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EVALUATION OF ANALYTICAL PROCEDURES FOR ESTIMATING SEISMICALLY INDUCED PERMANENT DEFORMATION IN SLOPES

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TECHNICAL ABSTRACT

Recently, attention has been focused on the development and refinement of analytical procedures for estimating seismically induced permanent deformations in landslides and earth structures. The continued evolution of these procedures has led to a significant amount of confusion in the seismic hazard community that has centered mainly on issues of method applicability, accuracy and validity. The objective of this research project is to systematically assess the accuracy and applicability of several analytical procedures used to predict seismically induced deformations by validating these methodologies against a series of well-documented case histories. A database of thirteen of earthquake-induced landslide and earth-structure deformation case histories has been developed, ranked and evaluated for data quality. A new limit-equilibrium approach based on Spencer's method that will be used to directly estimate the seismic coefficient is discussed. Since the nature of this work relies heavily on computational methods, a several analyses were performed to using a series of simple homogeneous slopes in order to establish baseline trends of dynamic response and calculated deformations using rigid sliding-block and decoupled methods.

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NON-TECHNICAL SUMMARY

Continued development and refinement of analytical procedures for estimating seismically induced permanent deformations in landslides and earth structures has resulted in a considerable amount of confusion in the seismic hazard community. Of particular concern are issues of method applicability, accuracy and validity. Using a series of well-documented case histories of actual earthquake-induced landslides it is possible to evaluate the accuracy, applicability and overall validity of these analytical procedures used to predict deformations. A series of analyses on several simple slopes were performed to gain insight into several important issues related to the deformation-based methods and the computational tools used in their calculation.

INTRODUCTION

In recent years considerable attention has been focused on the development and refinement of analytical procedures for estimating seismically induced permanent deformations in slopes and embankments. Today, practitioners and researchers have an array of increasingly sophisticated deformation-based analytical procedures from which to choose when assessing the seismic stability of slopes. While the ongoing development, evolution and refinement of these analytical procedures offer many obvious benefits to the seismic hazard community, this has also led to a significant amount of confusion among practitioners and researchers trying to select an appropriate method of analysis. The accuracy of analytical procedures long thought to be reliable is now being called into question by some investigators. Moreover, procedures seen as acceptable by some regulatory agencies, which must often provide approval of seismic analyses, are considered objectionable by others. Some of the current deformation-based analytical procedures have been compared with small-scale laboratory tests, and in a limited number of instances, individual case histories. However, no one has systematically assessed the accuracy and applicability of these procedures by comparing predictions from a large number of slope deformation procedures against a database of well documented case histories of earthquake-induced deformations in actual slopes.

The current state of the practice for assessing seismically-induced deformations in slopes and embankments relies on one or more procedures that generally fall into three categories:

- *Rigid sliding block-type procedures*, which neglect the dynamic response of slopes;
- *Decoupled procedures*, which account for dynamic response, but "decouple" this response from the sliding response of slopes;
- *Coupled procedures*, which "couple" the dynamic and sliding response of slopes.

OBJECTIVES

This research aims to assess the accuracy and applicability of the analytical procedures used to predict seismically induced deformations by validating these methodologies against well-documented case histories. The principle goal of this research is to:

1. Systematically analyze a series of well documented earthquake-induced landslide case histories using a suite of deformation based analysis procedures.
2. Compare the actual "field" deformation measurements with those predicted by the analytical procedures.
3. Assess reliability and accuracy of each method using robust statistical analyses.
4. Develop recommendations for research and practice regarding the selection of an appropriate method (or methods) for performing these types of analyses.

This project was originally proposed as a two-year study and received first year funding (04-HQGR 0165) from the USGS National Earthquake Hazard Reduction Program (NEHRP). The first year effort began on September 1, 2004 and continued through October 1, 2005. At this time, second year funding has been secured and work will resume on January 1, 2006 and continue for one year.

