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Evaluation of the Effects of Aging and Different Site Conditions on the Seismic Response of Municipal Solid Waste (A Case of Kahrizak Landfill)

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ABSTRACT: Studying the behavior of landfills under earthquake conditions to maintain safety and prevent failure is of significant environmental importance. The purpose of this study is to investigate the effective parameters in the seismic behavior of landfills with a combination of laboratory, field, and numerical methods. In this regard, Kahrizak landfill center (KLC), located in Tehran, was selected as an example of landfills in developing countries to study different parameters. At first, a series of field and laboratory experiments, including CSWS tests and cyclic triaxial tests were used to determine dynamic parameters of the municipal solid waste (MSW), including shear wave velocity, damping ratio, and shear modulus in the ages of fresh, 7.5, and 16 years old. Then, using the available results, the one-dimensional equivalent linear analysis was performed by DEEPSOIL software to model the landfill behavior under different seismic accelerations. The effects of waste aging, types of foundations, the height of landfills, and seismic base accelerations on the dynamic response of MSW are presented in terms of peak ground acceleration, displacement, and stress ratio. The results of these studies showed various effects of the parameters on the landfill seismic behavior. Landfill behavior is highly dependent on the components of waste and age changes. Thus, the increase in the waste age and the process of decay can increase the surface acceleration and, ultimately, the resonance phenomenon in 7.5, and 16 years old samples.

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1- Introduction

The safety and serviceability of landfills during and after the earthquake are of great significance. Seismic movements can cause a rupture of covering systems and degradation of leachate circulation and gas collection systems (Chiquita Canyon in the USA 1994). Recently, many studies have been carried out on the assessment of waste behavior under static and dynamic conditions [1-4].

Many researchers have investigated the effect of aging on the behavior of waste [5-7]. In the study of landfills under seismic loads, the effects of different site conditions have been less investigated. In a study sample, the effect of parameters such as foundation types, height, and stiffness of MSW landfills and seismic base accelerations on the dynamic response of landfills was examined [8].

In this study, the CSWS (Continuous Surface Wave System) field method is used to evaluate the shear wave velocity and, finally, the maximum shear modulus for different ages of MSW. The main benefit of these measurements is the ability to evaluate at certain levels of stress and strain without soil disturbing [9]. In the laboratory field, evaluation of the shear stiffness and damping of fresh MSW was carried out using the results of cyclic triaxial tests with a diameter of 100 mm [10]. In this study, the results of cyclic triaxial tests (consolidated and undrained) on fresh and aged waste samples have been used. Finally, using field and laboratory results, the seismic behavior of the Kahrizak landfill was investigated using one-dimensional equivalent linear analysis with DEEPSOIL software [11]. A comparison of one-dimensional and two-dimensional analysis indicates conservatism of 1-D analysis responses [12].

Considering a more precise examination of technical literature in recent years, the need to investigate the dynamic behavior of landfill sites has been identified, and studies in this field have been carried out in various countries, especially developed countries. In this regard, Kahrizak landfill, located in Tehran with a high seismic hazard, has been studied for this case as an example of landfills in developing countries.

2- Material and Modeling Properties

To evaluate the seismic response, two earthquakes with different seismic accelerations and four foundation models in shallow and semi-deep states are considered. Finally, the equivalent linear seismic response of the landfill has been evaluated by using the results of field and laboratory experiments and DEEPSOIL software.

2- 1- Landfill characteristics and location

This study was carried out on the Kahrizak landfill with an area of about 1500 hectares located south of Tehran. KLC, as the largest Middle East landfill, receives an average of 11500 tons of waste per day. In this condition, 500 tons are recycled, and the remainder is buried.

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Table 1. Different types of foundations used in the landfill modeling

Landfill type	Foundation type (layers from landfill base)	Thickness (m)	Shear wave velocity (m/s)	Specific weight (KN/m^3)
I	Rock	∞	2000	**22**
II	Sand	20	300	**16**
	Sand	20	400	**17**
	Sand	20	500	**18**
	Rock	∞	2000	**22**
III	Soft Clay	15	200	**12**
	Soft Clay	20	250	**14**
	Sand	20	500	**17**
	Rock	∞	2000	**22**
IV	Stiff Clay	20	300	**16**
	Soft Clay	15	200	**12**
	Sand	20	500	**17**
	Rock	∞	2000	**22**

The study of the components of KLC, according to the taken samples, indicates a wide range of particle sizes that organic substance or paste forms the most significant part of the ingredients. The amount of the pasty portion of the specimens decreases by about 25 to 40 percent with an increase of age compared to fresh samples. This is due to the progress of the decay process and the decomposition of the waste material over time. The results of the component analysis also showed that most changes were related to the share of plastic components. The share of this group in samples has increased by more than 100 percent as age rises. It seems that this is due to the incorruptibility and relative stability of this group as age rises.

In this study, four models of landfills with different heights of 20, 40, 60, and 80 meters, four types of foundation, and waste with different ages were used to study landfill behavior. The information about the material properties, including stiffness and shear wave velocity, is derived from the field and experimental tests.

2- 2- Foundation details

Landfills may be placed on various foundations such as rock, sand, or clay. Four foundation types have been used to evaluate the various effects of the site, which are named from I to IV, respectively (Table 1). Each of these foundations represents different soil conditions which are in shallow and semi-deep ranges [8]

Type (I): rock

Type (II): sand underlay by rock

Type (III): soft clay and sand layers underlay by rock

Type (IV): stiff clays and sand layers underlay by rock with a soft clay layer sandwiched between stiff clay and sand

To obtain Stiffness properties, specific unit weight, and shear wave velocity of rock, clay, and sand, default information of software have been used. Software information was based on Vucetic and Dobry, (1991); Seed et al. (1991) [13,14].

2- 3- Available Seismic motions

In this study, two different earthquakes as probable earthquakes in the region were considered for seismic analysis, Kobe and Northridge earthquakes with base accelerations of 0.821g and 0.217g, respectively.

