13th World Conference on Earthquake Engineering
Vancouver, B.C., Canada
August 1-6, 2004
Paper No. 2402

SEISMIC RESPONSE AND STABILITY ANALYSIS OF AN AREA METHOD MSW LANDFILL

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SUMMARY

This paper presents the results of a numerical study of the seismic response and stability analysis of a municipal solid waste (MSW) landfill. The landfill was an area method type, 16m high, and 200m × 150m in plan view, with a total capacity of 200,000 Tons, constructed in southern Tehran in 1998. Soon after the landfill was closed, the leachate seeped through the surrounding embankments, causing contamination of mid to lower elevation of the embankments and some local shear failures at the exit points. Therefore, the overall stability of the landfill under seismic loading was questioned. A 2-D plain strain non-linear dynamic model was used to study the seismic response and stability of the landfill. Parametric study was also performed to investigate the effect of shear wave velocity, daily covers, and landfill width on the behavior. The results indicate that landfill in condition of contaminated surrounding embankment will fail, if the assumed design earthquake occurs in the region.

INTRODUCTION

Tehran is a highly populated city, located in southern central Alborz mountain ranges with quite a few major and minor faults. This situation has contributed to a seismically high risk classification of the city, especially in northern and southern parts. Over 7000 Tons/day of municipal solid waste is collected and transported to Kahrizak, the only major landfill site located 25 km south of Tehran. Reasonable distance from the city, ideal geotechnical and morphological conditions, and very low GWT has made it an attractive site under operation for the past 40 years. Most of the landfills in the site are traditional excavations (trench method), more than 20 m deep, filled with MSW in several stages and finally covered by soil.

The first engineered landfill in Kahrizak was constructed in 1998. It was an area method landfill, 200m × 150m in plan view, and 16 to 18 m high, surrounded by 6 layers of embankments, 3m high each (Fig.1).

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Daily and intermediate covers were used consisting of about 30 cm of fine silty sand. The Fukuoka concept, a semi-aerobic type landfill, was considered for design and construction. More details of the constructed method are presented in the next section. Some technical problems during construction caused the leakage of leachate through the surrounding embankments, threatening the stability of the area method landfill. It was, therefore, decided to embark on an elaborated experimental and numerical study of the constructed landfill.

Within the past decade, landfills as a geotechnical structure have been studied as research projects both experimentally and numerically. Examples of lab and field tests to investigate the properties of MSW materials are the works presented by Augello et al., 1995 and Fasset et al., 1994. Recording the response of several earthquakes such as Pasadena (1988), Landers (1992) and Northridge (1994) in OII landfill, made it possible to perform numerical studies to find dynamic behavior of landfills, so that the result could be verified with field measurements. In 1995, comparison between 1- and 2-D behavior of OII landfill under the aforementioned earthquakes was made (Idriss and Fiegel, 1995). Several parametric studies on dynamic properties of MSW (such as shear wave velocity and density) have been reported to emphasize on the importance of the parameters on dynamic response of landfills (e.g. Kavazanjian and Matasovic, 1995). Other studies illustrate some differences between the equivalent linear and nonlinear analyses of OII landfill in 1-D condition (Kavazanjian et al., 1995). Review of all these studies reveal that non-linear dynamic behavior of landfills in 2-D condition together with parametric studies, have rarely been reported for landfills. This paper attempts to contribute to such shortcomings by a numerical method, to further understand the general behavior of landfills under dynamic loading.

Prior to the dynamic and seismic study of the landfill under study, experimental study of both the polluted soil and MSW of Tehran was performed by Abdi (2002) and Fakharian and Abdi (2002). The results are used in this study to obtain the model parameters.

Alemi (2003) and Fakharian et al. (2003) studied the behavior and stability of this landfill under static conditions. A factor of safety of 1.3 was obtained for the critical condition, i.e. when all the daily and intermediate covers plus the embankments 1 to 3 (below the leachate seepage elevation) were fully contaminated by leachate.

The main objective of the current study was to investigate the stability and response of the landfill to a dominant design earthquake in Tehran area.

