A Comparative Study on Decoupled Methods for Determination of Permanent Deformation of Slopes

Gaurav Singh[1] S.M Ali Jawaid[2]
[1]M. Tech Student [2]Professor
[1,2]Department of Civil Engineering
[1,2]Madan Mohan Malaviya University of Technology, Gorakhpur, India

Abstract— There are quite methods available for estimating earthquake-induced permanent deformation of slopes. Comparisons between the pseudo static and fully-coupled surfaces, conclude that the geometry of the failure mechanism is affected by the dynamic response for wavelength ratios (λ /H) between 1 and 4 where surfaces can be smaller in volume by 20%.The coupled analyses are suggested for these situations because the pseudo static surface assumption is not appropriate. The methods on the basis of pseudo static surface assumption (rigid-block and decoupled) are appropriate and dynamic response has less influence on the failure mechanism geometry, for λ/H greater than 4. In the earliest time a limit-equilibrium pseudo static approach was used for analysis of seismic slope stability and the stability is considered in terms of a simple factor-of-safety. During the 1960s and 1980s, these very basic procedures evolved into more sophisticated deformation-based approaches. To calculate seismically-induced displacements in slopes, we are using one of the available deformation-based analysis method. Such an approach is appropriate as, displacements ultimately govern the serviceability of a slope after an earthquake

Key words: Seismic Slope Stability, Permanent displacement, Decoupled Analysis, etc

I. INTRODUCTION

To compute seismic slope displacements there are approximately 30 different deformation-based methods have been developed over the past 50 years. These procedures generally fall into one of three categories: (1) rigid block-type procedures, which ignore the dynamic response of slopes. (2) Decoupled procedures, which account for dynamic response, but "decouple" this response from the sliding response of slopes and (3) coupled procedures, which 'couple' the sliding and dynamic response of slopes. The decoupled model was originally proposed by Makdisi and Seed (1978). The model is based on the concepts of permanent deformation proposed by Newmark (1965), but is modified to account for the dynamic response of the structure. The incentive for modifying the rigid-block model came from a series of research efforts studying the seismic behavior of earth dams and was commensurate with the development of finite-element codes. From this work it was recognized that a structure's response to earthquake loading can significantly affect the magnitude and distribution of inertial forces acting throughout the structure and more specifically on a potential slide mass. As originally proposed by Makdisi and Seed (1978), the decoupled model is consist of two parts: (1) a dynamic response analysis and (2) a sliding response analysis. The decoupled model assumes that these analyses can be performed separately in a two-step process (hence the name "decoupled"). The purpose of the dynamic response analysis is to quantify the accelerations experienced by the slide mass and can be computed for one- or two-dimensional systems. These time-variant accelerations are referred to as the horizontal-equivalent acceleration time history (or HEA) and represent a spatial average of the accelerations acting on the slide mass. This analysis can carried out using equivalent-linear dynamic response codes or non-linear codes. The sliding response analysis is then performed by double-integrating the HEA time history to calculate the displacements.

II. SIMPLIFIED DECOUPLED METHODS

In compared to the simplified rigid-block methods, much fewer simplified decoupled methods exist. As such, only methods that are commonly used in practice were selected. The following sections described the simplified decoupled methods evaluated in this study. The most important feature of the decoupled model is the fact that the slide mass is modeled as a compliant, non-rigid block. This means that the slide mass is a deformable body that can respond dynamically to earthquake shaking. The main implication of this is that accelerations within the slide mass and slope will be different than those in the foundation material below the slope. This is because accelerations originating from the foundation level and propagating up cause the slope to move by different amounts and in different phases thereby creating a spatial distribution of accelerations. The dynamic response analysis models this behavior and its effect on the slide mass is quantified through the HEA time history. In comparison the rock outcrop motion used with the rigid-block model, the HEA time history is a much more realistic representation of the seismic loading experienced by the slide mass.

A. *Makdisi and Seed (1978) Decoupled:*

Makdisi and Seed (1978) formulated the decoupled model. Moreover, they were the first to develop a series of simplified design charts based on their model. These charts have been used in number of studies as a benchmark for comparing rigid-block methods or analytical decoupled analysis results and remains a popular simplified method in practice. The Makdisi and Seed (1978) simplified decoupled method consists of two charts that essentially represent the two-step procedure performed as part of the analytical form of their approach. The first chart is used to evaluate the seismic demand experienced by the slide mass and the second is for estimating the permanent deformation. Both charts are represented in Figure 1.

