Application of simplified seismic slope displacement procedures in South Africa

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ABSTRACT: Although South Africa is generally considered a region of low seismic hazard, many international standards and guidelines require that earth slopes and embankments be designed for seismic loading conditions. Rigorous, nonlinear deformation analyses require detailed knowledge of the seismicity of the area as well as the soils under consideration, information which is not routinely available for many sites in South Africa. Therefore, simplified seismic slope displacement procedures are commonly used as a screening approach to determine whether a more rigorous assessment is necessary. Such procedures have been proposed since the early 1960s but these procedures have generally been considered overconservative and inaccurate. In recent years, there have been several new procedures developed which greatly improve on the shortcomings of the early procedures. In this study, an overview of several modern simplified seismic slope displacement procedures is provided. A typical workflow is suggested that can be followed for implementing simplified slope displacement procedures for earth embankments in South Africa. The workflow results in a seismic hazard classification of the site as well as estimated permanent deformations induced by the shaking caused by the design earthquake. These parameters can then be used to inform the need for further assessment.

1 INTRODUCTION

The seismicity of South Africa has generally been considered moderate by world standards (e.g. Brandt 2011) and is characterised by low to minor earthquakes (e.g. Alabi et al. 2013). However, in recent years there has been the introduction of several standards and guideline documents that require the seismic performance of many geotechnical structures to be assessed for large recurrence interval events. In particular, the introduction of the Global Industry Standard on Tailings Management (GISTM) (Oberle 2020) in many cases requires that the performance of tailings dams be routinely evaluated against the shaking caused by earthquakes with recurrence intervals of 5 000 and even 10 000 years.

Although the seismic setting of South Africa is such that seismic events for short recurrence intervals are minor, these larger recurrence interval events can become moderate. For example, the 1969 Ceres earthquake was estimated to have a Moment Magnitude (M_w) of 6.2 (Midzi et al. 2013). More recently, the 2006 Mozambique earthquake was estimated to have had a M_w=7.0 (Copley et al. 2012). M_w describes the size of an earthquake and is presented on a logarithmic scale. These are large earthquakes which have the potential to cause significant damage.

To evaluate the performance of a geotechnical structure against the shaking caused by an earthquake, a seismic assessment is usually required.

Seismic assessments of earth slopes vary significantly in terms of scope and complexity. The simplest methods involve the use of indicator parameters to define the earthquake and slope characteristics and simple checks are then conducted, usually validated against a few known case histories. The most rigorous methods on the other hand, typically involve nonlinear deformation analyses where complex soil constitutive models are used to model the seismic soil response (e.g. Fell et al. 2015).

Although the more advanced methods typically yield more accurate results, they are generally far more costly and time-consuming to implement and the benefit of such improved accuracy is generally not worth the additional effort. This is especially true where loss of life or significant environmental or infrastructure damage is not of a concern. A pragmatic approach that is typically followed is to start with the simpler methods as they are quick to implement. Based on the outcome of these assessments, a decision can be made whether or not to pursue a more rigorous method (e.g. Bray 2024). This paper focuses on simplified procedures to estimate deformations induced by shaking caused by earthquakes.

2 SIMPLIFIED SEISMIC SLOPE DISPLACEMENT PROCEDURES

2.1 Overview

A key limitation to the use of simplified seismic slope displacement procedures is that they have traditionally not been able to capture the effect of both volumetric-induced and deviatoric-induced displacements. In addition, early simplified procedures were often criticised for being overly conservative (e.g. Tokimatsu & Seed 1984).

However, recent procedures have been proposed which, when used in combination, are capable of capturing both the volumetric and deviatoric components of earthquake-induced displacement. By leveraging the information available in large open-access seismic databases, such as those collated by the Pacific Earthquake Engineering Research Centre (PEER), the accuracy of these methods has also been significantly improved.

In this section, two simplified seismic slope displacement procedures are discussed. The first procedure is used to estimate volumetric-induced displacements and the second procedure is used to estimate deviatoric-induced displacements.

