Cloud-Based Tools for the Probabilistic Assessment of the Seismic Performance of Slopes

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ABSTRACT

The seismic performance of slopes is typically evaluated based on the sliding displacement predicted to occur along a critical sliding surface. A probabilistic assessment of sliding displacement can account rigorously for the aleatory variability in earthquake ground shaking and in the dynamic response and sliding displacement predictions, providing a more complete assessment of the risk associated with seismic slope failure. Rathje and Saygili (2008) developed probabilistic frameworks for the displacement hazard assessment of rigid sliding masses and Rathje et al. (2014) extended these probabilistic frameworks to deeper and/or softer sliding masses. This paper describes efforts to script the developed frameworks within publicly accessible, cloud-based Jupyter notebooks (www.jupyter.org). The developed Jupyter notebooks use as input the yield acceleration (k_y) and natural period (T_s) of the slope, and ground motion hazard information in terms of the hazard curve for peak ground acceleration (PGA) and the associated magnitude and distance deaggregations. The Jupyter notebooks are developed to interface directly with the U.S. Geological Survey Unified Hazard Tool such that the required ground motion hazard information can be input directly from the U.S. Geological Survey website. The developed Jupyter notebooks are available to the public as a published dataset within the Data Depot of DesignSafe (www.designsafe-ci.org), the cyberinfrastructure for the Natural Hazards Engineering Research Infrastructure (NHERI).

INTRODUCTION

The seismic performance of slopes is typically evaluated based on the sliding displacement predicted to occur along a critical sliding surface. This displacement represents the cumulative, downslope movement of a sliding mass due to earthquake shaking. The magnitude of sliding displacement relates well with observations of seismic performance of slopes (e.g., Jibson et al. 2000), and thus has been a useful parameter in seismic design and hazard assessment.

The magnitude of sliding displacement is strongly affected by the intensity, frequency content, and duration of earthquake shaking. Earthquake ground motions also display significant aleatory variability, yet current evaluation procedures for computing sliding displacement are based on a deterministic or a pseudo-probabilistic approach, in which the aleatory variability in the expected ground motion, dynamic response, and predicted displacement are either ignored or not treated rigorously (Rathje and Saygili 2011). Thus, there is no concept of the actual hazard associated with the displacement computed by the deterministic approach. A probabilistic assessment of sliding displacement can account rigorously for the aleatory variability in earthquake ground shaking and in the dynamic response and sliding displacement predictions, providing a more complete assessment of the risk associated with seismic slope failure. A probabilistic assessment of sliding displacement produces a displacement hazard curve, which provides the annual rate of exceedance for a range of displacement levels. This allows the engineer to predict the performance for a known hazard level, rather than simply identifying the design motion based on a specified hazard level and predicting a deterministic displacement.

Rathje and Saygili (2008) developed scalar and vector hazard approaches using displacement hazard curves to account for aleatory variability and later introduced a logic-tree analysis for slope properties to take epistemic uncertainties into account (Rathje and Saygili 2009). For the scalar probabilistic displacement procedure, the displacement hazard curve can be developed using the hazard curve for the single ground motion parameter (i.e. PGA). For the vector hazard procedure, the joint hazard curve for the two ground motion parameters (i.e. PGA and peak ground velocity, PGV) is required. This calculation is more exhaustive than calculating the scalar hazard curve, but the vector approach is important because the uncertainty in the predicted sliding displacement can be significantly reduced when multiple ground motion parameters are used. However, the work by Rathje and Saygili (2008) was based on a rigid sliding block analysis, which assumes the sliding mass is a rigid sliding block and ignores the dynamic response of deep/soft soil sliding masses. In essence, deeper and/or softer sliding masses subjected to earthquake motions behave as flexible bodies such that the rigid block model is not appropriate. Rathje et al. (2014) extended the aforementioned probabilistic frameworks to flexible sliding by characterizing the ground shaking through maximum seismic coefficient (k_{max}) and the maximum velocity of the seismic coefficient-time history ($k\text{-}vel_{max}$).