SITE CONDITION AND LANDFILL

Kahrizak is the zone that over 7000 Tons of MSW is transported and landfilled and/or composted on a daily basis. The site is located on a short hill, consisting of conglomerate and fined-grained soil layers distributed randomly allover the site. The GWT is very low and not reachable during ordinary excavations. Low GWT and relatively high cohesion of the soil layers allow for deep temporary excavations without any support, but the practice is no longer recommended by the professional engineers.

A new engineered landfill was designed and constructed in the area in 1998. A schematic cross section of the 200,000-Ton capacity area method landfill is shown in Fig. 1. There are a total of 6 embankment layers, 3m high each. After completion of each embankment, the inside volume was filled with two 1.5m layers of MSW, with a 30cm cover soil layer on top of each MSW layer. The daily and intermediate covers were built by silty sand and sandy silts available at the site. Same material was used for the construction of the surrounding embankments. After completion of each embankment and filling the inside area, the new embankment is built on top of it in such a way that it is partly supported by the underlay embankment and partly by the MSW of lower layer. The procedure is then continued to reach the final height (Fig.1).

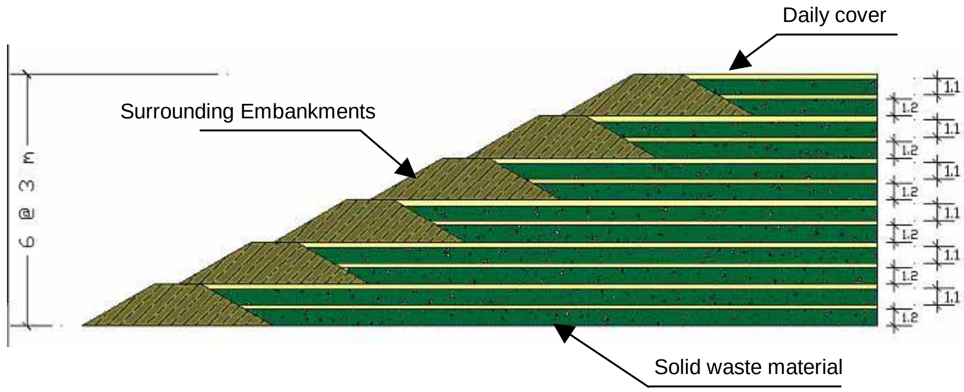


Figure 1- Schematic geometry of the area method landfill constructed in Kahrizak, Tehran

Fukuoka landfill is a concept initially developed in the city of Fukuoka of Japan, as a collaborative project between university of Fukuoka and the Fukuoka City. As stated, it is a semi-aerobic landfill, in which the placement of vertical chimneys (for ventilation) at various locations with top end exposed in air, and bottom connected to the bottom drainage system (Fig.2). This combination allow the air circulation through the landfill due to the temperature difference between inside (as a result of MSW fermentation) and outside of the landfill. The air circulation accelerates the biodegradation of the MSW and improves the leachate quality (BOD, COD, …) and also reduces the leachate volume and the generated greenhouse gases such as CO_2, and CH_4. Figure 3 shows the construction stage of the bottom drainage system.

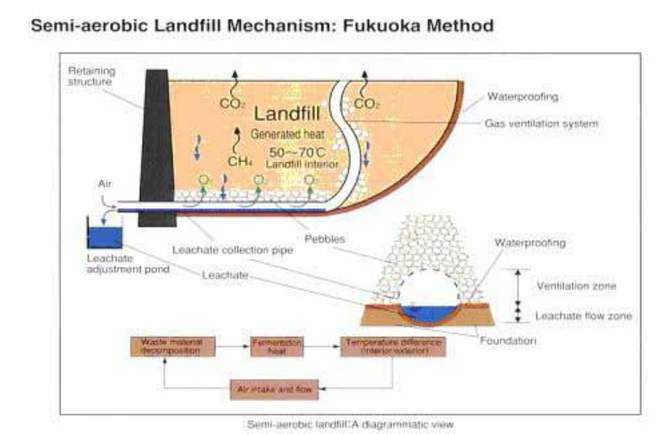


Figure 2- Schematic of a semi-aerobic landfill similar to Fukuoka Method

Unfortunately, the landfill ceased to function properly due to some unexpected problems during construction and operation. Initially, the landfill was supposed to be developed as a pilot project, however, for some reasons such as scarcity of available traditional landfills at the time, it turned out to be used as a substitute for real landfilling. Since the operation staff for such a large volume of MSW were not trained yet of how to manage the transportation, deposition, spreading out and compaction of the MSW, some construction problems arised such as breaking most of the ventilation chimneys during overnight deposition.

