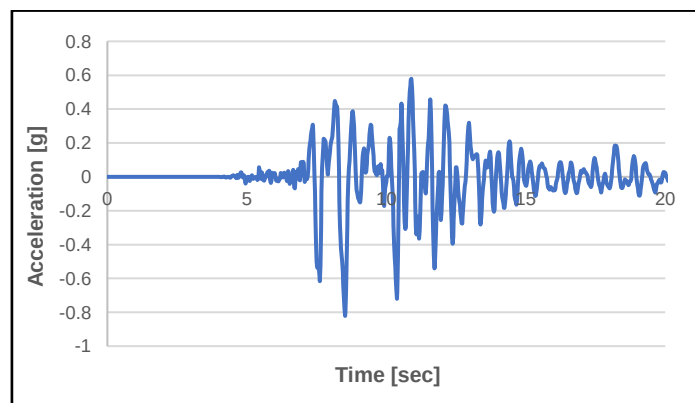


Fig. 4: Acceleration time history of Kobe earthquake (1995).

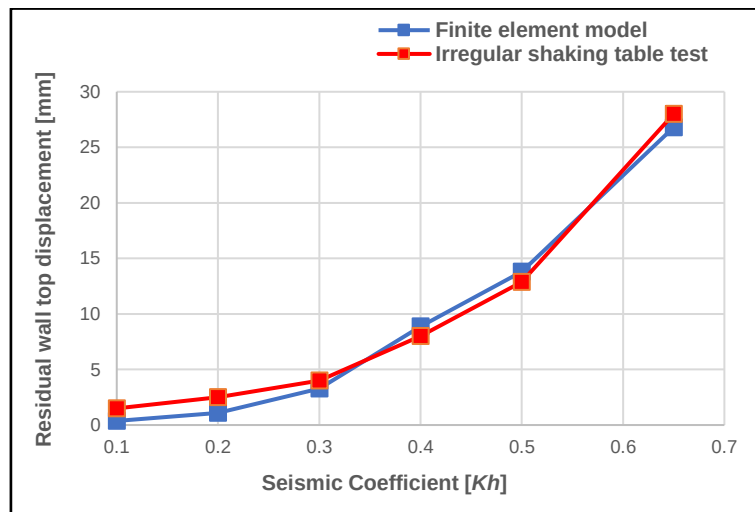


Fig. 5: Comparison of residual wall top displacement with seismic coefficient between the present study (FINITE model) and physical model (Irregular shaking table test).

2.2 Numerical analysis

A non-linear dynamic implicit solver in ABAQUS Finite element software package was utilized to conduct the modelling of the system. Three steps were performed in this study. Initially, an analysis of a free vibration was run in order to maintain the retaining walls' natural periods.

Secondly, a general static step for gravity loading was defined while the surcharge loading is defined in a separate static step for more accurate simulation with 10 kPa. However, the wall was fixed horizontally to get static equilibrium. The bottom of the soil was fixed with a hinge support. While, the sides of the soil were braced with roller support [14]. After that, as in the field the wall support was released. Finally, seismic loading was applied to the system with a dynamic-implicit step.

Two stations of the Kocaeli 1999 ground motion with (7.51) moment magnitude were chosen. The strong motions were approved by "the Center of Pacific Earthquake Engineering Research" (PEER) [19]. The first station of (Gebze) refers to the near-fault pulse-like record with a distance of 10.92 km from the rupture plane. The second station of (Eregli) represents the far-field record, which is located at a 142.29 km distance from the source of the earthquake. In order to make a fair comparison, peak ground accelerations (PGA) of both stations mentioned were scaled to (0.4 g). The far field and the near-fault pulse-like ground motions' acceleration time histories after scaling are shown in Fig. 6.