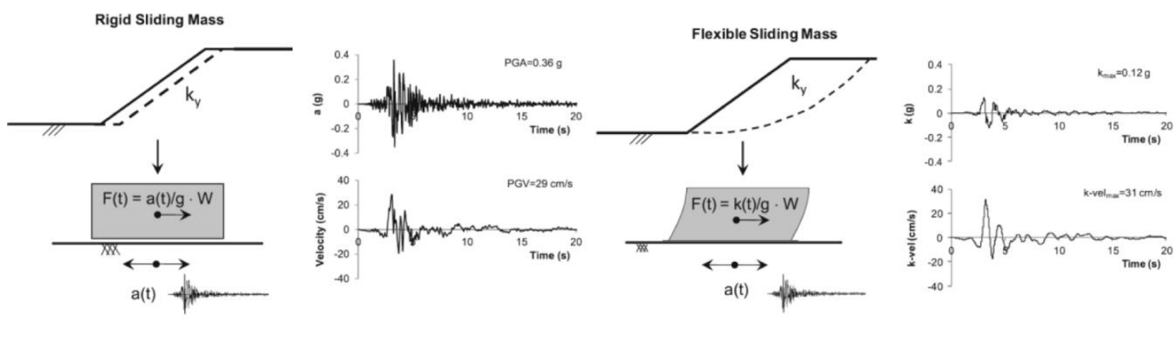
The DesignSafe cyberinfrastructure (www.designsafe-ci.org, Rathje et al. 2017) component of the NSF-supported Natural Hazards Engineering Research Infrastructure (NHERI) aims to address the data and computational needs of researchers by providing a cloud-based data repository and computational platform. This paper describes efforts to script the developed probabilistic displacement frameworks within publicly accessible, cloud-based Jupyter notebooks. The developed Jupyter notebooks are available to the public as a published dataset within the Data Depot of DesignSafe. The developed Jupyter notebooks use as input k_y and T_s of the slope, and ground motion hazard information in terms of the hazard curve for PGA and the associated magnitude and distance deaggregations. Importantly, the Jupyter notebooks are developed to interface directly with the U.S. Geological Survey Unified Hazard Tool such that the required ground motion hazard information can be input directly from the U.S. Geological Survey website. This paper first describes the main components of the probabilistic framework for predicting sliding displacements, and then demonstrates the implementation within the Jupyter notebooks.

SLIDING BLOCK DISPLACEMENT

Sliding displacements are commonly used to assess the seismic performance of slopes as they are simplified representation of the cumulative, downslope movement of a sliding mass due to earthquake shaking. The seismic coefficient that produces a factor of safety equal to 1.0 is called the yield acceleration (k_y), and it represents the "static force" that initiates sliding along a critical surface. To estimate sliding displacements, k_y of the sliding mass and the earthquake strong motion representing the seismic loading are required.

The dynamic response has a minor impact on the sliding displacements of shallow soil masses because the natural period of a thin soil layer is very small. Thus, shallow slope failures can be modeled as a rigid block sliding on a failure plane. In the rigid sliding block analysis, the seismic loading is represented by the acceleration-time history beneath the sliding base (Figure 1a). The ground motion parameters for the sliding displacement prediction are obtained from acceleration-time history or velocity-time history (e.g. PGA, PGV). However, the rigid sliding block assumption is not appropriate for deeper and/or softer sliding masses because the longer natural period of the sliding mass leads to a significant dynamic response (Figure 1b). For flexible sliding masses, the average seismic coefficient (k)-time history represents the seismic loading force due to the spatially variable accelerations within the sliding mass at any time (Figure 1b) and this time history is used in the sliding displacement calculation.

The sliding displacement of a rigid sliding mass can be calculated by numerical integration for the sliding episodes for a suite of recorded *a – t* histories. Alternatively, empirical models that use as input k_y and various ground motion parameters, such as PGA, PGV, Arias Intensity (I_a), can be employed to predict sliding displacement (D). For the calculation of the sliding displacement of a flexible sliding mass, k-time histories for the sliding mass are required. They can be obtained through a dynamic response analysis using a suite of recorded *a – t* histories as input. Next, each k-time history is numerically integrated for the sliding episodes. Alternatively, empirical predictive models can be used that predict the dynamic response (e.g., k_{max}, k-vel_{max}) and D of a sliding mass based on various ground motion parameters (e.g., PGA, PGV) and slope parameters (e.g., T_s, k_y).