INVESTIGATIONS UNDERTAKEN

This report covers the first year research efforts that began on September 1, 2004 through October 1, 2005. During this period the following tasks have been accomplished:

1. Review of available literature on earthquake-induced deformations and collection of case histories.
2. Validation of a pseudostatic slope stability method to directly estimate the yield seismic coefficient (k_y).
3. Benchmarking of several deformation-based analysis methods using a "simple, homogeneous slope."

The following sections present a brief discussion of the accomplished tasks. The first section presents the final selected case histories as well as a preliminary assessment of their overall quality. The second section presents a discussion of a new limit-equilibrium approach based on Spencer's method that will be used to directly estimate the seismic coefficient. The final section describes preliminary analyses that were performed to gain insight into several important issues related to the deformation-based methods and the computational tools used in their calculation.

RESULTS

Case History Development

A comprehensive literature review identified approximately 200+ published (journal or conference articles, professional reports) or unpublished references (e.g. consulting and inspection reports) pertaining to case studies of "coherent" (Keefer 1984) earthquake-induced landslides or earth structure movements. Case histories that had very large measured displacements (many meters), described evidence of liquefaction or rock-fall or earth-flow deformation mechanisms were excluded. The literature review was performed using several electronic databases. A cursory review found that 150 of these references included significant discussion of one of more field case-studies of earthquake-induced landslides. These references were read in detail and ranked according to the quality and quantity of their data. The results were tabulated and about 13 of the best quality case histories were identified for subsequent analyses (Table 1).

TABLE 1 – Selected Case Studies of Earthquake-Induced Landslides

Landslide & (Earthquake Event)	*Main References*	*Cross-Sections*	*Field Testing*	*Lab Testing*	*Dynamic Soil Properties*	*Earthquake Ground Motion*	*Deformation Measurements*
Villa Del Monte Landslide (Loma Prieta)	**9, 10, 13, 14, 15**	●	●	●	○	⦿	●
Upper Schultheis Road Landslide (Loma Prieta)	**1, 8, 9, 13**	●	●	⦿	○	⦿	●
Upper Laurel Landslide (Loma Prieta)	**1, 2**	●	●	⦿	○	⦿	●
Ditullio Landslide (Loma Prieta)	**1, 2**	●	●	⦿	○	⦿	●
Calabasas Landslide (Northridge)	**18**	●	●	●	●	⦿	●
Coyote Lake Slope Failure (Coyote Lake)	**24**	●	○	⦿	○	⦿	●
Fourth Avenue Slide (Prince William Sound)	**21, 22, 25**	●	●	●	○	⦿	●
Romig Hill Landslide (Prince William Sound)	**21**	●	●	●	○	⦿	●
Gav-Khosh Landslide (Manjil)	**11**	●	●	●	○	⦿	●
Nikawa Slide (Kobe)	**12, 19, 20**	●	○	●	○	⦿	●
La Villita Dam (Mexico City)	**3, 4, 7 23**	●	●	●	○	●	●
La Infiero Dam (Mexico City)	**3, 4**	●	●	●	○	●	●
Sürgü Dam (Malatya)	**16, 17**	●	●	●	●	⦿	●

● - Present or "High Quality" ⦿ - Present or "Fair Quality" ○ - Not Present or "Poor Quality"

The selected case histories include a variety of slopes and embankments in both natural and anthropogenic soil shaken by several different earthquakes. Thus, bias to a particular type of slope or seismic event does not exist. The selected case histories generally have excellent quality topographic information and deformation measurements and generally have a good to fair definition of the index and strength properties of the soil materials. Most of the sites lack direct measurement of dynamic soil properties (i.e. shear wave velocity, v_s), which is a required input for the more sophisticated analysis procedures. Typically, soil property evaluation for the case history sites is in the form of subsurface exploration and/or laboratory testing programs. However the quality of these programs as well as the quantity of information reported varies greatly. To address these issues, probabilistic approaches will be adopted in order to treat these uncertainties in a formal, consistent and quantitative manner. Although it is rare that an earthquake ground motion was recorded directly at the landslide site, each of the case studies involve events that are generally well recorded and therefore make it possible to deterministically estimate site-specific motions with a reasonable degree of confidence.