3- Field and experimental tests

Damping coefficient and shear modulus are two required seismic parameters for equivalent linear seismic analysis in municipal solid waste [15]. The waste structure is the most influential factor in determining seismic parameters. For this purpose, a series of field and laboratory tests were used to evaluate the field-specific weight and seismic parameters of shear wave velocity, maximum shear modulus, damping coefficient, and normalized shear modulus.

3- 1- Physical analysis and field-specific weight

To recognize and identify the components involved in waste with different ages, the physical analysis and separation of the constituent parts were taken. In this research, due to the need for large-scale measurements, the determination of local specific weight was performed by measuring the volume of water needed to fill the test pit. Using the method mentioned by [16], the specific weight at a depth of the landfill can be estimated at any age by having a specific weight on the surface and the rate of compaction operations during waste burial in the landfill. Specific weight variations for samples with different ages and depths are shown in Table 2. The specific weight of the waste is almost constant at the depth, and the values increase as the age increases.

3- 2- CSWS tests

CSWS is a field method based on the use of Rayleigh

Table 2. Unit weight and Gmax values.

No.	Age (Years)	Depth (m)	Unit Weight (KN/m3)	G_{max} (MPa)	Ave, G_{max} (MPa)
1	Fresh	5.93	9	12.14	**13.04**
2	Fresh	5.61	8.93	12.61	
3	Fresh	5.96	9.01	14.37	
4	7.5	3.33	12.05	20.50	**21.19**
5	7.5	3.40	12.06	21.39	
6	7.5	3.42	12.06	21.68	
7	16	1.24	12.55	24.97	**25.61**
8	16	0.76	12.46	25.76	
9	16	1.06	12.52	26.10	

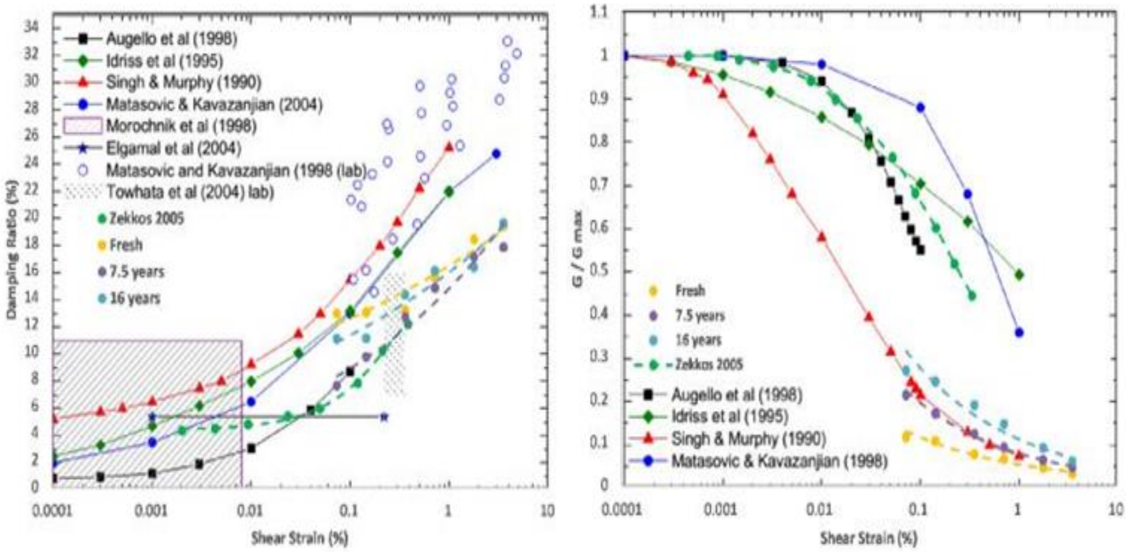


Fig. 1. Comparison of damping ratio and normalized shear modulus curves with the curves available in the technical literature.

waves, which is capable of recording shear waves velocity by propagating waves in a region [17]. The relationship between the dynamic parameters of the waste, including shear wave velocity and maximum shear modulus, is according to the relation [18]. The results of field studies indicate variations in shear wave velocity values for fresh, 7.5, and 16 years old waste in terms of the depth at KLC. The maximum shear modulus (G_{max}) value for fresh waste is about 13 MPA, which has a relatively low rise relative to the depth. As the waste age rises to 7.5 and 16 years, the shear modulus increases by 2 - 3 times (Table 2). The reason for this is the progression of the decay process, the reduction in the percentage of organic matter as the main constituent, and the increase in the percentage of fiber as the reinforcing components of waste.

3- 3- Cyclic triaxial tests

To evaluate the parameters such as damping coefficient and normalized shear modulus, a series of cyclic triaxial tests (consolidated and undrained (CU)) with a diameter of 100 mm and a height of 200 mm at various strains levels were performed on waste samples with different ages [19]. The results of laboratory and field data indicate the process of increasing the shear modulus (G) in samples with higher age relative to fresh age, which could be due to changes in the structure of waste over time and the increase of plastic materials in waste samples. The results of this series of experiments also show a decrease in damping ratio (D) with aging, which occurs for reasons such as organic matter decreasing with aging. The shear modulus and damping ratio obtained from these experiments are two parameters required for equivalent linear seismic analysis (Table 3), which indicate the stiffness of municipal solid waste and the amount of energy dissipation in the waste.

In the below figures, the damping ratio and normalized shear modulus curves evaluated in this study are presented along with the results of other researchers (Fig. 1). A comparison of the results restates the need for a local and regional survey of waste behavior.