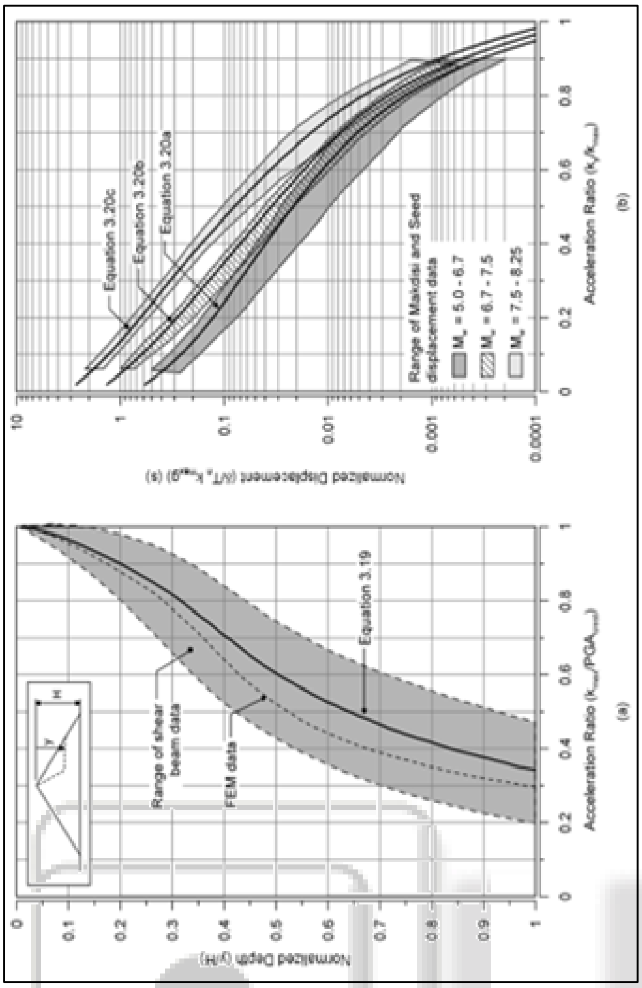

Fig. 1:

Formulating the seismic demand in this way is particularly problematic since there are no known simplified procedures for estimating *PGAcrest* for slope geometries other than triangular embankment dams (Blake et al. 2002). As such, for this study, it was necessary to perform a formal dynamic response analysis in order to determine *PGAcrest*; values obtained from two-dimensional *FLAC* analyses were used. Functioning as a simplified method, this may seem contrary to its intended purpose however, this was necessary as it is the only rational way to properly estimate *PGAcrest*. Moreover, Makdisi and Seed did not provide analytical expressions for the relationship. The following equation is for the average curve indicated in Figure 1a.

$$\frac{y}{H} = -27.728\left(\frac{k_{max}}{PGA_{crest}}\right)^6 + 98.779\left(\frac{k_{max}}{PGA_{crest}}\right)^5 - 114.636\left(\frac{k_{max}}{PGA_{crest}}\right)^4 + 99.385\left(\frac{k_{max}}{PGA_{crest}}\right)^3 - 30.820\left(\frac{k_{max}}{PGA_{crest}}\right)^2 - 0.172\left(\frac{k_{max}}{PGA_{crest}}\right) + 2.206$$

For this study, *H* is the landslide height (defined as the difference in elevation between the landslide crown and the bottom-most point of the slip surface) and *y* is the maximum slide mass thickness.

Results from the dynamic response analyses were used to calculate permanent displacements. Makdisi and Seed made the observation that for the same *ky/kmax* ratio, computed deformations (through double-integration) varied uniformly between a maximum value obtained by using the *crest acceleration* time history (that is *kmax =PGAcrest*) to a minimum value by using an *HEA* time history for a sliding mass that extended through the full height of the model embankment (Makdisi and Seed 1978). This assumption allowed the authors to calculate displacements that represented reasonable upper and lower bound limits. Here, upper bound estimates are obtained by using the crest acceleration and lower bound estimates from the *HEA* time history. Displacements were normalized with respect to the *kmax* and the fundamental period of the embankment dam (*Tn*). It is not exactly clear from Makdisi and Seed (1978) if *Tn* is the initial small strain period or degraded natural period due to material non-linearity (Bray and Rathje 1998). The data was also categorized according to the earthquake event magnitude of the ground motions used in the dynamic response analysis.