It is important to distinguish between these two type of seismic displacement (deformation) as the slope movements resulting from deviatoric straining within the sliding mass (deviatoric-induced displacements) are mechanistically different to the slope movements resulting from volumetric compression of the materials forming the slope (volumetric-induced displacements) (e.g. Bray 2007).

Due to these fundamental differences, it is recommended that these two displacements are evaluated independently and that their individual calculated displacements be summed. This is in line with the recent recommendations of the Montana Department of Natural Resources and Conservation's state guidelines on the simplified seismic analysis procedure for Montana dams (DNRC 2020).

2.2 Procedures to estimate volumetric-induced displacements

In earthquake engineering, volumetric-induced displacements are sometimes referred to as seismic compression which is defined as the accrual of contractive volumetric strains in an unsaturated soil during strong shaking from earthquakes (e.g. Stewart & Whang 2003).

A simplified procedure to estimate seismic compression was initially proposed by Tokimatsu & Seed (1984). This procedure was developed strictly for clean sands under both saturated and unsaturated conditions.

The procedure proposed by Stewart & Whang (2003) offers an improvement on the Tokimatsu & Seed (1984) procedure. The updated procedure includes recent developments in the field of earthquake engineering, as well as specifically incorporates the behaviour of nonplastic silts and low plasticity clays. This method was validated against known case histories.

2.3 Procedures to estimate deviatoric-induced displacements

Deviatoric, shear deformations can either be rigid body slippages along a distinct failure plane or distributed deviatoric shearing within a deformable sliding mass (e.g. Bray 2007). Most methods to estimate deviatoric-induced displacements are based on the sliding block model proposed by Newmark (1965). These analyses are typically referred to as "Newmark-type" procedures in the literature.

With the improvement of global seismograph networks in recent years, there have been several extensive ground motion datasets developed around the world. For example, the PEER strong motion database currently contains over 29 000 records from 81 earthquake events and 1379 recording stations in Central and Northern America alone (UCB 2025).

Despite its size, a key limitation to this dataset is that is does not include associated measured soil structure displacements. This limitation was addressed by Travasarou (2003), who created a database of estimated displacements for the associated ground motions. This displacement database was used by Bray & Travasarou (2007) to develop a simplified procedure to estimate the shear-induced displacements.

Bray & Macedo (2019) improved on the Bray & Travasarou (2007) procedure in a few key aspects. The first was the size of the ground motion database that was used to develop the procedure. While the Bray & Travasarou (2007) procedure considered 600 ground motions, the Bray & Macedo (2019) procedure considered over 6 000 ground motions.
Although this dataset is larger, the authors' wish to point out the significant scatter in the dataset.

Figure 1 shows the relationship between the spectral acceleration (S_a) at 1.3 times the initial fundamental period (T_s) and the seismic displacement, as used in the development of the Bray & Macedo (2019) simplified procedure. It is clear that the scatter in the data is significant.

The second aspect involved the nonlinear coupled sliding block model, which was updated with a modification proposed by Bray et al. (2018). Finally, the period at which the spectral acceleration was selected was modified to better reflect the amount of site degradation.

The performance of the method was validated against a separate database to that used to develop the procedure. The validation database comprised both recorded ground motions and recorded soil structure deformations for several case histories, including earth dams and solid waste landfills.

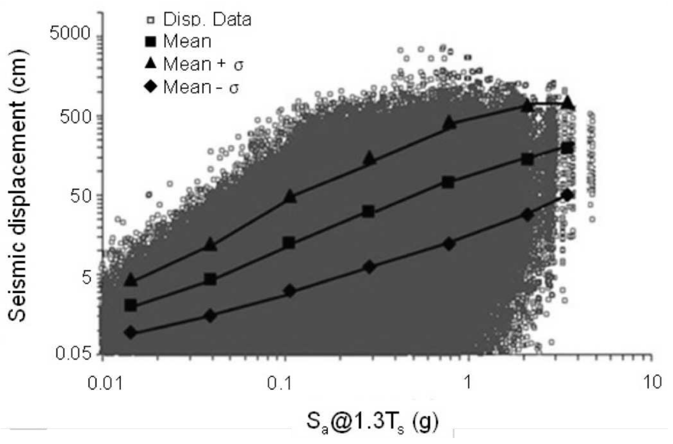

Figure 1. Indication of scatter in the seismic displacement database (after Bray & Macedo 2019)