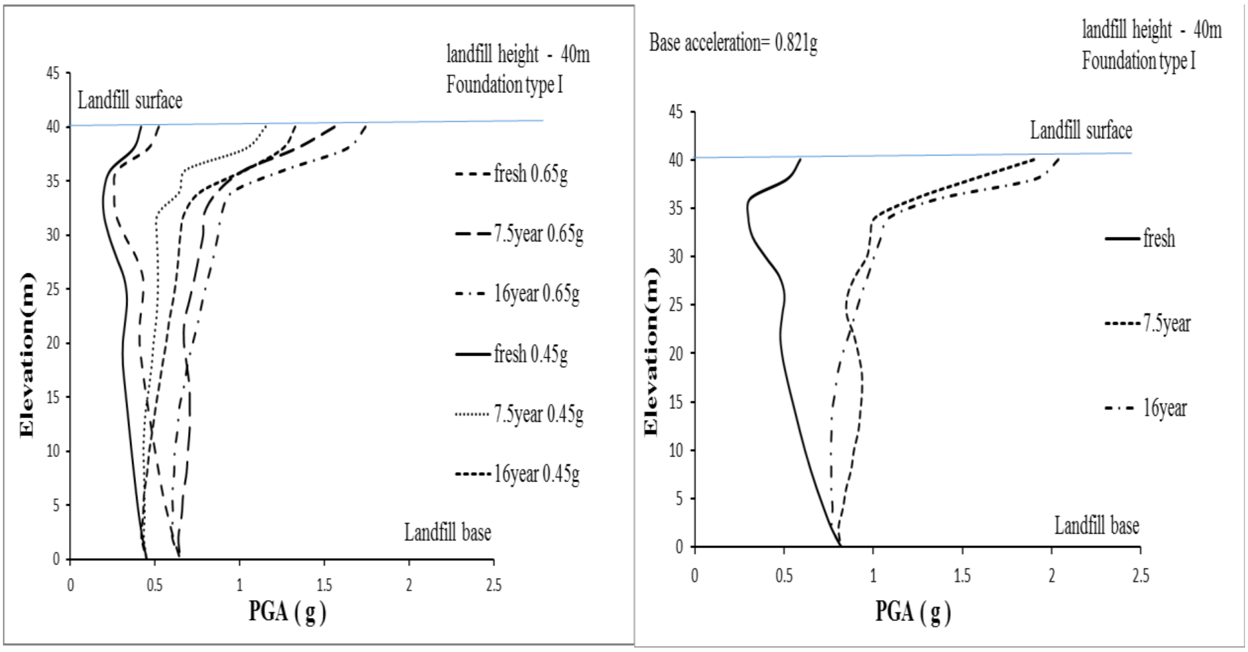


Fig. 2. Variation of PGA with elevation for different MSW ages.

4- Results and Discussion

The effects of various parameters on landfill seismic behavior are presented in terms of surface acceleration, displacement, and stress ratio. These parameters are the age of the waste, the type of foundation, the height of the landfill, and the seismic base acceleration, respectively. The results of various seismic accelerations are expressed using 1-D analysis for Kobe and Northridge earthquakes with peak accelerations of 0.821 g and 0.217 g.

4- 1- Effect of MSW aging

Fig. 2 shows the landfill with a height of 40 meters from the base level, which is affected by the Kobe earthquake with PGA = 0.821 g, the landfill is studied at different ages of fresh, 7.5, and 16 years. In fresh waste, due to the nature and behavior of the composite materials, dissipation is greater. As a result, the incoming wave will dissipate, and the acceleration will reduce, so the acceleration (PGA) reached to the surface is a bit less than the input acceleration. As age passes, the waste is decomposed and turned into finer material. This has created material with more continuity (continuous environment).

It seems that according to the components of the studied municipal solid waste, wastes with older ages have higher specific weights and stresses (due to crushing of the constituent components during compaction), and their dynamic behavior has more continuity and is closer to clay with high PI. As a result, the phenomenon of resonance is quite evident. In the 7.5-year waste, the amount of acceleration resonance is less, and in the 16-year waste, this amount is higher.

Towhata, 2008 presented the range of shear modulus and damping modifications in different discrete soil types. More discrete soil represents a coarse aggregate soil, such as sand and gravel, and less discrete soil represents fine soil. As the soil becomes finer, the continuity of materials increases, and consequently, its behavior becomes closer to the elastic behavior, and the range of its elastic behavior increases. Therefore, if the constituent components of the material become more continuous, elastic behavior increases, and consequently, shear stiffness increases, and dissipation decreases [20].

The displacement of various levels of a landfill is one of the most critical factors in earthquakes, which causes failure in landfills. As shown in Fig. 3 the highest displacement occurs at the surface of the landfill and gradually decreases with increasing depth. At low accelerations (less than 0.5 g), fresh waste has the highest, and then the 7.5, and 16 years waste respectively have the least amount of displacement. In accelerations above 0.5 g, with the increase in PGA, the amount of displacement also increases. However, the important thing is the behavior change of 7.5 and 16-year waste, which their displacement is close to fresh waste. It can be argued that the displacement of various levels of the landfill site is heavily dependent on the age of the waste and the rate of acceleration.

Concerning the effective stress ratio, which is the ratio of shear stress to the effective vertical stress, in the Kobe earthquake and the fresh waste, due to the properties of the constituent materials, the shear stress has the lowest value, after which the amount of shear stress rises in the 7.5 and 16-year waste, respectively. In the Northridge earthquake, however, the behavior is different. As the amount of acceleration in this earthquake decreases, the amount of stress in the fresh waste still has the lowest amount, but in the upper parts of the landfill, the 7.5- year waste, gets more than 16-year waste. This illustrates the strong dependence of PGA changes on waste materials (Fig. 4).