Lack of circulation of air (hence converting the landfill to a non-aerobic system), caused the increase of leachate volume and also lowered the leachate quality. In addition, the low permeable daily and intermediate covers caused the trap of leachate over the layers, and eventually seeping through the surrounding embankments, thus contaminating the soils, as observed in Fig. 4.

This unset of construction caused several problems, one of the most important of which was threatening the static, and particularly seismic stability of the whole system (Fig.4). Before explaining the numerical model, a brief description of experimental results of non-contaminated and fully contaminated soil with leachate is presented first.

Figure 3- Drainage system of bottom of the landfill, Kahrizak, Tehran

Figure 4- leakage of leachate from surrounding embankment after completion

LAB TESTS

An elaborated experimental study was conducted at Amirkabir University of technology on the non-contaminated soil, partly contaminated soil, and fully-contaminated soil. Also, physical and mechanical properties of Tehran MSW were evaluated to determine the required parameters for stability and load-deformation analysis. The details of the results can be found in Abdi (2002) and Fakharian and Abdi (2002). A summary of the results required for the numerical analysis is presented in Tables 1 and 2. It should be noted that Elastic modules and shear wave velocity were estimated on the basis of available data in literature.

NUMERICAL MODELING

$FLAC^{2D}$ (V.4.0) was used for the non-linear static and dynamic numerical modeling of the system. FLAC (Itasca Consulting Group, Inc, 2000) is a finite difference numerical software and has proven to be a powerful and versatile package for solution of complex geotechnical problems. Figure 5 shows the 2-D plane strain model including the landfill foundation (which is the natural soil layers of the site), surrounding embankments, MSW, and daily and intermediate soil covers. A summary of static and dynamic analysis procedures are presented in the next subsections.

Table 1- Properties of soil of embankment and daily/intermediate covers (Abdi, 2002)

Parameters	Non-contaminated soil	Fully contaminated soil
Category of soil	SC-SW	SC
γ_d (kN/m^3)	19	19.85
W%	14	11.4
ϕ	38.5	7.8
C (kPa)	17.3	11.7
E (MPa)	10	3.5
ν	0.3	0.35
Vs (m/s)	140	85

Table 2- Properties of MSW (Abdi, 2002)

Parameters	Magnitude
γ_w(kN/m^3)	8.3-10.4
ϕ	27
C(kPa)	0
E(MPa)	5-7
ν	0.25
Vs (m/s)	100

STATIC ANALYSIS

Mohr-Coulomb model was used for both soil and MSW, using the parameters of Tables 1 and 2. Stage construction feature of FLAC was used to simulate the layer-by-layer construction of the embankment and MSW.

Figure 6 illustrates the vertical stress distribution within the cross section. The maximum vertical stress is 5 MPa located in the center part and at the bottom of the section, as expected.

Vertical and horizontal displacement distributions are presented in Figs. 7 and 8, respectively. The maximum vertical settlement has occurred in the mid height of the landfill which is equivalent to 250 mm. This observation is very similar to field observations of earthfill dams during construction from the results of instrumentation. The maximum horizontal displacement is measured 50 mm related to the mid height left and right edges of the section, as can be seen in Fig.7.

