PERMANENT SEISMIC DISPLACEMENT EVALUATION AND COMPARISON OF METHODOLOGIES

H. James Law
Solid Waste Division
SCS Engineers
Raleigh, North Carolina

Joseph J. Miller
Solid Waste Division
SCS Engineers
Pleasanton, California

Ambrose A. McCready
Solid Waste Division
SCS Engineers
Sacramento, California

ABSTRACT

A recent simplified seismic analysis procedure published by Bray et al (1998) is gaining popularity in evaluating seismically induced deformations at the base of a landfill. The Bray et al (1998) simplified procedure is based on the results of fully non-linear decoupled one-dimensional dynamic analyses that combine with the Newmark (1965) rigid sliding block or the Makdisi and Seed (1978) procedure. Therefore, this simplified procedure provides a more comprehensive assessment of the seismic ground motions, seismic loading, and seismically induced deformation calculations than that of the Makdisi and Seed (1978) procedure, resulting in more accurate and realistic prediction of the seismically induced displacements due to an earthquake event.

This paper presents the analytical results of a case study site in California using this procedure and comparing the results to those using the traditional Makdisi & Seed (1978) method. The case study presents the results and the methodology used in support of application for a seismic impact zone waiver which demonstrates that a Class III landfill can be safely constructed in northern part of California. Global final slope stability was evaluated for the Maximum Credible Earthquake (*MCE*) with a near-field magnitude of 6.25 and at peak horizontal ground acceleration (*PHGA*) of 0.42g. The thickness of the bottom liner system is 3 feet. The maximum slope height from the base of the landfill to the proposed final landfill surface is approximately 200 feet. The maximum excavated sideslope at the bottom of the landfill is at 2(H):1(V), with the cell floor bottom at approximately 2%. The maximum final landfill sideslope is at 3 (H): 1(V).

The estimated permanent displacement in a near-field event using the Makdisi and Seed (1978) displacement chart was estimated to be 14 cm, or less than 6 inches.

Whereas the Bray et al (1998) analysis shows that the estimated maximum permanent displacements for the same slope analyzed were equal to 1.2 cm, or less than 0.5 inches, which are negligible. The results are compared and conclusions are made regarding these seismic analysis procedures.

INTRODUCTION

In response to U.S. Environmental Protection Agency (EPA) Subtitle D regulation requirements (1993), seismic design procedures used for municipal solid waste landfills (MSWLFs) in seismic impact zone is an important part of the design and permit application. The analytical methodology has evolved rapidly over the past twenty years. As required by EPA and most state regulatory agencies, when a computed seismic factor of safety is less than unity, the seismic stability of a MSWLF unit can be evaluated with seismically induced permanent deformations (or displacements) that need to be within an acceptable limit. Typically the acceptable limit is no greater than 12 inches in most states. However, for some recent site-specific project situations in California (EPA Region 9), this acceptable limit is set to be no greater than 6 inches.

Simplified techniques, such as Makdisi and Seed (1978) permanent displacement chart, that use a rigid sliding block procedure, are routinely used to evaluate permanent displacements that may occur due to sliding along the base of the landfill under a seismic ratio of the yield acceleration and the peak ground acceleration (PGA), for a given earthquake magnitude. Hence, this displacement chart constitutes the basis for seismic design procedure of MSWLF units in seismic impact zone with the PGA greater than 0.1g on a 90 percent probability of non-exceedance over a 250 year time period (or 2% in 50-year) as written in the Subtitle D regulations.

A more recent simplified seismic analysis procedure published by Bray et al (1998) requires: (a) expressing design bedrock motions in terms of intensity, frequency content, and duration, (b) estimating the seismic loading at the base of the landfill, and (c) evaluating performance in terms of seismically induced permanent displacements at the base of the landfill. The procedure also includes the displacement of the final cover system but is not discussed in this paper. The Bray et al (1998) simplified procedure is based on the results of fully non-linear decoupled one-dimensional dynamic analyses that combine with the Newmark rigid sliding block procedure.