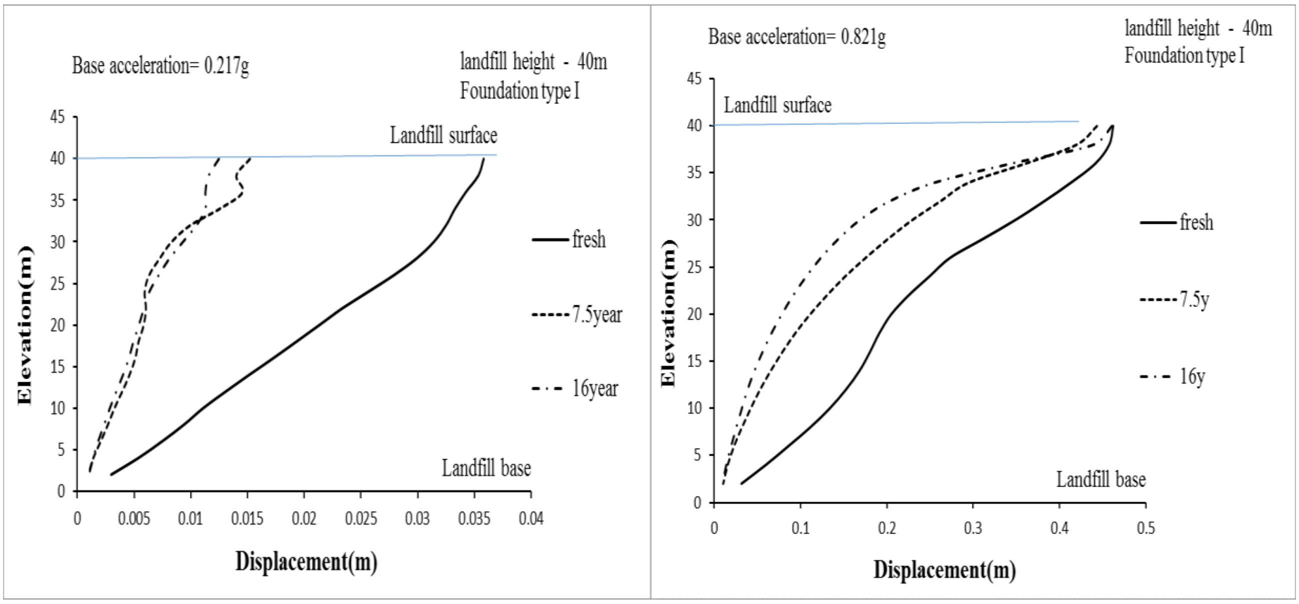


Fig. 3. Variation of displacement with elevation for different MSW ages (Kobe and Northridge earthquakes).

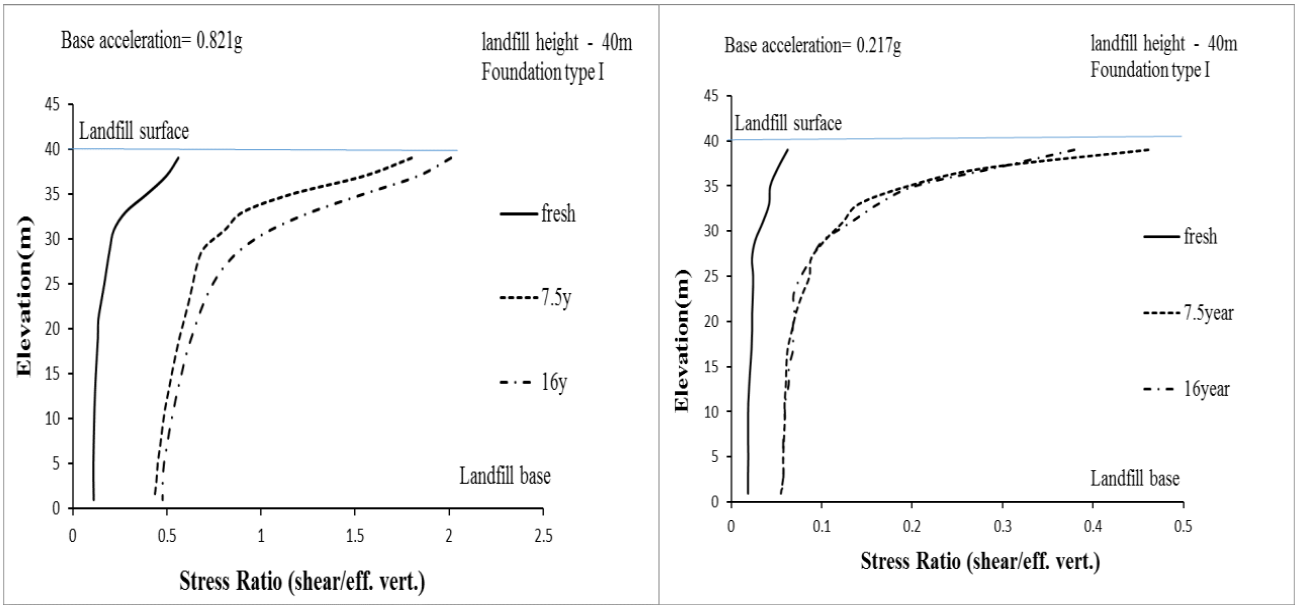


Fig. 4. Variation of stress ratio with elevation for different MSW ages (Northridge and Kobe earthquakes).