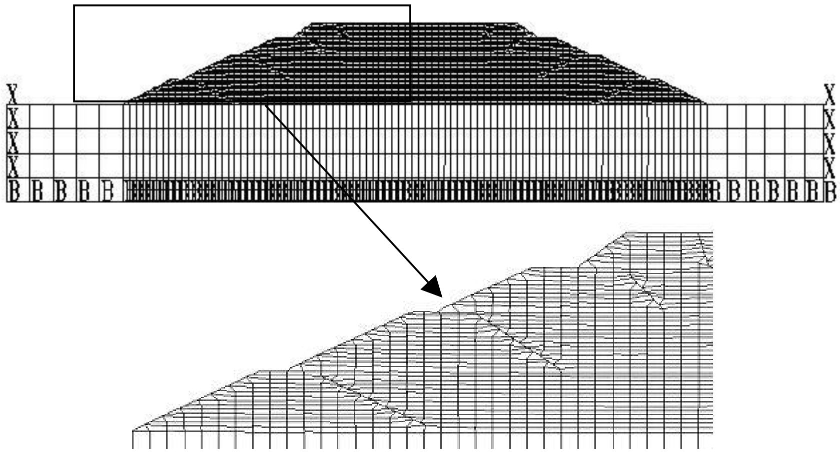


Figure 5- Mesh of the landfill and its foundation

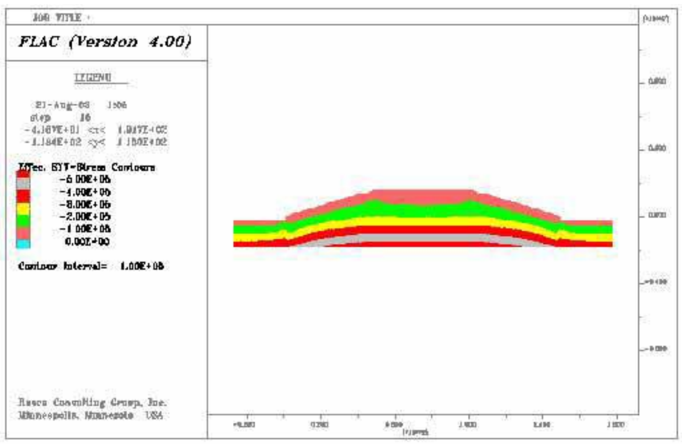


Figure 6- Vertical stress contours on landfill section

The ϕ-c reduction method was used to calculate factor of safety (F.S.) in different conditions of non-contaminated and contaminated soil of surrounding embankments and covers. The lowest F.S. was 1.3 for the condition of fully contaminated soil below the seepage line of leachate (see Fig. 4)

All the static analysis results agree very well with those performed by Alemi (2003) and Fakharian et al. (2003), using PLAXIS 7.2, which is a well-known FEM. This agreement is considered as part of the verification of the numerical results of the current study.

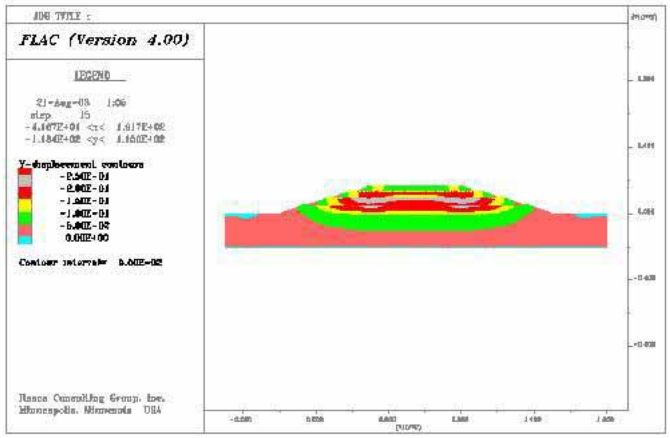


Figure 7- Settlement contours on landfill section

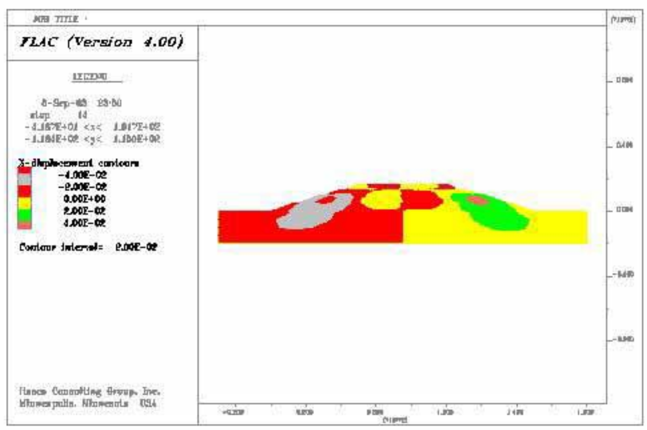


Figure 8- Horizontal displacement contours

DYNAMIC ANALYSIS

Design Earthquake (Manjil)

The main objective of the current study was to investigate the seismic response of the constructed landfill. The same mesh and boundary conditions described in static analysis were used for the dynamic analysis. The viscous boundary condition is used that prevents the reflection of shear waves. (Itasca Consulting Group, Inc, 2000)

The analysis was performed under drained conditions, and the effect of leachate is only considered in deteriorating the soil parameters. Therefore, there are no such effects like undrained condition and also effective stress and pore pressure balances.