B. Hynes-Griffin &Franklin (1984) Decoupled:

This method was developed as a screening procedure for assessing the seismic stability of earth dams; however it also can be used in a permanent displacement analysis. This section focuses discussion on its secondary function; details of its screening procedure capability are not discussed. As with Makdisi and Seed's method, this simplified decoupled method consists of two charts that essentially represent the two-step procedure of the analytical decoupled method. The first chart is used to evaluate the seismic demand experienced by the slide mass and the second is for estimating the permanent deformation. Both charts are represented in Figure 2.

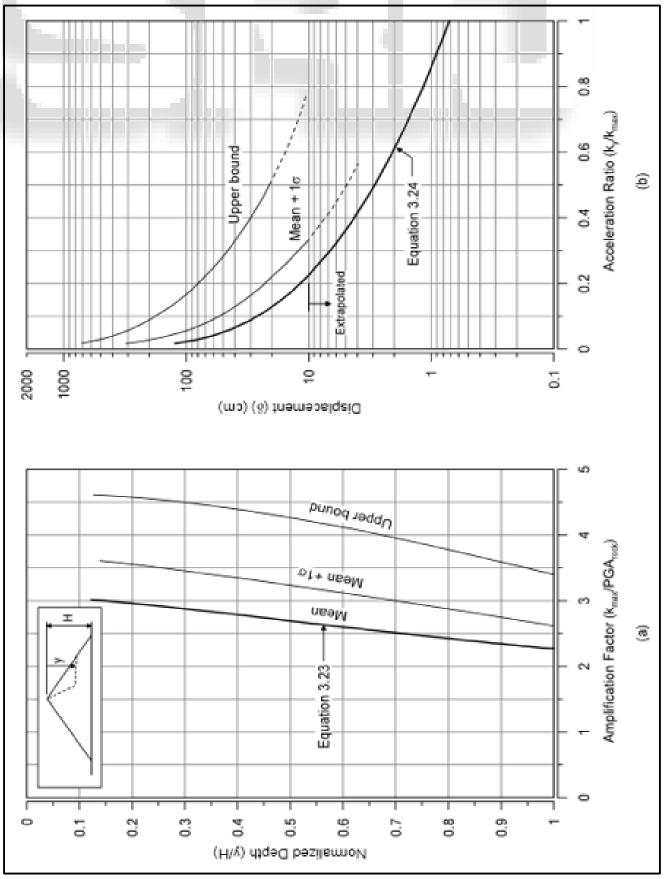

Fig. 2:

Hynes-Griffin and Franklin developed very conservative approach consistent with the method's primary function as a screening procedure. In a similar fashion to Makdisi and Seed, the authors developed a relationship that modeled the variation of accelerations experienced by slide mass (*HEA*) with depth for a range of embankment dam geometries and earthquake loading conditions.

Hynes-Griffin and Franklin derived mean, mean plus one standard deviation and upper bound estimates of the amplification factor. The following equation is for the mean curve indicated in Figure 2a.

$$\frac{y}{H} = -0.705\left(\frac{k_{max}}{PGA_{rock}}\right)^3 + 5.638\left(\frac{k_{max}}{PGA_{rock}}\right)^2 - 16.101\left(\frac{k_{max}}{PGA_{rock}}\right) + 16.741$$

To determine the permanent displacements, results from the dynamic response analyses were *not* used. Instead, Hynes-Griffin and Franklin generated the displacement data by double-integrating 348 earthquake ground motions and 6 synthetic acceleration time histories. The authors note that these motions correspond to earthquake events with magnitude less than 8.0 (the number of earthquake events was not reported). Details of the regression analysis were not provided. Using this data, a relationship derived between acceleration ratio (*ky/kmax*) and the displacement. Relationships for mean, mean plus one standard deviation and upper bound estimates of displacement were developed. As with the seismic demand chart, Hynes-Griffin and Franklin did not provide expressions. The following equation is for the mean curve indicated in Figure 2b.

$$\delta = -0.174\left(\frac{k_y}{k_{max}}\right)^3 - 0.870\left(\frac{k_y}{k_{max}}\right)^2 - 2.260\left(\frac{k_y}{k_{max}}\right) - 0.144$$

C. Bray Et Al. (1998) Decoupled:

The simplified decoupled method by Bray et al. (1998) was originally developed for seismic stability evaluations of geosynthetic-lined, municipal solid waste (MSW) landfills and was built upon earlier work by Bray et al. (1995) and Bray and Rathje (1998). As with Hynes-Griffin and Franklin (1984), this method can function as a screening procedure or a stand-alone deformation analysis method. The screening procedure proposed by Bray and Rathje (1998) was improved upon by Stewart et al. (2003) and is recommended by CGS (2008) for analyzing earthquake-induced landslide hazards. This simplified decoupled method consists of two charts and associated equations that essentially represent the two-step procedure of the analytical decoupled method. The first chart is used to evaluate the seismic demand experienced by the slide mass and the second is for estimating the permanent deformation. Both charts are represented in Figure 3.