REVIEW OF SEISMIC DISPLACEMENT METHOLOGIES

For comparison purposes, **Table 1** provides a summary of the key site factors and inputs used in the evaluations for the Makdisi and Seed (1978) and the Bray et al (1998) seismic displacement methodologies.

The Makdisi and Seed (1978) simplified seismic displacement chart is based on a limited number of recorded and modified ground motions. Its analytical method is relatively simple and uses a decoupled approximation to estimate displacement. However, this method is still widely accepted as one of the most used procedures in geotechnical earthquake engineering over the past few decades. As suggested by Bray et al (1998), the bounds shown in the Makdisi and Seed (1978) design curves are not true upper and lower bounds, since the estimate of uncertainly is not included.

The following are the Makdisi and Seed (1978) analytical procedures:

1. Estimate peak ground acceleration (*PGA*) using the applicable ground motion maps (such as 1996 or the latest USGS seismic hazard maps for the continental USA) based on an appropriate probability level (peak value at 2% exceedance in 50 years for Subtitle D).
2. Calculate the yield acceleration (k_y) for the landfill base using conservative residual interface shear strengths.
3. Calculate seismically induced displacement (*U*), using Makdisi and Seed (1978) displacement chart (see **Figure 1**).

The Bray et al. (1998) methodology is based on the results of fully nonlinear decoupled one-dimensional dynamic analyses combined with the Newmark rigid sliding block procedure. It also includes a greater number of recorded earthquake ground motions available at the time and with recorded earthquake rock input motions ranging from 0.2*g* to 0.8*g*. This method was calibrated using data collected from the 1989 Loma Prieta and 1994 Northridge earthquakes in California, against several landfill performance as well as validated against observed earth fill performance. Hence, the Bray et al. (1998) procedure provides not only a more comprehensive assessment of the earthquake ground motions, seismic loading, and seismic displacement calculations, but it requires more effort than the Makdisi and Seed (1978) procedure.

The following are the Bray et al (1998) analytical procedure:

1. Review the regional and site geology, seismicity, and identify potential earthquake sources and type of fault.
2. Characterize the ground motion: estimate intensity at rock surface (MHA_{rock}), frequency content (T_m), and duration ($D_{5\text{-}95}$) for each design earthquake governing event.
3. Develop seismic loading: estimate the maximum horizontal equivalent acceleration at base of landfill ($MHEA_{base}$) or the maximum seismic acceleration coefficient (k_{max}).
4. Calculate the yield acceleration coefficient, k_y (at pseudo-static $FS = 1.0$).
5. Estimate the displacements at base (*U*), using estimates of k_y/k_{max} , k_{max} , and $D_{5\text{-}95}$ (see **Figure 2**), for median and 16% probability of exceedance lines.

The procedure is more comprehensive than that of the Makdisi and Seed method (1978) because it requires characterizing the design bedrock motions in terms of intensity, frequency content, and duration. It also requires an estimation of the seismic loading at the base and/or cover of the landfill. And finally, as shown in **Figure 2**, an evaluation of seismically induced permanent displacement is performed using the normalized seismic loading and displacement values estimated at the median and 16% exceedance levels to develop a range of estimated seismic displacements. Appropriate engineering judgment is necessary as this method was not developed in a rigorous probabilistic manner and is also limited by the decoupled approximation employed in the seismic response and Newark sliding block calculations. Although it is not discussed in this paper, other methods such as Bray and Travasarou (2007) may also be use to evaluate seismic displacement estimation, since the number of well-recorded events occurred since 1998 are available and was included in their method.