Manjil earthquake of summer 1990 was selected to simulate the dynamic loading. The acceleration-time history of this earthquake is presented in Fig. 9. This is the nearest and the most recent major earthquake around Tehran province, which its epicenter is around 220 km NW of the site. Manjil earthquake had a magnitude of 7.3 Richter with maximum acceleration of 0.35g.

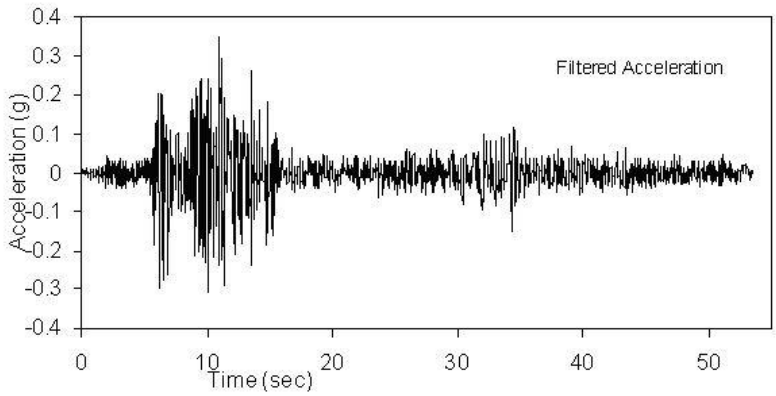


Figure 9- Acceleration time history of input motion; Manjil Earthquake of 1990

Duration=54s
Amax=0.35g
Predominant frequency=1.7Hz

Figure 10 shows the acceleration response at crest, mid-height and bottom of the landfill, for the non-contaminated condition. The maximum amplification ratio at crest of the landfill with respect to bottom is measured as 2.1. Table 3 presents a summary of analysis results at three elevations. Due to plastic deformation in some zones, permanent displacements have occurred, the maximum of which is at the mid-height. The mid-height maximum permanent displacement is an important observation and requires further investigation for its justification.

The analysis of fully-contaminated condition showed that the landfill would have failed, if a Manjil earthquake had hit the region. Figure 11 shows the displacement vectors at the failure condition. The failure initiated through the fourth embankment which is at the elevation of around 9m. The maximum permanent horizontal displacement is 1.5m, as its development with time is shown in Fig.12.

Parametric Study (Single wave)
A parametric study was conducted to see the effect of shear wave velocity, damping ratio, friction angle and daily cover. Results of two of the parameters is presented here. For simplicity, a single wave time history with predominant frequency of 3Hz, maximum acceleration of 0.35g and duration of 1.5 sec was used for the parametric studies. The time history is shown in Fig. 13.

A 3-D space is considered to process and present the results of the parametric study. Three quantities are used for this 3-D space including, i) relative height of different points between base elevation and crest elevation, ii) dimensionless frequency, and iii) amplitude of acceleration. Such a 3-D space is a generalized framework which may be used for comparison purposes of other landfills or other earthquakes. The dimensionless frequency was defined by Pederson (1994) as follows:

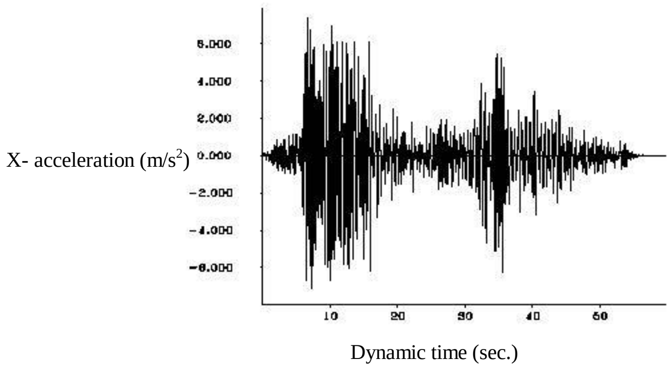
$$F = \frac{\omega . a}{2Vs} \quad (1)$$