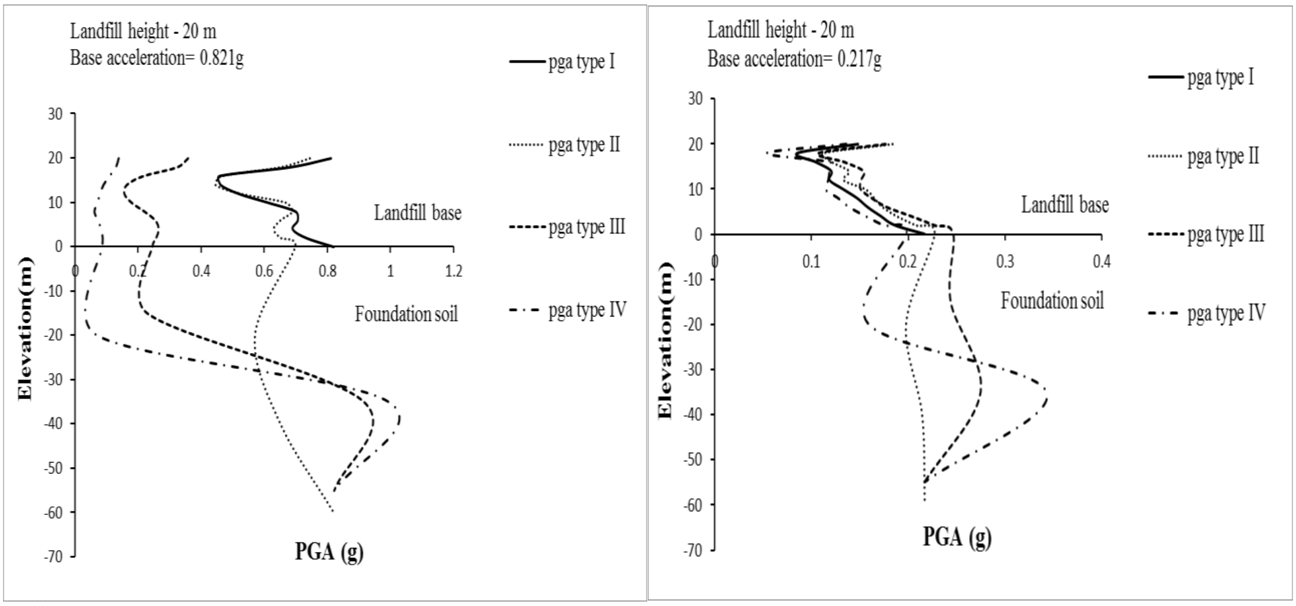


Fig. 5. Variation of PGA with elevation for different types of foundation (Kobe and Northridge earthquakes).

4- 2- Effect of foundation type

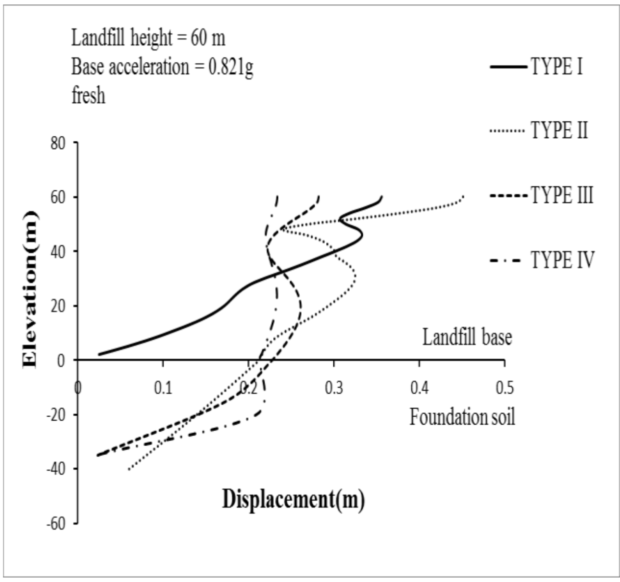
According to Fig. 5, for the 20-meter landfill located on the type I foundation, the input acceleration has been significantly reduced to a height of 10 meters and again, increases until it reaches the surface of the landfill. The amount of acceleration that reaches the surface is slightly less than the initial input acceleration. In other foundation types of II, III, and IV, base acceleration is reduced. In the foundation types of III and IV, in the bottom part of the foundation the acceleration raised, and in the lower part of the landfill base, acceleration reduction was observed. The reason for this behavior is the presence of high resistance clay layers. As can be seen, the behavior of the foundation type II, which does not have clay, is different and there is acceleration reduction in the depth of the foundation. In general, the foundation of type IV has the best performance, and in this model, the least acceleration has reached the surface of the landfill. However, by investigating the Northridge earthquake with an acceleration of 0.217 g, it can be seen that by entering the input acceleration, the landfill and foundations exhibit different behavior from the Kobe earthquake. In the foundation types of II and III, the entrance acceleration has increased as it enters the landfill. Both types of foundations have intensified the earthquake acceleration, while in the Kobe earthquake, all foundations have reduced the acceleration. Therefore, it can be concluded that the behavior of landfills and foundations in all earthquakes is not constant and depends on other factors such as wave type and input frequency. In this research, it is observed that the main period of the earthquake and the landfill is nearly equal, which can be the reason for this behavior change.

Comparing the result of Choudhury's research on the 20-meter landfill under the Kobe earthquake, the foundation's behavior is almost the same in the two studies. However, since the accelerometers considered for the Kobe earthquake are not the same, a slight difference is observed. In the landfill depth, behaviors show much variation concerning each other because of the difference in the dynamic properties of the two modeled landfills.

Fig. 6 shows the 60-m landfill located on various foundations under the Kobe earthquake, in which type IV foundation has the least displacement, and type II has the highest one. Therefore, the IV foundation has the best performance in landfill displacement. By changing the input earthquake (the Northridge earthquake), behavior becomes different, and this time, the highest displacement is associated with the foundation of type IV, which has the worst performance in landfill displacement. As the diagrams show, the change in foundation materials has a significant impact on the surface displacement of the landfill, but the change in the type of earthquake also causes considerable changes in the behavior of the landfill, which should always be considered.

Fig. 7(a) shows the variation of spectral amplification with frequency for a 60-meter high landfill resting on the different types of foundations subjected to a seismic acceleration of 0.821 g. The highest spectral amplification is observed in the type I foundation at a frequency of 232.0 Hz. After that, the foundations of type II, III, and IV show lower spectral amplification values, respectively. Similar behavior was observed for other earthquakes. Considering that the lowest spectral amplification was observed in soft soil foundations, it can be argued that this behavior can be due to the damping effects associated with more substantial non-elastic damping of fine-grained soil.