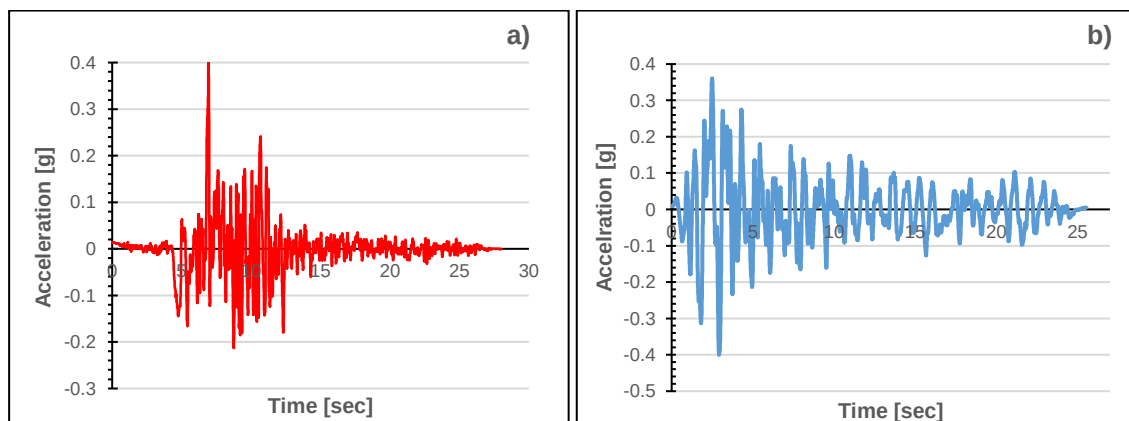


Fig. 6: Scaled acceleration time histories of Kocaeli 1999 earthquake; a) Gebze - Near fault station, b) Eregli- Far field station.

3 Analysis Results and Discussion

The results of the nonlinear time history analysis of proposed models are evaluated in terms of top wall Horizontal Displacement, Seismic active earth pressure, and acceleration response.

3.1 Horizontal Displacement results

Table 3 and Fig. 7 show the results analysis of the maximum top wall horizontal displacement of models. For model-1 of the cantilever retaining wall with a height of 3 m, the response of NF was higher than FF ground motion. The results of NF (Kocaeli, Gebze sta.) to FF (Kocaeli, Eregli sta.) ratio of maximum top horizontal displacement was (NF/FF=142.7%). While for Model-2 of the cantilever retaining wall with a height of 5 m, the (NF/FF) ratio was (149%) with a NF structural demand higher than FF. However, for model-3 of the cantilever retaining wall with a height of 7 m the response of the structure of NF was higher than the FF station with no more (46%) increment in terms of top horizontal displacement. Far-field earthquakes produce smaller displacements for all models. These results evidence the importance of NFGMs and illustrate that making a judgment on just the base acceleration may lead to terrible consequences as Milad [9] described in his research which is consistent with the present study results. Noting that the negative sign refers to the opposite side of the backfill soil.

Table 3: Summary of the Horizontal Displacement results [cm].

Model	NF results	FF results	Ratio %
1	64.3638	45.1016	142.7
2	68.9961	46.3825	149
3	71.4515	48.9292	146