A CALIFORNIA CASE STUDY

A case study landfill site in California is presented below using the Bray et al (1998) procedure and comparing to the results using the traditional Makdisi and Seed (1978) method. This case study uses the Bray et al (1998) methodology in support of a permit application for a seismic impact zone waiver to demonstrate that a Class III landfill can be safely constructed in northern California. The proposed landfill is a canyon-type fill, with underlying geologic formations consisting of surficial deposits underlain by bedrock material. Most of these surficial deposits are to be removed during construction of the landfill. A toe-buttressing fill, consisting of about 160 cubic yards per linear foot of soil/rock material, is designed to be placed within the cell limit, on the cell inner sideslope and to about 25 feet above the top of the perimeter berm and below the final design slope surface.

Global final slope stability was evaluated for the *MCE* with a near-field magnitude of 6.25 and at the *PHGA* of 0.42g. The thickness of the bottom liner system is 3 feet and includes both soil and geosynthetic components. The final cover system it is 4 feet thick and also includes soil and geosynthetic components. The maximum slope height from the base of the landfill to the proposed final landfill surface is approximately 200 feet. The maximum excavated sideslope at the bottom of the landfill is at 2(H):1(V), with the cell floor bottom sloped at approximately 2%. The maximum final landfill sideslope is at 3 (H): 1(V). A section profile used in the analysis is shown in **Figure 3**.

RESULTS OF ANALYSIS AND COMPARISON

Global slope stability was evaluated at selected critical slope section profiles using the *MCE* with a near-field magnitude of 6.25 and at the *PHGA* of 0.42g. From the analysis, a block-type failure surface was the most critical slope section profile. Using the *PHGA* of 0.42 g, the pseudo-static slope stability was evaluated for the selected slope profile, resulting in a factor of safety of less than unity. As a result, by varying the input value of the seismic coefficient to yield at a factor of safety of 1.0, a yield acceleration (designated as k_y) of 0.17 g was calculated.

The permanent displacement calculated using Makdisi and Seed (1978) method is shown **Figure 1**. For this method, the ratio of yield acceleration to the maximum average acceleration was first calculated and the estimated permanent displacement is estimated using the Makdisi and Seed (1978) chart for a given earthquake magnitude (in this case magnitude of 6.25 on the Richter scale). Thus the ratio of $k_y/k_{max\ (PGA)}$ used was (0.17)/(0.42) = 0.40. The estimated permanent displacement in a near-field event using the Makdisi and Seed (1978) chart is estimated to be 14 cm, or less than 5.5 inches. This result is considered acceptable for a municipal solid waste landfill subject to seismic forces.

The seismic slope permanent displacement analysis was also performed using the Bray, et al (1998) method. The use of Bray et al (1998) permanent displacement chart is shown in **Figure 2**. Using the ratio of $k_y/k_{max\ (at\ base)}$ of 0.71, a $k_{max\ (\text{at base})}$ of 0.24, and a $D_{5\text{-}95}$ of 8 seconds, the analysis shows that the estimated permanent slope displacements for the same slope analyzed were equal to 1.2 cm, or less than 0.5 inches, which is negligible. The results of the analysis are summarized in **Table 2**.

The calculated seismically induced permanent deformation varies between the two methodologies. In this case study, the displacement estimated using the Bray et al (1998) method is about 12 times less than the Makdisi and Seed (1978) method.

Based on the general classification and range of displacement estimates suggested by Bray and Travasarou (2007) and as shown in **Table 3**, the permanent displacement calculated using Makdisi and Seed (1978) method can be described as “minor” displacement whereas for the Bray et al (1998) method, it is considered a “negligible” displacement.

CONCLUSION

As shown in the case study, analysis via either method shows the design meets the site-specific regulatory requirement that seismically-induced displacements not exceed 6 inches.

As shown in **Table 2**, it is apparent that the Bray et al (1998) method would result in smaller displacement at the case study site. The reason for a smaller displacement estimate could possibly be due to the use of a more comprehensive assessment of the site-specific seismic loading of known earthquake magnitude from a known fault some distance from the site. It could also be explained by the use of a displacement design chart that is based on a larger data base and thus resulting in more accurate and realistic prediction of the seismically induced permanent displacements. It is suggested that the Makdisi and Seed method is a more conservative approach of estimating the seismically induced deformation.