3 SEISMIC HAZARD MAPS

3.1 Published datasets

The Global Seismic Hazard Assessment Program (GSHAP) was designed to assist in global risk mitigation by providing a useful global seismic hazard framework (Shedlock et al. 2000). This framework has become known as the "Shedlock criteria" and relies on the calculated Peak Ground Acceleration (PGA) for a return period of 475 years to classify the seismic hazard of an area as either low, moderate, high or very high. This recurrence period is equivalent to a 10 percent probability of exceedance in 50 years. Areas with high to very high hazard classifications are of most concern regardless of where they occur while areas with a moderate hazard are of a concern when they are in areas of dense populations or old infrastructure. Areas with a low hazard are of a lesser concern.

In terms of civil engineering design in South Africa, the South African National Standard (SANS) 10160 provides a national seismic hazard map for the horizontal PGA for a return period of 475 years (SABS 2017). This map provides contours of PGA overlain on a map of South Africa showing the provincial borders. These contours have increments of 0.025g.

This national seismic hazard map was recently updated by Midzi et al. (2020) to include more reliable seismicity and geological data. A particular effort was made to incorporate seismic source zones in the hazard map. This map also provides contours of horizontal PGA on a map of South Africa showing provincial borders. In this case, the contours are shown in non-linear increments ranging from 0.005g to 0.06g.

An alternative seismic hazard map is that developed by the Global Earthquake Model (GEM) foundation. This hazard map was created by collating maps computed using national and regional probabilistic seismic hazard models developed by various institutions in collaboration with GEM foundation scientists and is accessible via a web-based application (https://maps.openquake.org/map/gshm-2023-1/#3/32.00/-2.00) (Johnson et al. 2023). Using the map, the PGA for a return period of 475 years can be calculated for region of approximately 10 kmx10 km, almost anywhere in the world.

3.2 Comparison of hazard maps

To provide an example of how these datasets can be used, two sites in South Africa were selected. The first site is the conference venue (Protea Hotel Umhlanga) and the second site is the Merriespruit Tailings Dam 4. The three previously mentioned datasets were used to estimate the PGA for a return period of 475 years. In addition, the seismic hazard was determined using the Shedlock criteria (Shedlock et al., 2000). These values are summarised in Table 1. It can be seen that although the PGA values do vary between the methods, the seismic hazard classification is consistent across all three sources. Based on the size of the dataset used to develop the model, the Johnson et al. (2023) seismic hazard map is suggested for use if no additional information is available.

Table 1. Summary of PGA values and associated seismic hazard classifications after Shedlock et al. (2000)

Location	PGA for a return period of 475 years		
	SABS (2017)	Midzi et al. (2020)	Johnson et al. (2023)
Protea Hotel Umhlanga	0.050 low hazard	0.020 low hazard	0.025 low hazard
Merriespruit Tailings Dam 4	0.175 moderate hazard	0.100 moderate hazard	0.175 moderate hazard

4 PROBABILISTIC SEISMIC HAZARD ASSESSMENTS

Several key inputs in the simplified seismic displacement methods are derived from Probabilistic Seismic Hazard Assessments (PSHAs). These are studies that investigate the seismic setting of the site under consideration. The outcome of a PSHA is a series of hazard curves which define the average PGA for various return periods. These hazard curves can then be used to generate other relevant seismic curves for the site. For example, damped elastic response spectra curves, which are used directly in some design applications such as Eurocode 8 (CEN 2004).