Comparing the result of Choudhury's research for a similar landfill under the base acceleration of 0.278 g, different values are found due to the difference in the types of



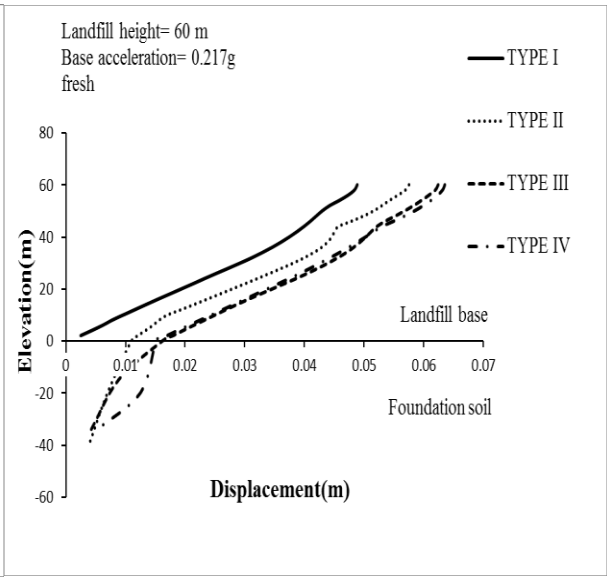
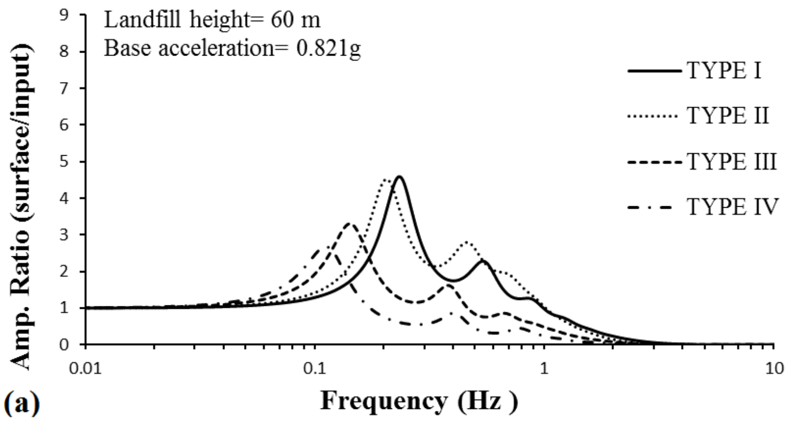


Fig. 6. Variation of displacement with elevation for different types of foundation (Kobe and Northridge earthquakes).



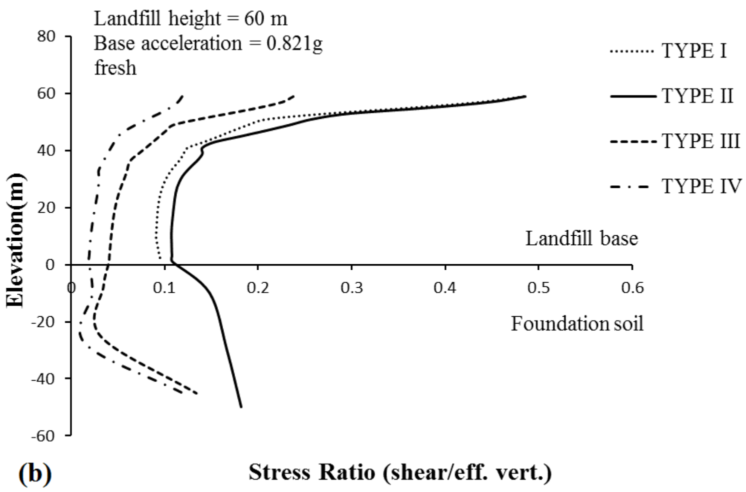
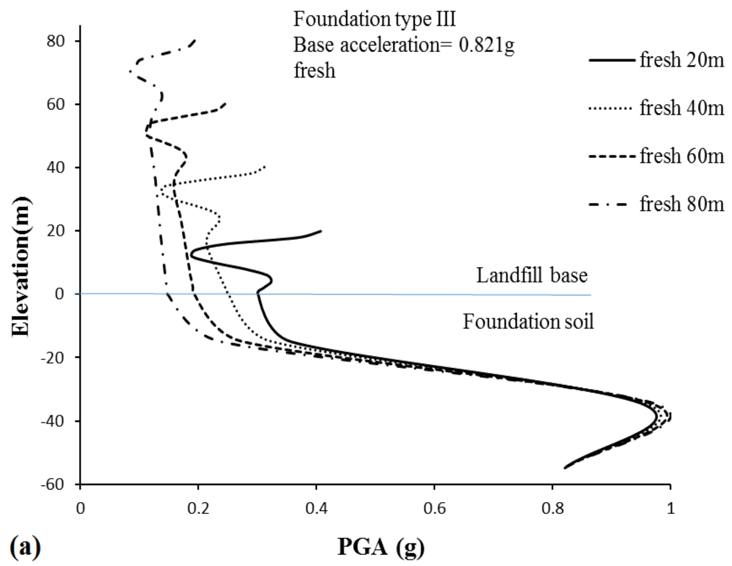


Fig. 7. Variation of (a) Spectral amplification and (b) Stress ratio for a different types of foundations (Kobe earthquake).



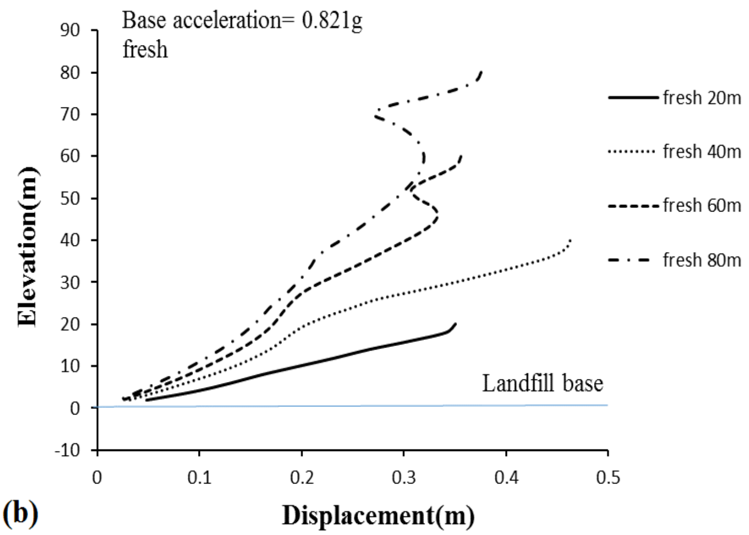


Fig. 8. Variation of (a) PGA and (b) Displacement with elevation for different heights of landfill (Kobe earthquake).

earthquake in the two studies. However, the behavior of the foundations is similar.