(2)

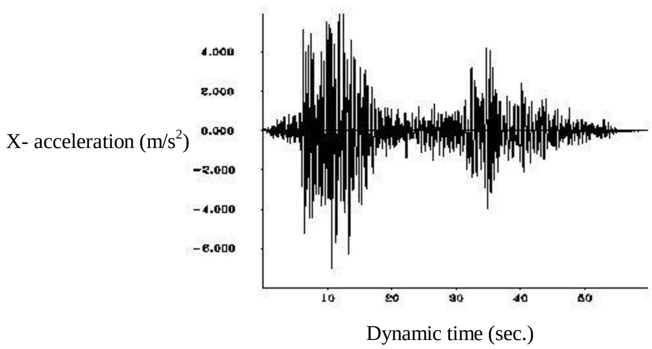
$$F = \frac{\pi . f . a}{Vs} \tag{3}$$

Where *F* is the dimensionless frequency, *f* is the frequency of wave at each point, *a* is half width of landfill, and *Vs* is the mean shear wave velocity of solid waste materials. For the subject landfill with width of 150m and *Vs* of 150m/s, the equation will be simplified as:

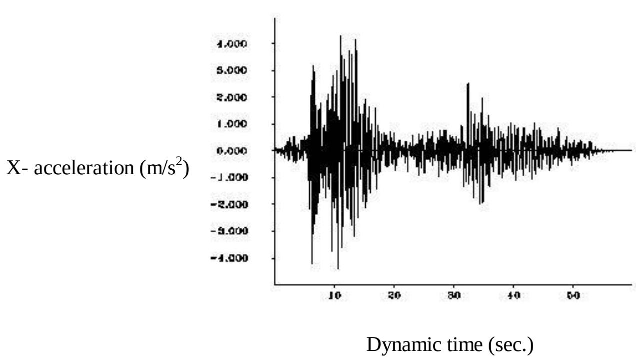
$$F = 1.7 f \tag{4}$$



c- at the crest of landfill



b- at the mid-height of landfill



a- at the bottom of landfill

Figure 10- Time history acceleration at different elevations of landfill

Table 3- Summary results of dynamic analyses for non-contaminated embankment

Height (m)	Max. Acc(g)	Max. Disp(cm)	Perman. Disp(cm)	Ampli. ratio
0	0.427	1.65	0.18	1.22
8	0.594	3.30	0.50	1.70
16.6	0.738	5.10	0.15	2.10

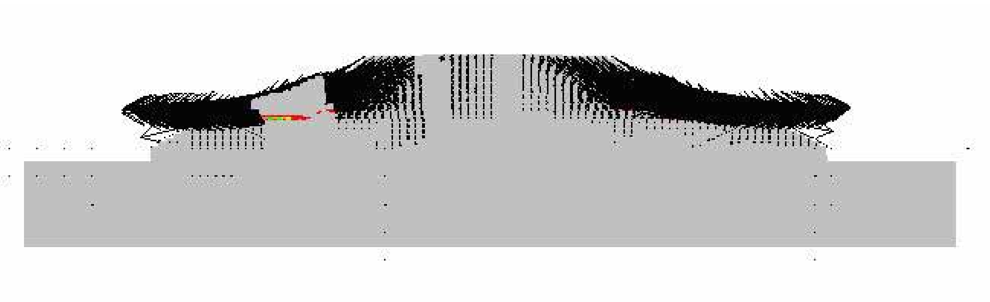


Figure 11- The failure zone passes through contaminated embankment

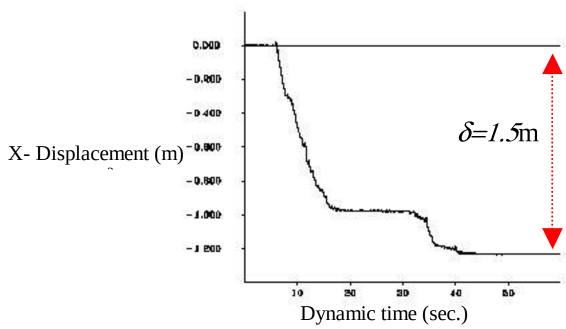


Figure 12- Time history of displacement in case of contaminated embankment

It is emphasized that solid waste materials are highly compressible and biochemical reactions change their properties with time. Therefore, parametric studies seem to be important to study their behavior and response over their lifetime.