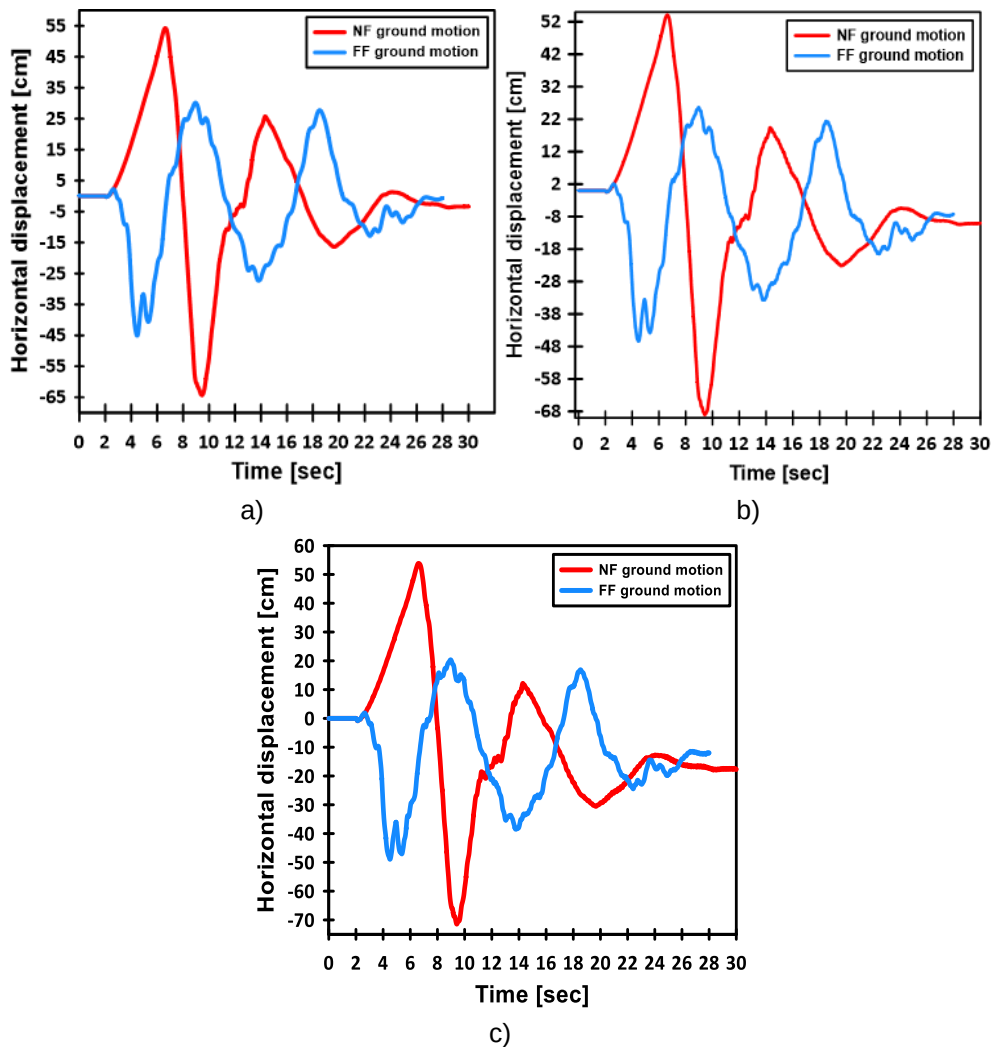


Fig. 7: Maximum top horizontal displacement for wall models of different heights; a) 3 m, b) 5 m, and c) 7 m under near fault and far field ground motion.

3.2 Seismic active earth pressure

Table 4 and Fig. 8 show the results analysis of the maximum Seismic active earth pressure of the models. For model-1 of the cantilever retaining wall with a height of 3 m, the response of NF was higher than that of FF ground motion. The NFGM to FFGM result ratio of maximum seismic active earth pressure was (NF/FF=115%). While for Model-2 of a cantilever retaining wall with a height of 5 m, the (NF/FF) ratio was (104.2%) with a NF structural demand higher than FF. However, for model-3 of the cantilever retaining wall with a height of 7 m, the (NF/FF) ratio was 89.5% in terms of maximum seismic active earth pressure in which FF gives a response higher than NF ground motions. The distribution of the dynamic active earth pressure is observed to be non-linear and depends on the applied ground motion. In common, it was noticed that the seismic active earth pressure increases considerably in the direction of the bottom retaining wall which is consistent with [7, 14].

Table 4: summary of the Seismic active earth pressure [kN/m²].

Model	NF results	FF results	Ratio %
1	60.5529	52.6661	115
2	93.4916	89.7497	104.2
3	114.425	127.845	89.5