Concerning the stress ratio, it is observed that by changing the foundations from I to IV, the diagrams have shifted to the left. The increase in shear strength and the reduction of stresses are the main causes of this behavior, (Fig. 7(b)).

4- 3- Effect of landfill height

Fig. 8(a) shows the maximum obtained PGA of the landfill with variable heights of 20 to 80 meters located on the foundation type III and under the base acceleration of 0.821 g. It can be observed that by increasing the height of all landfill models, initially, the amount of input acceleration is reduced, and this trend continues to a certain height. After that, the acceleration increases and reaches the surface of the landfill. In sum, the acceleration that reached the surface of the landfill is more than the amount of the incoming acceleration to the base of the landfill. The important point here is that all models continue to reduce acceleration up to a height of 6 meters to the surface of the landfill, and then the acceleration value increases. This height has always remained constant, and with an increase in the height of the landfill, it has not changed again and remains 6 meters. As a result, the model with a higher height has a higher acceleration reduction value. The reason for this behavior can be due to compression (confining stress).

Comparing the result of Choudhury's research and considering the differences between dynamic characteristics

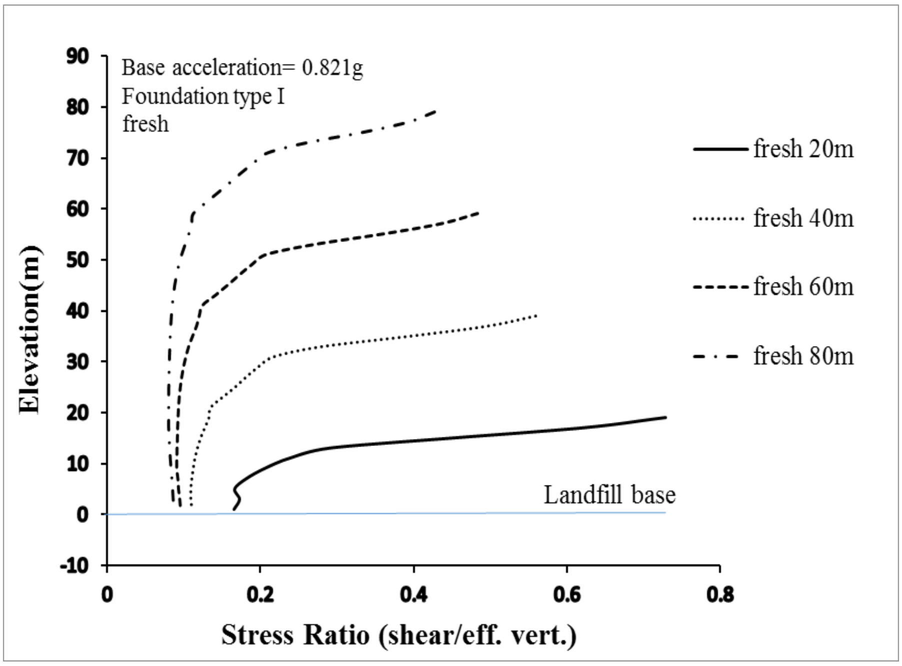


Fig. 9. Variation of stress ratio with elevation for different heights of landfill (Foundation types I and IV).

of landfills and also applied earthquakes in two studies, the maximum acceleration is related to the landfill with a height of 40 m. However, in our study, the highest value is related to the landfill with a height of 20 m.

According to Fig. 8(b) with a constant foundation (type I) and constant input acceleration, at a certain height (e.g., 10 m height), it is clear that increasing the height of the landfill reduces the displacement at that height, which is evident due to the presence of more confining stress. The important point, in this case, is the displacement of the landfill crest, which has the maximum value for the landfill with a height of 40 m.

In the case of the landfills located on foundation types of I and IV, with different heights of 20 to 80 meters, under the impact of the Kobe earthquake with input acceleration of 0.821 g, it can be seen that by increasing the height of the landfill and, as a result, increasing the confining stress, the slope of the graphs is increased and graphs are shifted to the left. In this case, the landfill with the height of 20 meters has the highest and the landfill with a height of 80 meters has the lowest amount of normal stress (Fig. 9), similar behavior is still observed with the establishment of the type IV foundation, but in this case, the highest amount of normal stress belongs to 40-meter landfill. In Choudhury's research, the behavior is similar but with different values.

4- 4- Effect of base acceleration and mean period of earthquake

To evaluate the effect of seismic base acceleration, a 60-meter high landfill model has been used on the type I foundation (bedrock). The Kobe earthquake with base accelerations of 0.25g, 0.45g, 0.65g, and 0.821g, and constant frequency is applied to the model. According to Fig. 10(a), in each of the four models, the acceleration decreases first and then increases in the top few meters. Considering the output acceleration at the surface of the landfill, it is seen that by entering the seismic base acceleration of 0.25 g, the amount of acceleration that reaches the surface of the landfill is constant and equals 0.25 g. By increasing the amount of seismic base acceleration to 0.45 g, acceleration decreased, and this time acceleration with a decrease of 0.084 g reaches the surface of the landfill. Once again, the input acceleration is increased, and this time, the acceleration of 0.65g is applied to the model. Here, the acceleration at the surface reaches 0.452g, indicating a decrease of 0.198g. In the fourth state, the acceleration is also increased to the value of 0.821g. As it is clear, the acceleration at the surface has decreased, and it has reached 0.506 g. It can be stated that the model of the landfill reduces the higher accelerations to a higher degree.