Most modern PSHAs follow the "Cornell-McGuire" procedure (Cornell 1968; McGuire 1976, 1978). These studies are generally desktop studies supplemented by some field work. In particular, the estimation of the average shear wave velocity in the first 30 m below ground level (V_{s30}) usually requires some field testing to determine. This parameter is required to perform a convolution analysis of the accelerations calculated at bedrock, transmitted to surface.

Interestingly, there has been significant work in the field of estimation of V_{s30} values using satellite data (e.g. Wald & Allen 2007). These estimation techniques relate the slope in the topography to the V_{s30} of the underlying soil. A particular method has been implemented in the open access United States Geological Survey (USGS) global V_{s30} mosaic, which is an interactive web-based map where the V_{s30} value can be estimated for almost any location in the world (https://usgs.maps.arcgis.com/apps/webappviewer/index.html?id=8ac19bc334f747e486550f32837578e1) (USGS 2023).

The authors and their colleagues have reported remarkable correlation between field measured values and the values presented in this dataset where comparisons have been made. Therefore, a first estimate of the PSHA can almost completely be conducted as a desktop study.

For an example of a typical PSHA study for a South African setting, the PSHA conducted for the proposed Thyspunt nuclear power plant is a good reference. This document is publicly available (Bommer et al. 2015).

5 IMPLEMENTATION OF SIMPLIFIED SEISMIC SLOPE DISPLACEMENT PROCEDURES

5.1 Parameters required

Table 2 provides an overview of the parameters required to implement the simplified seismic displacement procedures. For each parameter, a description of the parameter is provided, as well as some guidance on how the parameter can be obtained.

5.2 Suggested workflow

The following workflow is recommended where the displacements caused by shaking induced by the design earthquake is of interest:

1. Determine the seismic hazard classification of the site.
   a. Determine the PGA for the 475-year return period event. The web-based GEM model can be used (Johnson et al. 2023).
   b. Classify the site according to the Shedlock criteria (Shedlock et al. 2000).
2. Determine the volumetric-induced deformation. The Stewart & Whang (2003) procedure can easily be implemented in a spreadsheet.
   a. Determine the horizontal PGA at the base of the fill ($PHA_{surface}$). This value is obtained from the PSHA study.
   b. Select an amplification factor to calculate PGA at the surface of the fill. Observations by Stewart et al. (2002) indicate that this amplification factor averages at around 2.0.
   c. Determine the average shear wave velocity of the fill material ($V_{s(fill)}$).
   d. Determine the density of the fill material (ρ_{fill}).
   e. Determine the height of the fill (H).
   f. Determine the Plasticity Index of the fill (PI_{fill}).
   g. Determine the M_w of the design earthquake. This value is obtained from the PSHA study.
   h. Use Figure 4 and Figure 5 from Stewart & Whang (2003) to determine the volumetric strain at 15 equivalent cycles ($(\varepsilon_v)_{N=15}$) and the volumetric strain ratio (C_N).
   i. Follow the procedure described by Stewart & Whang (2003) to determine the volumetric-induced strain due to earthquake shaking.
3. Determine deviatoric-induced deformations. To implement the Bray & Macedo (2019) and Macedo et al. (2023) procedures, an open-access spreadsheet is available on Professor Bray's webpage on the University of Berkeley website (https://ce.berkeley.edu/people/faculty/bray).
   a. When using the spreadsheet, the "case" needs to be selected. For South African conditions, the "Ordinary GM (EQ2&3)" option is the most appropriate. Pulse-like earthquakes are not common in South Africa. Subduction earthquakes, which are relevant in many countries in South America due to their proximity to known geological faults, are not relevant in South Africa.
   b. Determine the seismic slope yield coefficient (k_y). A limit equilibrium slope stability analysis is required.
   c. Determine the initial fundamental period (T_s). As recommended by Bray (2007), this can be calculated based on H and $V_{s(fill)}$.
   d. Determine the spectral acceleration at 1.3 times the initial fundamental period ($S_a(1.3T_s)$). This can be obtained from the PSHA study.
   e. Determine the M_w of the design earthquake. This value is obtained from the PSHA study.
   f. Extract the calculated deviatoric-induced displacement as calculated within the spreadsheet.
4. Sum the calculated volumetric- and deviatoric-induced displacements to determine a total estimated seismic displacement caused by the design earthquake.
5. Compare the calculated displacement to the embankment performance requirements (i.e. available freeboard) and determine whether additional seismic assessments are required.