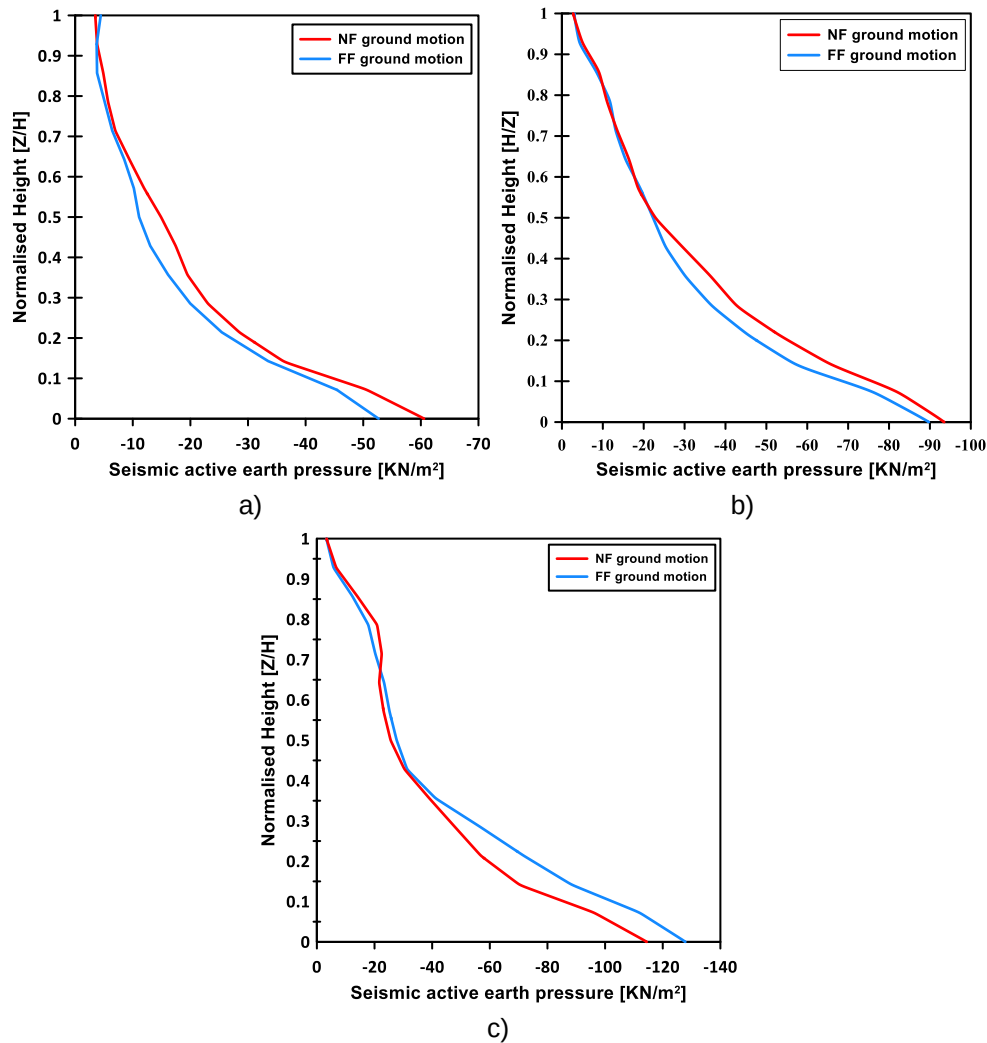


Fig. 8: Maximum values of the Seismic active earth pressure [kN/m²] for wall models of different heights; a) 3 m, b) 5 m, and c) 7 m under near fault and far field ground motion.

3.3 Acceleration response of cantilever retaining wall models

Tables 5, 6, and 7 and Figs. 9, 10, and 11 respectively, show the results analysis of the maximum acceleration response at the top wall, top soil, and bottom wall of the models. As shown the results of all models at different locations give an acceleration response in case of NF higher than that of FF except for Fig. 11c. It is observed that the results of the acceleration response of the three models at the top wall are approximately the same as at the top of the soil which is evident that both the backfill soil and wall's stem move together which means they are in phase with each other. However, it is higher than the results at the bottom of the wall. These findings are consistent with the results of [7].

Table 5: The maximum acceleration response at top wall [m/sec²].

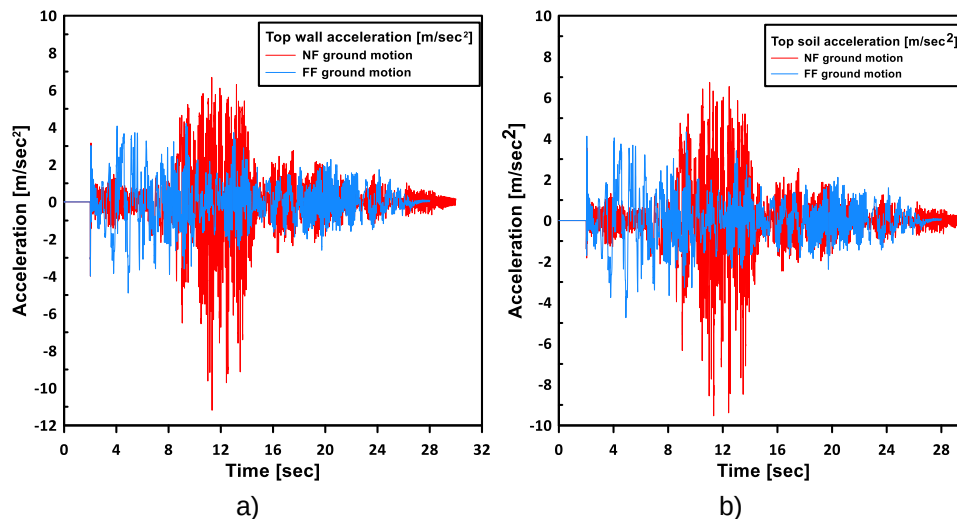
Model	NF results	FF results	Ratio %
1	11.1878	4.89477	229
2	12.7348	8.22056	154.9
3	13.6463	11.4592	119.1

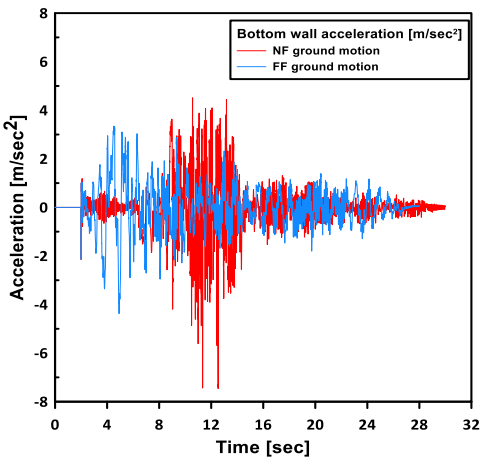
Table 6: The maximum acceleration response at top soil [m/sec²].