The case history data ratings in Table 1 are presented here as qualitative assessments for brevity. "High quality" implies, where appropriate, that a sufficient quantity of data was obtained in a professional manor using recognized test methods; "Fair quality" refers to, for example, to situations where data parameters are reported in text but not shown. Refer to Appendix A at the end of the document for a numbered reference list of the selected case histories. Appendix B contains the complete reference database.

Pseudostatic Analysis for Yield Seismic Coefficient

All deformation-based procedures (with the exception of coupled method) require that the yield seismic coefficient (k_y) be estimated. Procedurally the determination of the yield seismic coefficient is iteration-based (trial and error) where various assumed values of horizontal acceleration are applied in an incremental fashion to the center of mass of the slide mass. The smallest value that reduces the factor of safety to unity is taken as (k_y).

The major disadvantage involved in the estimation of k_y lies in the fact that the procedure is iteration-based. If utilized in a probabilistic framework where the material properties (c, ϕ, γ etc.) are modeled as random variables and where numerous runs are necessary, estimating k_y in an iterative manner immediately becomes computationally burdensome. Research efforts by others in the area of probabilistic earthquake induced deformation analysis (e.g. Murphy and Mankelow 2004, Luzi et al. 2000, Refice and Capolongo 2002, Jibson 1993) have made significant assumptions to avoid this problem. Typically, researchers have used either one-dimensional infinite slope theory or a simplified expression for the seismic coefficient that is a function of the static factor of safety (FS) and the thrust angle of (α) of the slip surface (Newmark 1965).

Kim (2001) adapted Spencer's original two-dimensional limit-equilibrium formulation and subsequent work (Spencer 1967, 1973, 1978) to estimate the yield seismic coefficient k_y directly without iterations. Spencer's method is recognized as one of the more accurate limit-equilibrium approaches (Duncan and Wright 1980) and due to its versatility has been recommended for usage in seismic hazard analyses (Blake et al. 2002). The computing efficiency of this method is equivalent to traditional factor of safety evaluations and thus facilitates integration into a probabilistic framework (Kim and Sitar 2004). This more efficient limit-equilibrium method has been complied into a program called GLEM that was obtained with permission from Dr. Jinman Kim, an Assistant Professor of Civil Engineering at Pusan National University, Korea. Given any failure surface (circular or non-circular), GLEM can calculate either factor of safety or the yield seismic coefficient; the program does not perform a slip surface search.

A direct validation of the seismic coefficient estimation capability of GLEM cannot be performed on a large scale since commercially-available slope stability software packages only offer an iteration-based procedure to estimate the yield seismic coefficient. Thus, a series of straightforward and well defined "benchmark" slopes were developed in order to validate the GLEM program on a case-by-case basis. SLIDE (v.5), a two-dimensional limit-equilibrium slope stability package developed by Rocscience, Inc., was used to compare against GLEM. Originally defined in Loukidis et al. (2003) and subsequently modified, these four (4) benchmark cases are simple, homogeneous slopes with a slope angle of 30° and a height of 20 meters (Figure 1). The slope materials are broadly classified as: frictional-cohesive, purely frictional and purely cohesive. The pseudostatic surfaces (all circular), that are classified as either a shallow toe surface, slope failure surface or

base failure surface. An excellent match was obtained between SLIDE and GLEM. For the static factor of safety, GLEM yields values that were within 1% of static factor of safety value obtained with SLIDE. For the yield seismic coefficient, GLEM yields values that are within 1 to 4% of the values obtained using SLIDE.