The size of the toe-buttressing fill plays an important role of meeting the regulatory static factor of safety requirement and also limiting the permanent seismic deformation to within the acceptable range. Other important factors such as the waste mass and interface residual shear strengths used in the analysis need to be reviewed carefully as part of the site-specific conditions. However these factors will not be discussed here since both analytical methods assumed same values in the pseudo-static stability analysis.

For other states where the allowable permanent displacement is equal to or less than 12 inches, either method can be used to calculate the anticipated permanent displacement under a seismic event. Therefore, it is recommended that prior to performing the seismic analysis, one should attempt to obtain accurate site-specific seismic information and to use appropriate engineering judgment when deciding which method to use in estimating seismically induced displacements.

In conclusion, based on this project site evaluation, it is recommended that for sites where the seismic fault zones are well-known and the bedrock surface is near surface, Bray et al (1998) method should be used, especially for sites where there is more stringent regulatory requirement. For sites where the soft soil layer below a lined landfill is thick, then Makdisi and Seed (1978) method can still provide reasonable approximation results. Overall, both methods should be used for comparison of results in order to gain confidence in the final outcome of the analyses.

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TABLE 1. KEY SITE FACTORS AND INPUTS USED IN EVALUATIONS

Site Factors & Evaluation	***Makdisi & Seed (1978)***	***Bray et al (1998)***
Key potential Seismic Source(s) to Site:		
Magnitude(s)	Y	Y
Distance(s)		Y
Intensity for Outcropping Rock, *MHA*	Y	Y
Frequency Content, T_m		Y
Duration , $D_{5\text{-}95}$		Y
Shear Wave Velocity, V_s		Y
Initial Fundamental Period of the Potential Sliding Mass, *Ts*		Y
Fault Type(strike-slip, reverse)		Y
Seismic Loading at Base, $MHEA_{base} = K_{max}$		Y
Pseudo-Static Stability Analysis Calculate Yield Acceleration, k_y, (at FS=1)	Y	Y
Estimate Seismic Displacement	Y	Y

Y – Site factor under consideration and appropriate evaluation performed.

TABLE 2. COMPARISON OF RESULTS

Methodology	**Ratio of k_y/k_{max}**	**Calculated Permanent Displacement, U** **cm (inches)**	**EPA Region 9 2011 Allowable Displacement, U** **cm (inches)**
Makdisi & Seed (1978)	0.40	14 (5.5)	15 (6)
Bray et al (1998)	0.71	1.2 (0.5)	

TABLE 3. GENERAL DISPLACEMENT CLASSIFICATION & ESTIMATE

General classification	**Displacement Estimates (cm)**
Negligible	< 1
Minor	1 to < 15
Moderate	15 to < 100
Large	> 100

* Based on Bray and Travasarou (2007), depending on factors such as the foundation system, consequences of displacement, soil behavior, etc.