Model	NF results	FF results	Ratio %
1	9.53296	4.74106	201
2	9.99663	9.11516	154.9
3	11.0754	10.2851	107.7

Table 7: The maximum acceleration response at bottom wall [m/sec²].

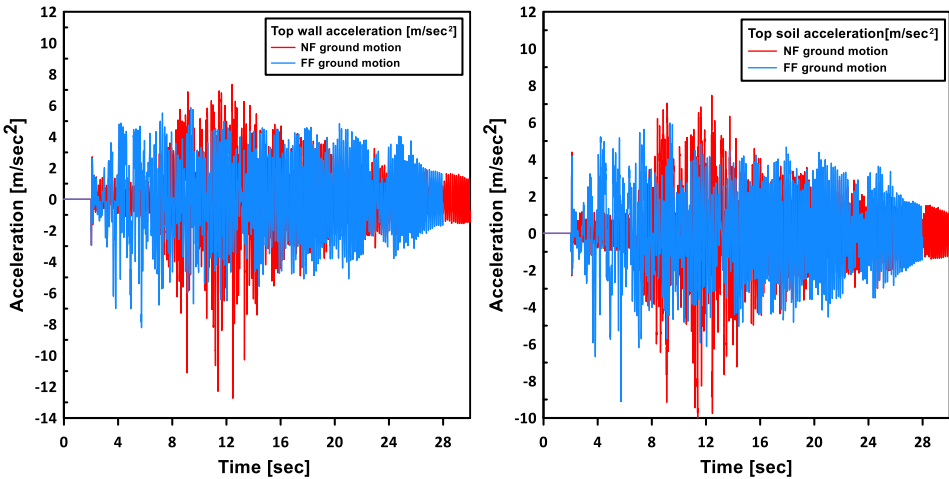
Model	NF results	FF results	Ratio %
1	7.46059	4.37289	171
2	6.9965	5.14702	135.9
3	6.81312	7.94167	85.8





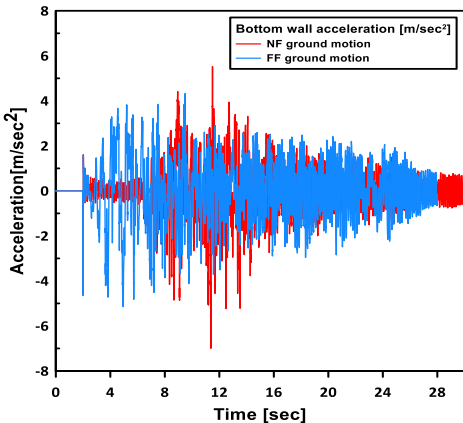
c)

Fig. 9: Acceleration response of model -1.



a)

b)



c)

Fig. 10: Acceleration response of model -2.