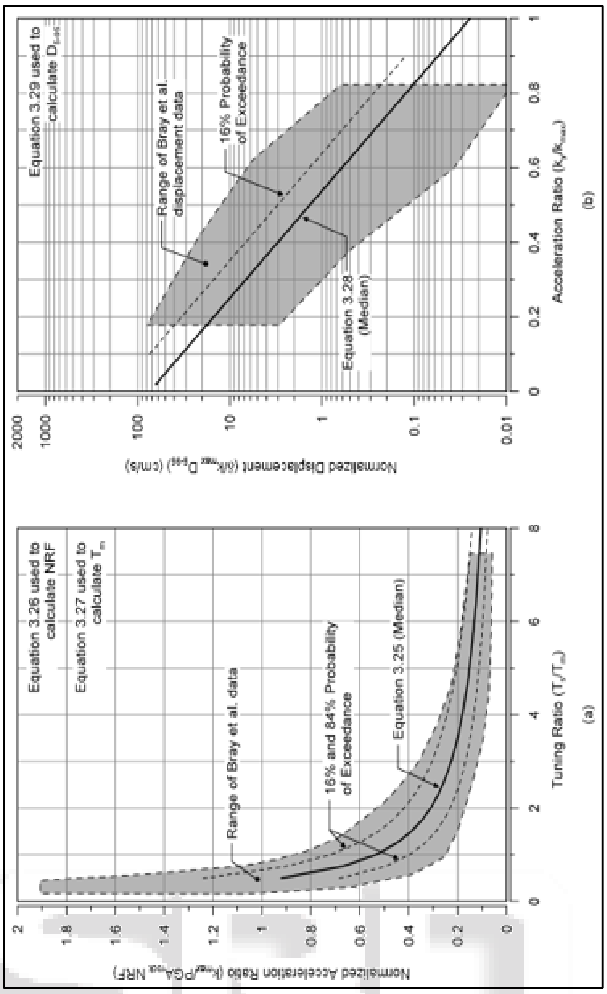

Fig. 3:

As shown in Figure 3a, Bray et al. expressed these results in a design chart that related the normalized acceleration ratio (*kmax/PGArock NRF*) as a function of the tuning ratio (*Ts/Tm*) of the waste fill (i.e. slide mass). The term *kmax* is the peak value of the *HEA* and *PGArock* is the peak acceleration of the rock outcrop motion. The parameter *NRF* is a non-linear response factor that accounts for site response effects that result from material non-linearity. The factors adopted for their work was originally developed by Seed et al. (1991). The authors derived median and 16% and 84% probability of exceedance curves for this relationship (Figure 3a). For this study the median curve was adopted and is given by the following expression Blake et al. (2002):

$$ln\left(\frac{k_{max}}{PGA_{rock}\ NRF}\right) = -0.624 - 0.7831\ ln\left(\frac{T_s}{T_m}\right)$$

The *HEA* time histories obtained from each landfill configuration evaluated for dynamic response analyses were double-integrated to calculate the permanent displacements; this data is shown in Figure 3b. For the development of this chart, the authors performed several more dynamic response analyses for additional landfill configurations using 19 more ground motions (additional information one these motions not provided). This additional data, it should be noted, was included in the sliding response analysis only and not for the seismic demand chart shown in Figure 3a. The displacement data for 4 acceleration ratios (*ky/kmax* = 0.2, 0.4, 0.6 and 0.8). Substantial variation in the calculated displacement prompted the authors to normalize the data in order to reduce the scatter. Displacements were normalized with respect to the *kmax* and the significant duration (*D5-95*) of the ground motion. Bray et al. (1998) derived median and 16% probability of exceedance curves for calculating the displacement (Figure 3b). For this study the median curve was adopted and is given by the following expression (Bray and Rathje 1998, Blake et al. 2002):

$$log_{10}\left(\frac{\delta}{k_{max}D_{5-95}}\right) = 1.87 - 3.477\left(\frac{k_y}{k_{max}}\right)$$