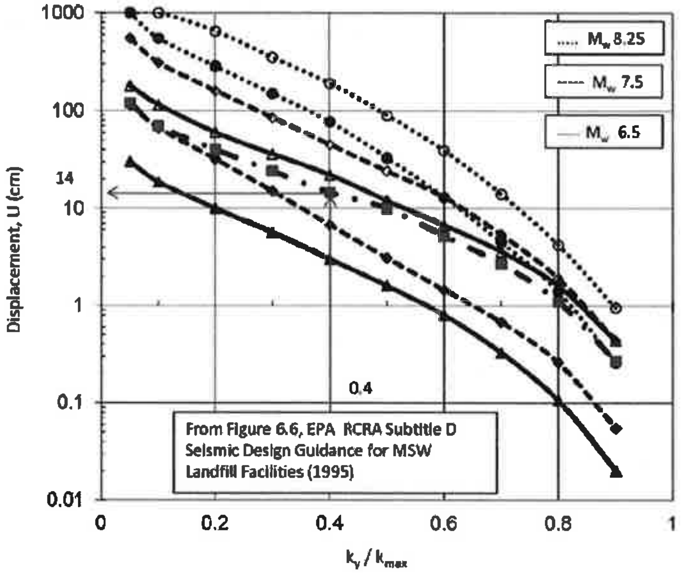

FIGURE 1. MAKDISI AND SEED (1978) PERMANENT DISPLACEMENT CHART

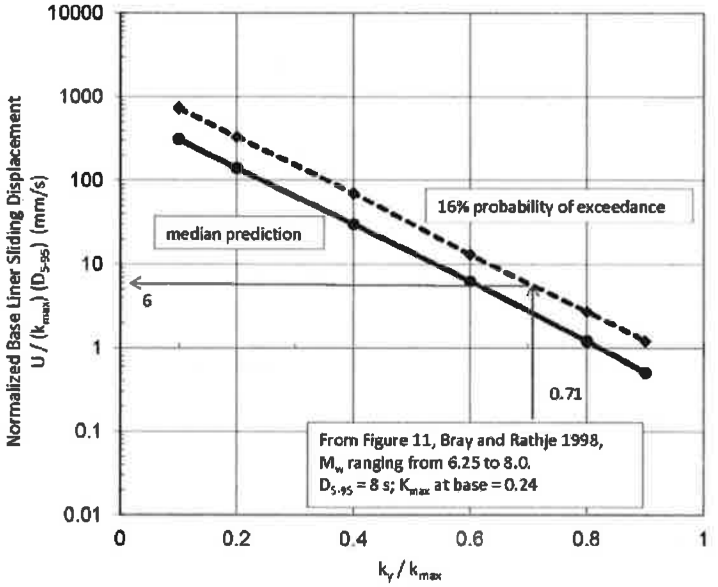

FIGURE 2. BRAY ET AL (1998) PERMANENT DISPLACEMENT CHART

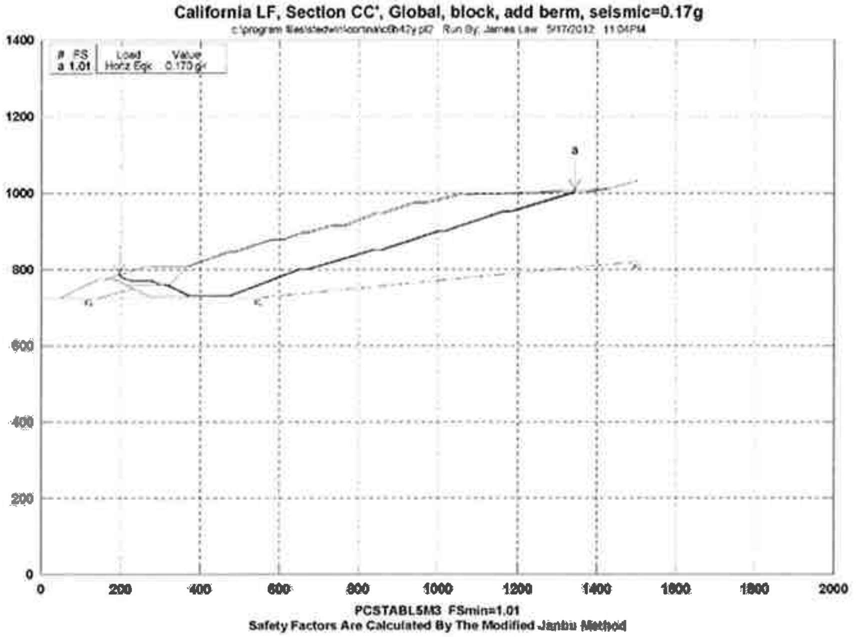

FIGURE 3. TYPICAL SLOPE SECTION PROFILE AND CRITICAL FAILURE SURFACE