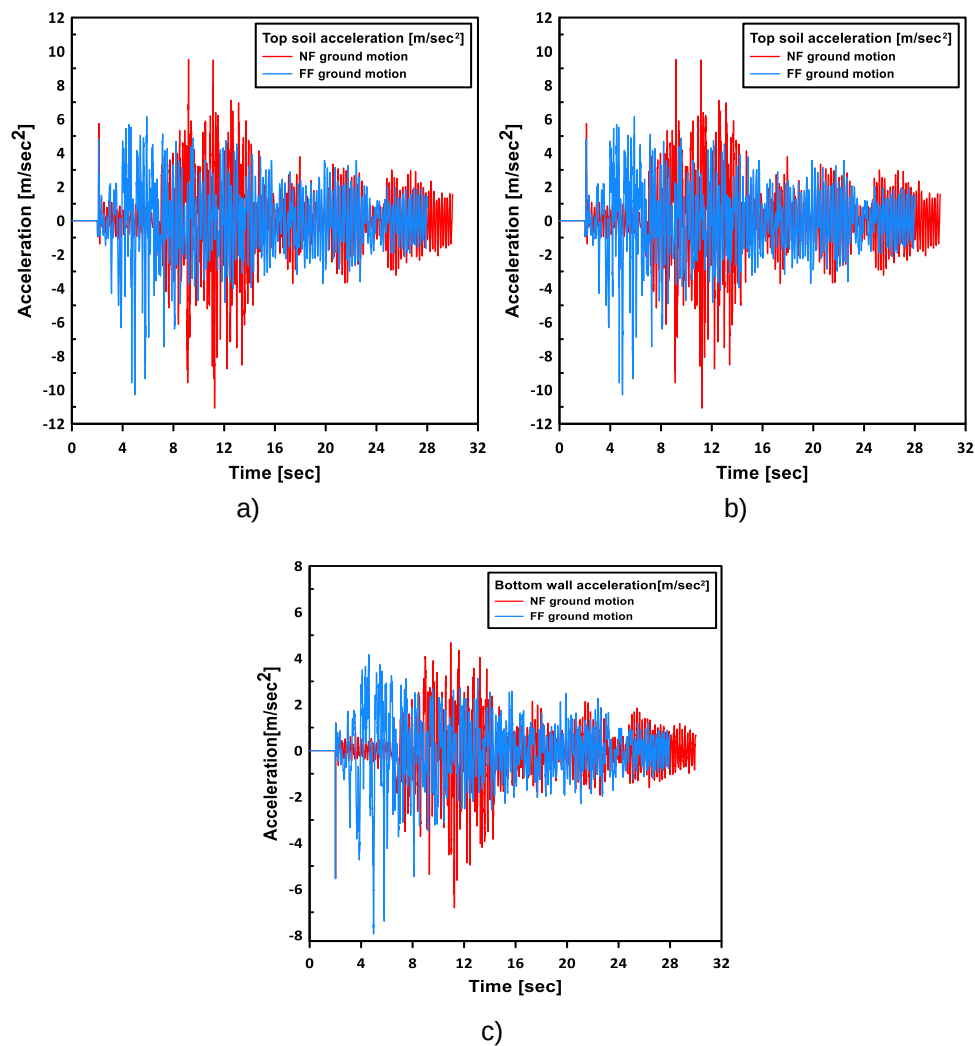


Fig. 11: Acceleration response of model-3.

4 Effect of different PGA of NF and FF earthquakes

Tables 8, 9, and 10 besides Fig. 12 illustrate the results of various PGA of NF&FF earthquakes on the maximum top horizontal displacement of the three mentioned models (3 m, 5 m, and 7 m). In the current study, it is found that the wall fails (i.e., gets a large lateral displacement) with PGA more than 0.1 g. Thus, studying this parameter is very important since it highlights the vital role of the proper design underground motions with various PGA. From results, it is observed that when the PGA increase, the difference between the responses of the wall under far field and near fault earthquake rises in a significant ratio. Additionally, it is found that at the same PGA, the wall's height effect on the maximum top horizontal displacement with a noticeable ratio which is consistent with [20]. At PGA of 0.1 g in case of far field and near fault earthquakes, the wall is observed to have a value of maximum horizontal displacement less than the failure state according to the standards reported in [21] except for the first model in the case of near fault earthquake which exceed this criteria.

Table 8: Maximum top horizontal displacement at [0.1 g].

Model	NF results [cm]	FF results [cm]	Ratio %
1	16.06	11.41	141
2	16.78	11.72	143
3	17.29	12.21	142

Table 9: Maximum top horizontal displacement at [0.3 g].

Model	NF results [cm]	FF results [cm]	Ratio %
1	47.93	33.8	142
2	50.65	34.73	145
3	52.86	36.3	146

Table 10: Maximum top horizontal displacement at [0.5 g].

Model	NF results [cm]	FF results [cm]	Ratio %
1	81.7	56.43	145
2	87.49	58.13	151
3	90.31	62.25	145