As with *Tm*, the significant duration can be calculated from site-specific rock outcrop ground motions, however to be consistent with the intentions of the authors, the attenuation model developed by Abrahamson and Silva (1996) was used. The significant duration (*D5-95*) (in s) is calculated as follows:

$$\ln(D_{5-95}) = ln\left[\frac{\left(\frac{exp[5.204+0.851(M_w-6)]}{10^{1.5M_w+16.05}}\right)}{15.7\times10^6} + 0.063(R_{rup}-10)\right] + 0.866$$

$$ln(D_{5-95}) = ln\left[\frac{\frac{exp[5.204+0.851(M_w-6)]^{-\frac{1}{3}}}{10^{1.5M_w+16.05}}}{15.7\times10^6}\right] + 0.866$$

where *Mw* is the moment magnitude of the earthquake event and *Rrup* is the site-to-source distance taken as the closest distance to the fault rupture plane. Equation 3.29a is for (*Rrup* > 10 km) and Equation 3.29b for (*Rrup* < 10 km). Using Equation 3.29 for a given earthquake event and site location, *D5-95* is a constant.

III. Conclusion

Simplified-type methods (rigid-block and decoupled) display the widest variety. As such, practitioners using these types of methods should always be cognizant of a method's intended purpose and use it according to that purpose. Misusing methods in this way can lead to unreliable estimates of displacement. In 438 particular, practitioners should be aware of the intended uses of methods by Jibson (2007) and Watson-Lamprey and Abrahamson (2006).

Biases were observed for individual deformation methods as opposed to a particular method category (rigid-block, decoupled, coupled) or method type (simplified or analytical). These biases were attributed to specific ground motion parameters (e.g. Yegian et al. 1991) and the use of attenuation models (e.g. Bray et al. 1998) to obtain ground motion parameters. Also, biases may have been introduced by the author by extrapolating trends and using the methods outside recommended ranges (e.g. Hynes-Griffin and Franklin 1984). It should be noted that the biases observed for these methods are only applicable to cases examined in this study. Extrapolating this conclusion to other situations is not recommended because this bias may not exist under all seismic loading conditions.

References

[1] Ambraseys, N. N., and Menu, J. M. (1988). "Earthquake-induced ground displacements." Earthquake Engineering and Structural Dynamics, 16(7), 985 1005.

[2] Ambraseys, N. N., and Srbulov, M. (1994). "Attenuation of earthquake-induced ground displacements." Earthquake Engineering and Structural Dynamics, 23(5), 467-487.

[3] American Society for Testing and Materials (ASTM). (2002) "Standard test method for direct shear test of soils under consolidated drained conditions." ASTM D-3080, West Conshohocken, Pennsylvania.

[4] Bray, J. D., and Rathje, E. M. (1998). "Earthquake-induced displacements of solid-wastelandfills."Journal of Geotechnical and Geoenvironmental Engineering, ASCE, 124(3), 242-253.

[5] Bray, J. D., and Travasarou, T. (2007). "Simplified procedure for estimating earthquake induced deviatoric slope displacements." Journal of Geotechnical and Geoenvironmental Engineering, ASCE, 133(4), 381-392.

[6] Bray, J. D., and Travasarou, T. (2009). "Pseudostatic coefficient for use in simplified seismic slope stability evaluation." Journal of Geotechnical and Geoenvironmental Engineering, ASCE, 135(9), 1336-1340.

[7] Goodman, R. E., and Seed, H.B. (1965). "Displacements of slopes in cohesionless materials during earthquakes." Report No. H21, Institute of Transportation and Traffic Engineering, University of California, Berkeley, California.

[8] Jibson, R.W., 1993. Predicting earthquake-induced landslide displacements using Newmark's sliding block analysis. Transportation Research Record 1411, 9-17.

[9] Jibson, R.W., 2007. Regression models for estimating coseismic landslide displacement. Engineering Geology 91, 209-218.

[10] Jibson, R.W., Rathje, E.M., Jibson, M.W., Lee, Y.W., 2010, SLAMMER—Seismic LAndslide Movement Modeled using Earthquake Records. U.S. Geological Survey Techniques and Methods (in press).

[11] Kramer, S.L., 1996. Geotechnical Earthquake Engineering. Prentice Hall, Upper Saddle River, NJ, 653 pp.

[12] Kramer, S.L., Smith, M.W., 1997. Modified Newmark model for seismic displacements of compliant slopes. Journal of Geotechnical and Geoenvironmental Engineering 123, 635-644.

[13] Lin, J.S., Whitman, R.V., 1983. Earthquake induced displacements of sliding blocks. Journal of Geotechnical Engineering 112, 44-59.

[14] Makdisi, F.I., Seed, H.B., 1978. Simplified procedure for estimating dam and embankment earthquake-induced deformations. ASCE Journal of the Geotechnical Engineering Division 104, 849-867