In Fig. 10(b), the effect of the seismic base acceleration on the displacement of the landfill is specified. Since displacement at the surface of landfill surface has the highest value, the most important part in displacement values under earthquake effect is the surface of the landfill. By increasing the amount of input acceleration, it can be observed that the increase in acceleration has a direct relationship with an increase in displacement, and the higher the input acceleration to the center of the landfill, the higher the displacement value.

Increasing the base acceleration also has a direct effect on the stresses. It means that by increasing the input acceleration, the diagrams are shifted to the right, and the shear stress ratio to effective stress increases Fig. 10(c).

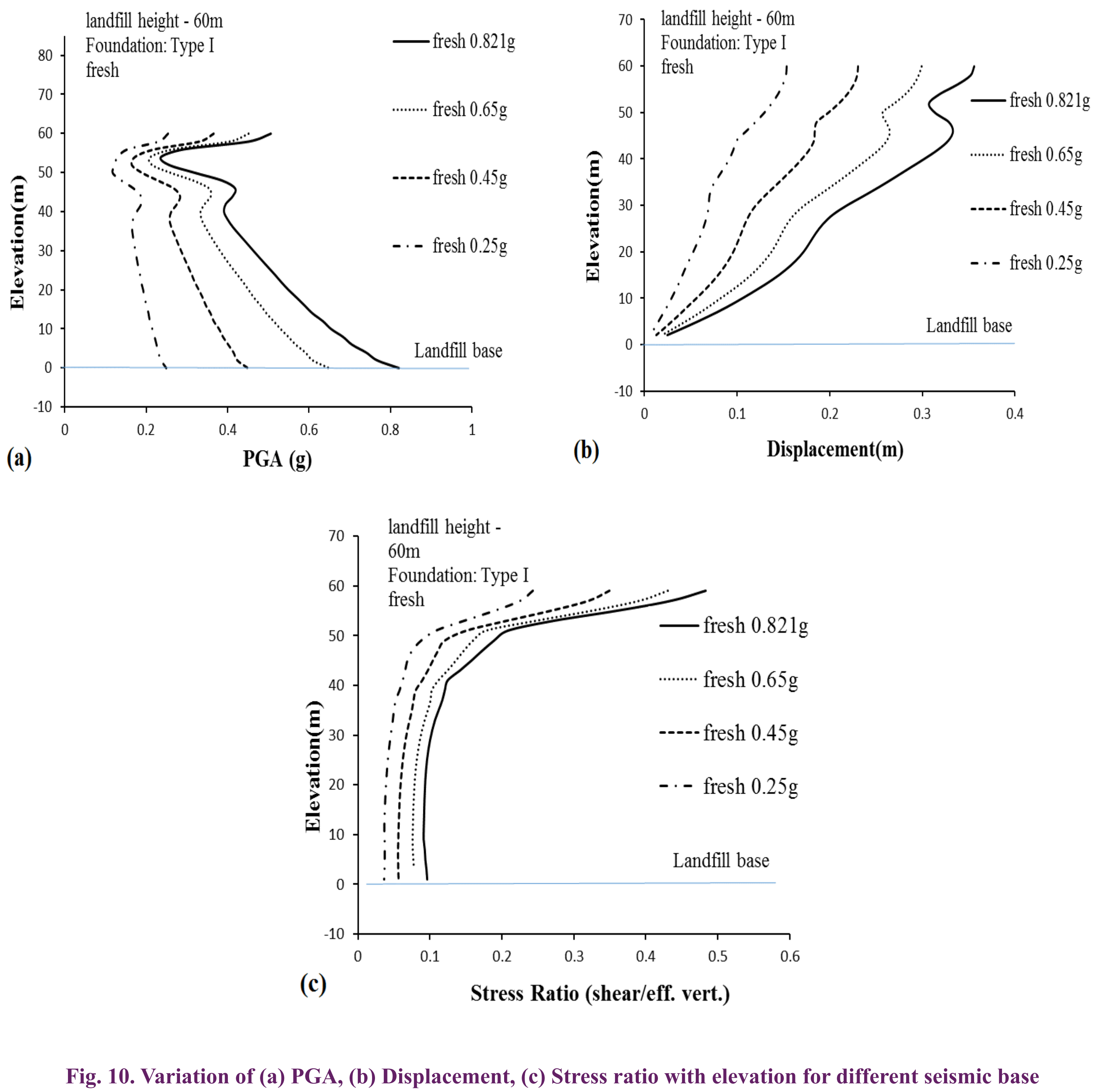


Fig. 10. Variation of (a) PGA, (b) Displacement, (c) Stress ratio with elevation for different seismic base accelerations

5- Conclusion

In this study, to investigate the dynamic behavior of landfills, the effects of parameters such as age, type of foundation, landfill height, and seismic base acceleration on the seismic response of KLC have been investigated. The required parameters for one-dimensional linear analysis are obtained from laboratory and in-situ tests. The results of investigating the application of various seismic accelerations indicate that the period of the fresh waste model is close to the period of the Northridge earthquake or, in other words, the Northridge earthquake has a higher loading frequency in fresh waste and it reduces damping and creates a resonance phenomenon. As age rises, the waste is decomposed and turned into finer material. This has led to an increase in the shear modulus or the creation of materials with greater continuity. The continuity of the grains reduces dissipation, and as a result, the phenomenon of resonance is quite evident. In the study of different structural conditions with different phrases, it is also observed that the effect of some parameters on the seismic behavior of KLC is important, and some are negligible. Comparing the modeling performed with Choudhury, the differences in dynamic parameters effects can be observed. In some cases, the charts are almost identical, but in other cases, the results are completely changed. Because of the consumption patterns in different regions, the waste in each area has its parameters, and therefore, the behavior is different. Finally, it is vital to consider the dynamic parameters associated with the studied landfill.

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