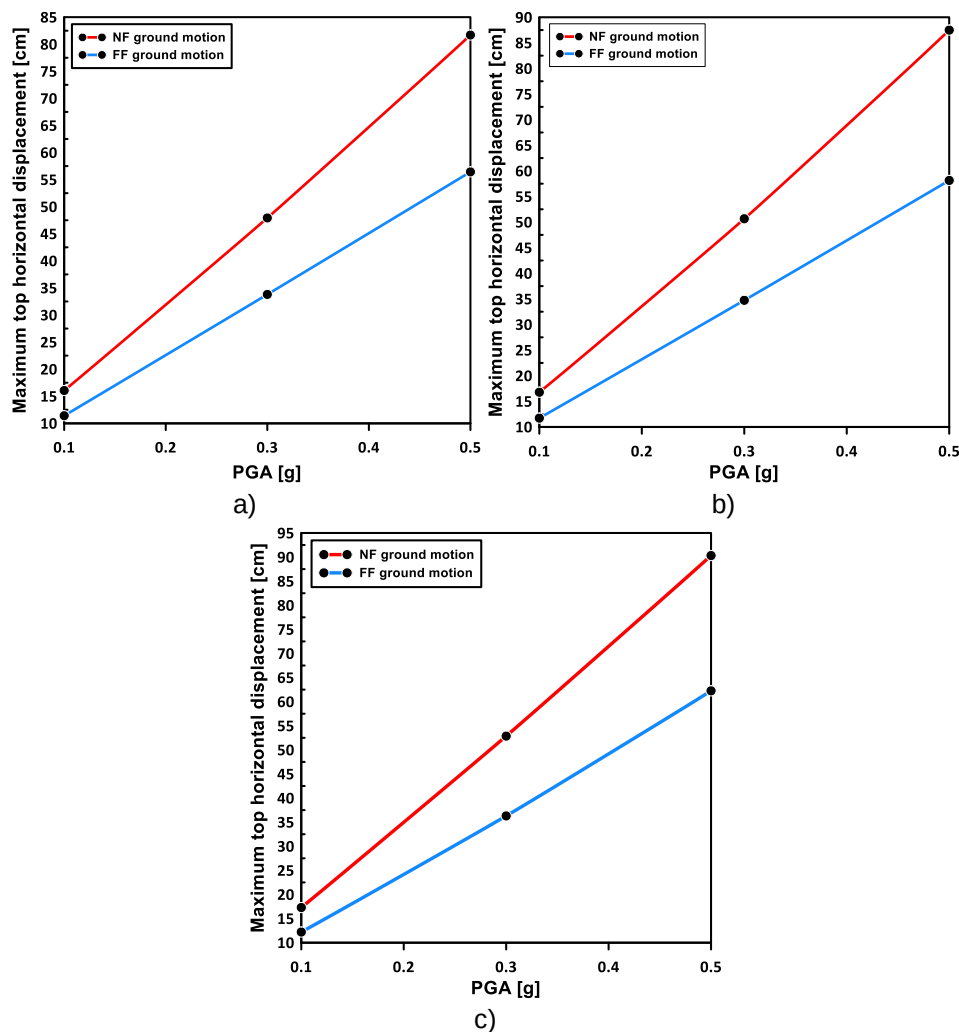


Fig. 12: The top maximum displacement of the three models respectively;
a) 3 m, b) 5 m, and c) 7 m.

5 Conclusion

Retaining walls have a high possibility to experience near fault earthquakes, so the current study may assist engineers to design this important system more accurate at regions with various faults. This research presents a numerical study utilizing Abaqus finite elements program in order to assess the seismic performance of retaining walls exposed to far field and near fault earthquakes. Two stages are conducted to gain this goal. At the first stage a finite elements model of cantilever retaining wall has been validated with the experimental model to get the reliability of the FE numerical model. However, the second stage include the three models' seismic analysis of cantilever retaining walls. Furthermore,

the effect of height and PGA have been studied. The following points could be list in order to summarize the essential findings based on the selected properties of soil, wall and the applied earthquake.

1) A considerable variance in the dynamic response of the cantilever retaining wall under NF and FF earthquakes in terms of seismic active earth pressure, acceleration response, and top wall horizontal displacement. This conclusion is approved for all three models that studied underground motions with a scaled PGA of 0.4 g.

2) Under seismic loadings, horizontal displacement increases with the increase in the height of the cantilever retaining wall.

3) The distribution of the dynamic active earth pressure is observed to be non-linear and depends on the applied ground motion. In common, it was noticed that the seismic active earth pressure increases considerably in the direction of the bottom retaining wall.

4) It is observed that the results of the acceleration response of the three models at the top wall are approximately the same as at the top of the soil. However, it is higher than the results at the bottom of the wall.

5) For various values of PGA, top wall displacement is studied, and it has been noticed that the difference between FF and NF ground motion gets smaller for lower PGA values.

6) At PGA of 0.1 g in case of far field and near fault earthquakes, the wall is observed to have a value of maximum horizontal displacement less than the failure state according to the standers reported by Huang et al., except for the first model in the case of near fault earthquake which exceed these criteria.