Table 2. Common parameters required to implement the simplified seismic slope displacement procedures

Parameter	Description	Typical source
PHA_{fill}[1]	Peak Horizontal Acceleration (PHA) at the surface of the fill	The PHA at the ground surface is generally determined from a PSHA study. This value is then amplified to determine the PHA at the surface of the fill.
$V_{s(fill)}$[1,2]	Average shear wave velocity of the fill material	Field measurements such as the Seismic Cone Penetration Test with pore pressure measurements (SCPTu) or geophysical methods such as Multichannel Analysis of Surface Waves (MASW) techniques.
$\rho_{(fill)}$[1]	Average bulk density of the fill material	Generally assumed, can also be estimated from field tests such as the SCPTu or sand replacement/nuclear density tests.
M_w[1,2]	Moment magnitude of the design earthquake	PSHA study.
$H_{(fill)}$[1,2]	Height of the fill	Determined by surveys.
$PI_{(fill)}$[1]	Plasticity Indec of the fill	Determined by performing Atterberg limit tests on the soil.
Case[2]	Choice of scenario to be assessed: ordinary, pulse-like or combined	Relevant to the workbook downloadable from the UC Berkley website. Ordinary ground motions appear to be appropriate for most South African cases.
k_y[2]	Seismic slope coefficient, also referred to as the yield coefficient	Determined as the horizontal acceleration required to obtain a calculated FoS of 1.0 in a limit equilibrium analysis.
T_s[2]	Initial fundamental period	Can be estimated using $H_{(fill)}$ and $V_{s(fill)}$. For 1D structures T_s=4H/V_s for 2D structures, T_s=2.6H/V_s as suggested by Bray (2007).
$S_a(1.3T_s)$[2]	Spectral acceleration, S_a at 1.3 times the initial fundamental period, T_s	PSHA study. The 5% damped Uniform Hazard Response Spectra for the design earthquake is commonly used.

[1] Required to implement the Stewart & Whang (2003) procedure
[2] Required to implement the Bray & Macedo (2019) procedure

6 CONCLUSIONS

South Africa is generally considered a region of low seismicity. However, many recent international standard and guideline documents require that the seismic performance of earth structures be assessed, sometimes for large recurrence interval events. Although rigorous nonlinear deformation analyses are considered to provide the most accurate results, these

assessments require detailed knowledge of the seismicity of the area as well as the soils under consideration, information which is not readily available for many sites in South Africa. In these cases, simplified seismic slope displacement procedures can be implemented as a screening tool.

Simplified seismic slope displacement procedures have improved significantly over the years. Early simplified methods were often criticised as being overly conservative and unable to capture the influence of volumetric and deviatoric strains. In this paper, two modern simplified seismic slope displacement methods were discussed, specifically those proposed by Stewart & Whang (2003) and Bray & Macedo (2019). The following was concluded:

- Modern simplified seismic slope displacement procedures are capable of capturing both the volumetric and deviatoric-induced displacements due to earthquake shaking.
- Modern simplified seismic slope displacement procedures are not overly conservative and can provide reasonably accurate estimates, as validated against known case histories.

A typical workflow describing the process that could be followed to estimate the permanent displacements caused by seismic events was then presented. The workflow results in a seismic hazard classification of the site according to the Shedlock criteria (Shedlock et al. 2000), as well as an estimate of the total permanent displacement that would be caused by the shaking induced by the design earthquake. These parameters can then be used to inform whether additional analyses are necessary.

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