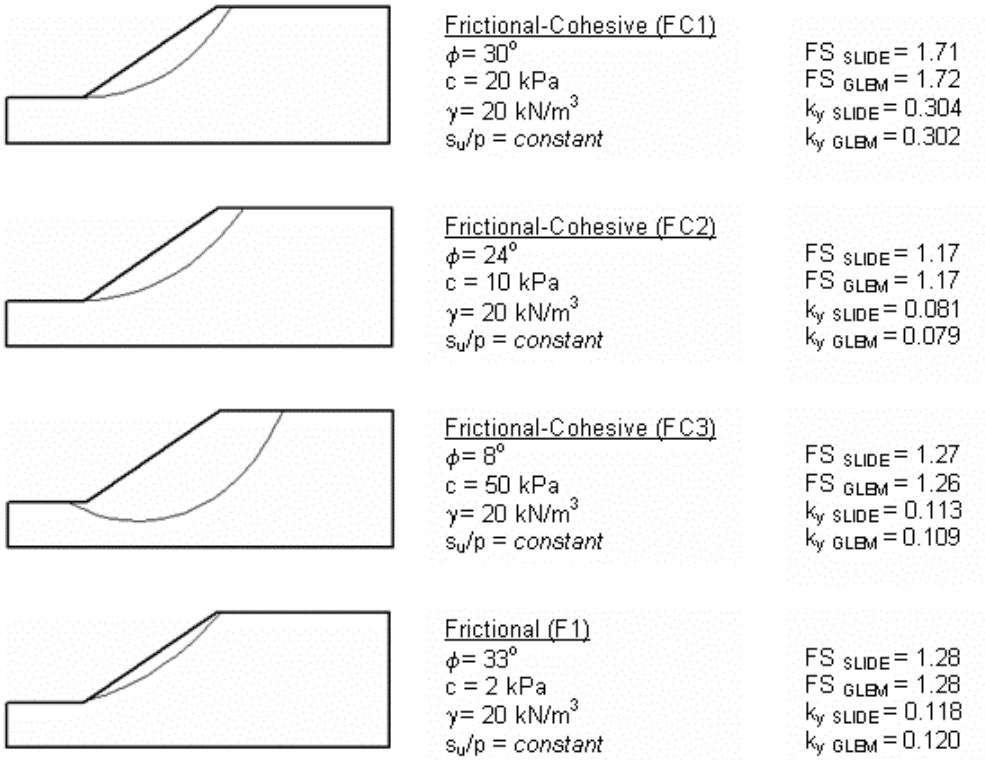
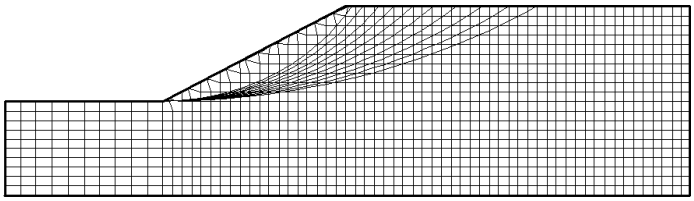


FIGURE 1 – Benchmark Slopes (based on Loukidis et al. 2003) – Case-by-Case Pseudostatic Analysis

Analysis Method Benchmarking

The deformation-based analysis methods and computational tools used in this study were carefully evaluated using the "benchmark" slope described above. The tasks include three parts: (1) validation of the two-dimensional horizontal equivalent acceleration (HEA) time history methodology, (2) evaluation and validation of dynamic response and (3) benchmarking of deformation-based procedures.

The geotechnical software package FLAC (Fast Lagrangian Analysis of Continua) (Itasca 2005) was selected to perform the seismic demand analysis associated with the two-dimensional decoupled procedure. The Chopra (1966) methodology (see the equation in Figure 2) for estimating the HEA time history is implemented as built-in routines in QUAD4M (Hudson et al. 1994) and TELDYN (Pyke 1992). Thus in selecting FLAC, validation of this methodology was required. Validation was performed using the simple benchmark slope (case FC1) and calculating two-dimensional HEA time histories for a series of different slip surfaces (Figure 2) using a simple ramped sine motion.



$$F_T(t) = \sum_{i=1}^{n} \sigma_h^i(t)\,\Delta h + \tau_h^i(t)\,\Delta w$$

$$HEA(t) = \frac{F_T(t)}{W}$$

FIGURE 2 – FLAC Mesh and Slip Surface Array Used in Validation of the Chopra (1966) Methodology

Comparisons were made against the HEA time histories obtained from TELDYN. For the purposes of equivalency, the FLAC model used degraded shear modulus values (based off of preliminary dynamic response runs using TELDYN) and a Rayleigh damping scheme. The Chopra (1966) procedure was successfully

implemented in FLAC and an excellent match was obtained between the two programs. On average, a 3% error was calculated for the k_{max} (i.e. peak of the HEA time history) between FLAC and TELDYN.