Effects of shear wave velocity

Kavzanjian et al. (1995) presented the variation of shear wave velocity with depth for MSW as shown in Fig.14. As observed a range of magnitudes is presented due to non-homogenous nature and variability with time. For the height of the landfill in this study (16.5m) three ranges of 100-125 m/s, 140-160 m/s and 180-205 m/s are selected. Each range is representative of the height of landfill, and variation of three ranges is representative of the parametric study.

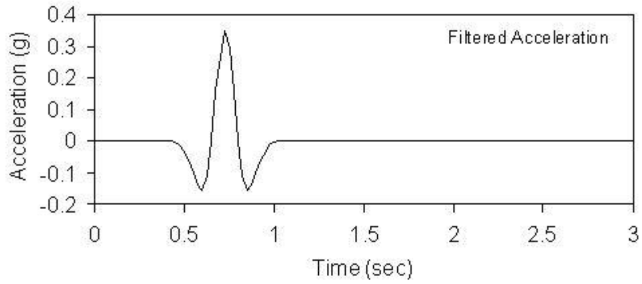


Figure 13- Time history of input wave

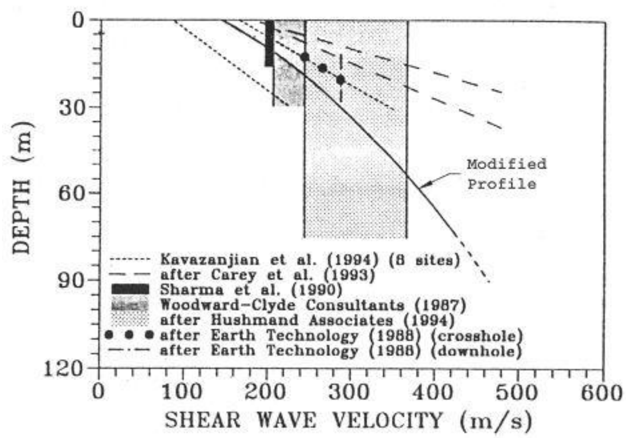


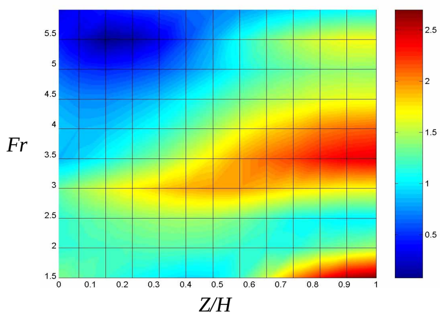
Figure 14- Shear wave velocity of solid waste materials (Kavazanjian et al., 1995)

The results presented in Table 4 and Fig. 15 show that with increase in shear wave velocity, amplification ratio goes up. It is important to note that the predominant frequency is close to the input frequency of 3Hz, irrespective of variations of shear wave velocity, which has caused the increase in amplification ratio.

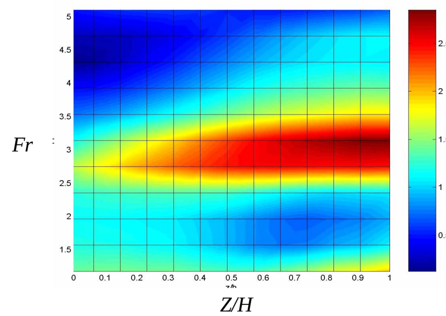
In table 4 is also shown the effect of landfill width on the frequency of response. It is observed that frequency is reduced to even less than 1 Hz for the 300m width. As most earthquakes have a predominant frequency of more than 1 Hz, therefore, increase in landfill width is one way of improving the response of the system.