References

- [1] SNEHAL, R.: Analytical Study of Cantilever Retaining Wall Including Effect of Soil Structure Interaction. International Research Journal of Engineering and Technology (IRJET), Vol.3, Iss.4, 2016, pp. 1579-1585.
- [2] MOHSEN, K. - DIMITRIOS, V. - PAOLO, B.: Pulse-like versus non-pulse-like ground motion records: spectral shape comparisons and record selection strategies. Earthquake Engineering & Structural Dynamics, Vol.48, Iss.1, 2019, pp. 46-64.
- [3] JONATHAN, D. - ADRIAN, R.: Characterization of forward-directivity ground motions in the near-fault region. Soil dynamics and earthquake engineering, Vol.24, Iss.11, 2004, pp.815-828.
- [4] ALI, V. - MOHAMMAD, S. - EHSAN, M.: Investigating the Performance of Viscoelastic Dampers (VED) Under Near field Earthquakes with Directivity Feature. Civil and Environmental Engineering, Vol.14, Iss.1, 2018, pp.21-27.
- [5] EROL, K. - SASHI, K.: Effects of fling step and forward directivity on seismic response of buildings. Earthquake spectra, Vol.22, Iss.2, 2006, pp. 367-390.
- [6] MOHAMMED, A. - ADNAN, F.: Soil-Structure Interaction of Retaining Walls under Earthquake Loads. Journal of Engineering, Vol.19, Iss.7, 2013.
- [7] JUNIED, B - SYED, M.: A finite element performance-based approach to correlate movement of a rigid retaining wall with seismic earth pressure. Soil Dynamics and Earthquake Engineering, Vol.114, 2018, pp.460-479.
- [8] PRAJAKTA, R. - AMIT, P.: Computation of seismic translational and rotational displacements of cantilever retaining wall with shear key. Soil Dynamics and Earthquake Engineering, Vol. 130, 2020, 105966P.
- [9] MILAD, A. - ALIREZA, S. - MOHAMMAD, H. - SADEGH, G.: Performance-based analysis of cantilever retaining walls subjected to near-fault ground shakings. Computers and Geotechnics, Vol. 130, 2021, 103924 P.
- [10] PARTHA, S. - MAHESHREDDY, G.: A Numerical Study on Dynamic Response of Cantilever Retaining Wall Subjected to Pulse-like Ground Motion. Indian Geotechnical Journal, Vol.51, Iss.6, 2021, pp. 1364-1373.
- [11] MOSTAFA, M.: Numerical Study For Improve Performance Of Retaining Structures Under Earthquake Loadings In Sandy Soils Master thesis. Department of civil engineering. Al-Nahrain University, 2023.
- [12] JOSEPH, E.: Foundation analysis and design, fifth edition. McGraw-Hill Book Company, New York, 1996.
- [13] PANOS, K. - ANNA, S. - AUGUSTO, P. - MATTHEW, D. - ALDO, E. - ARMANDO, L. - COLIN, T. - GEORGE, M.: Investigation of seismic response of cantilever retaining walls: Limit analysis vs shaking table testing. Soil Dynamics and Earthquake Engineering, Vol.77, 2015, pp.432-445.
- [14] ANURAG, U - MURALI, A. K. – SINGH, K. D.: Behavior of cantilever retaining walls under seismic conditions. th International Conference on Earthquake Geotechnical Engineering, 2011, pp. 10-13.

- [15] ABDELWAHHAB, N. - OMAR, Y. - MOHAMED, I.: Seismic loading on cantilever retaining walls: full-scale dynamic analysis. *Soil Dynamics and Earthquake Engineering*, Vol.130, 2020, 105962 P.
- [16] CONTI, R. - CAPUTO, G.: A numerical and theoretical study on the seismic behaviour of yielding cantilever walls. *Géotechnique*, Vol.69, Iss.5, 2019, pp. 377-390.
- [17] MADABHUSHI, S. - ZENG, X.: Simulating seismic response of cantilever retaining walls. *Journal of Geotechnical and Geoenvironmental Engineering*, Vol.133, Iss. 5, 2007, pp.539-549.
- [18] KENJI, W. - YULMAN, M. - JUNICHI, K. - MASARU, T. - KENICHI, K.: Behaviors of several types of model retaining walls subjected to irregular excitation. *Soils and Foundations*, Vol.43, Iss.5, 2003, pp. 13-27.
- [19] PEER STRONG MOTION DATABASE. 2023, from PEER Ground Motion Database - PEER Center (berkeley.edu).
- [20] ANUJ, T.: Earthquake Response of Different Types of Retaining Walls. Master thesis. Department of Civil and Transport Engineering. Norwegian University of Science and Technology, 2016.
- [21] HUANG, C. - WU, S. - WU, H.: Seismic displacement criterion for soil retaining walls based on soil strength mobilization. *Journal of Geotechnical and Geoenvironmental Engineering*, Volume 135, Issue 1, 2009, pp. 74–83.