For the dynamic response portion, FLAC was compared to the traditional linear-equivalent codes SHAKE91 (Idriss and Sun 1992, Schnabel et al. 1972) and TELDYN. The linear-equivalent dynamic response codes use an "iteration-based" computational scheme where the motion is passed through the model multiple times to approximate the hysteretic strain-dependent behavior of the soil. In FLAC, the hysteretic behavior is approximated more realistically using a "time-based" computational scheme where the modulus reduction and material damping are approximated in "each element at each time step" for a single passage of the motion through the model. A suite of 20 motions was developed for the analysis (16 sine motions and 4 earthquake recordings). The sine motion suites were developed with systematically varied PGA (0.1g to 0.6g) and mean-square frequencies (f_m) (1.25 Hz to 6.0 Hz). For all of the motions considered, FLAC with its time-based hysteretic damping logic generally produced a higher dynamic response in comparison to SHAKE91 and TELDYN. Typical dynamic response results for a recorded earthquake motion are shown in Figure 3 below. This difference was attributed to the very different computational scheme used in FLAC. Despite this, a very favorable match between the TELDYN and FLAC was obtained.

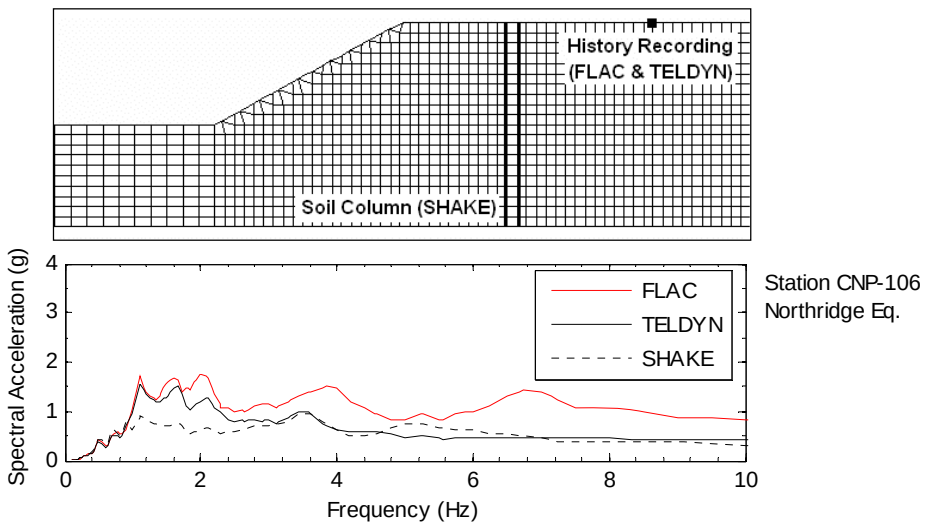


FIGURE 3 – Typical Dynamic Response Results - Benchmark Slope

The purpose of the final component was to identify and understand the trends in the calculated permanent deformations using a several different analysis methods and to see how they compare to trends established by other researchers (e.g. Bray et al. 1998, Rathje and Bray 1999). Three analysis methods were used: rigid sliding-block method (Newmark 1965, Jibson and Jibson 2003), 1-D decoupled method and 2-D decoupled method (Seed and Martin 1966, Makdisi and Seed 1978). For the decoupled methods, dynamic response was performed and HEA time histories were calculated using SHAKE91 and FLAC. These analyses were performed on the benchmark slope for cases FC2, FC3 and F1 using the 16 sine motions. The systematic variation of PGA and f_m for the 16 sine motions was used to evaluate the influence of these motion parameters on displacements trends calculated with different methods.

Project Publications

To date, no reports have been published regarding the results of this ongoing research project. It is anticipated that several publications will be generated from this work.

Data Availability

The complete reference database as well as the case history reference database is available from the authors in electronic format. The project Principal Investigator, Professor Joesph Wartman, can be reached via e-mail at joseph.wartman@drexel.edu.

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