Table 4- Values of amplification with different width of landfill and shear wave velocity

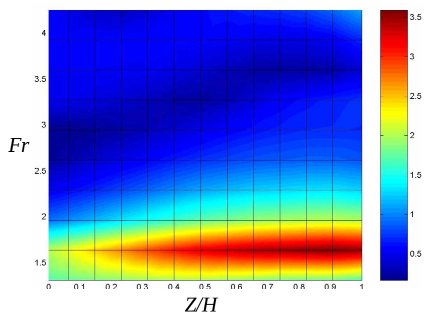
Shear wave velocity of MSW (m/s)	Amplification ratio	Relative frequency	Major frequency for width of 150m	Major frequency for width of 200m	Major frequency for width of 300m
100-125	2.50	3.40	1.75	1.30	0.8
140-165	2.85	3.15	2.00	1.50	1
180-205	3.50	3.15	2.40	1.80	1.2



a- Vs=100-125m/s



b- Vs=140-160m/s



Fr: Relative frequency
Z/H: dimensionless location of points in height of landfill

c- Vs=180-205m/s

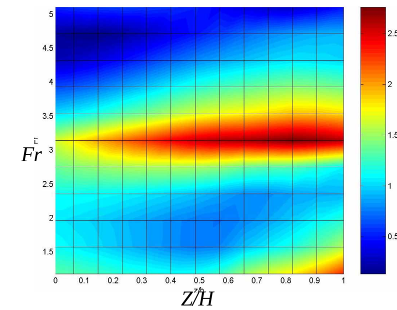
Figure 15- Amplification ratio versus depth with different shear wave velocities

Effect of daily cover

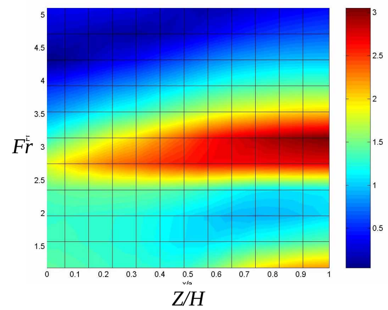
The effect of daily cover properties was also investigated on the response. The results are shown in Table 5 and Fig. 16. These situations were studied including assumption of no daily cover, daily cover with *Vs* of 150 m/s and daily cover with Vs of 450 m/s. Elimination of daily cover has improved the dynamic response, as the amplification ratio is reduced to 2.33. No difference is observed for the results of various *Vs* on the amplification ratio, but the major frequency of the system is lowered with reduction is *Vs*.

Table 5- Values of amplification with different width of landfill and properties of daily cover

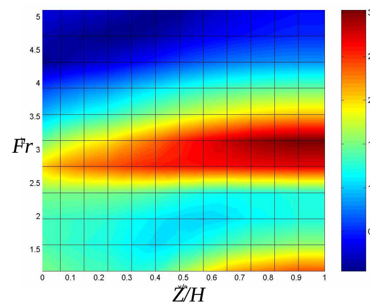
Properties of daily cover	Amplification ratio	Relative frequency	Major frequency for width of 150m	Major frequency for width of 200m	Major frequency for width of 300m
Without daily cover	2.33	3.15	2	1.50	1
Vs=150m/s	3.05	2.75	1.75	1.30	0.8
Vs=450m/s	3.03	3.15	2	1.50	1



a- Without daily cover



b- Daily cover with Vs=150 m/s



Fr: Relative frequency
Z/H: dimensionless location of points in height of landfill

c- Daily cover with Vs=450 m/s

Figure 16- Amplification ratio versus depth with different properties of daily cover

CONCLUSIONS

On the basis of the conducted study and presented results, the following conclusions can be made:

- FLAC which has been originally developed for modeling soil and rock structures, is also capable of the analysis of landfill structures having MSW which is quite different from soil in its physical and mechanical properties.
- The Fukuoka type landfill constructed in Kahrizak would have failed, if an earthquake similar to Manjil had occurred in the region.
- The proper design and construction of the surrounding embankments have an important role in stability of the area landfills, particularly in dynamic response. Low permeability, reinforcement, adequate compaction, and vegetation are some ways of improving the stability.
- Elimination of daily cover helps to improve landfill stability by allowing the leachate to reach the bottom drainage system and not leaking out the embankment, also reducing the amplification ratio.
- Using higher permeability soil and lower compaction of the daily cover also improves the response of the system.
- Increasing the width of the landfill (or in general the width to height ratio) contributes to reduction of the amplification ratio.

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