(a) (b)

Figure 1. Seismic loading parameters for (a) rigid sliding masses and (b) flexible sliding masses

Many empirical models for sliding displacement have been published in the literature (e.g., Rathje and Antonakos 2011, Rathje and Saygili 2009, Saygili and Rathje 2008, Bray and Travasarou 2007, Jibson 2007). The Jupyter notebooks presented in this study use the vector (PGA, PGV) predictive model for the displacements of rigid sliding masses (Saygili and Rathje 2008) and the vector (k_{max}, k-vel_{max}) predictive model for the displacement of flexible sliding masses (Rathje and Antonakos 2011).

PROBABILISTIC FRAMEWORKS FOR SLIDING DISPLACEMENT

A probabilistic assessment of sliding displacement produces a displacement hazard curve, which shows the relationship between the sliding displacement levels (D) and its annual rate of exceedance, λ_D, (e.g., Yegian et al. 1991a and b, Ghahraman and Yegian 1996, Travasarou et al. 2004, Rathje and Saygili 2008, and Rathje et al. 2014). A displacement hazard curve allows the engineer to predict the performance for a known hazard level; for example, the sliding displacement associated with a 10% probability of exceedance in 50 years.

Calculating λ_D requires knowledge of the probability that a displacement level is exceeded given a ground motion level and the annual probability of occurrence of that ground motion level. The product of these probabilities is computed and then integrated over all levels of ground motion to compute λ_D. For rigid sliding masses using the vector (PGA, PGV) model, the calculation of $\lambda_D(x)$ is given by:

$$\lambda_D(x) = \sum_i \sum_j P[D > x | PGA_i, PGV_j] \cdot P[PGA_i, PGV_j] \quad (1)$$

where D is the sliding displacement, $P[D > x | PGA_i, PGV_j]$ represents the probability that D > x given ground motion levels PGA_i and PGV_j, and $P[PGA_i, PGV_j]$ is the joint annual probability of occurrence of ground motion levels PGA_i and PGV_j. The double summation represents integration and is performed over bins for both PGA and PGV. $P[PGA_i, PGV_j]$ is computed via vector PSHA (Bazzurro and Cornell 2002). It can also be computed from the output of a traditional PSHA. Additional information can be found in Rathje and Saygili (2009).

For flexible sliding masses, seismic loading parameters k_{max} and k-vel$_{max}$ are used for the construction of the displacement hazard curves (Rathje et al. 2014). For the (k_{max}, k-vel$_{max}$) displacement model, λ_D is computed by:

$$\lambda_D(x) = \sum_m \sum_n P[D > x | k_{max\,m}, k-vel_{max\,n}] \cdot P[k_{max\,m}, k-vel_{max\,n}] \quad (2)$$

Where $P[D > x | k_{max\,m}, k-vel_{max\,n}]$ is the probability that D>x given the occurrence of seismic loading levels $k_{max\,m}$ and $k-vel_{max\,n}$ and $P[k_{max\,m}, k-vel_{max\,n}]$ is the joint annual probability of occurrence of $k_{max\,m}$ and $k-vel_{max\,n}$. $P[D > x | k_{max\,m}, k-vel_{max\,n}]$ can be calculated by using the mean and standard deviation provided by the empirical displacement model for flexible sliding (e.g. Rathje and Antonakos 2011). $P[k_{max\,m}, k-vel_{max\,n}]$ is computed from the probabilities of occurrence for different PGA and PGV pairs (i.e., $P[PGA_i, PGV_j]$) and the probabilities of obtaining $k_{max\,m}$ and $k-vel_{max\,n}$ given PGA_i and PGV_j. Additional information can be found in Rathje et al. (2014). The correlation coefficient between k_{max} and k-vel$_{max}$ is estimated as 0.45 (Rathje and Antonakos 2011).

JUPYTER NOTEBOOKS FOR SLIDING DISPLACEMENT HAZARD ASSESSMENT

A Jupyter notebook (www.jupyter.org) is an electronic notebook that includes both rich text and computer code. Jupyter notebooks can be run on a local computer, but they can also be executed on the Jupyter Hub within the Discovery Workspace of DesignSafe. The DesignSafe Jupyter Hub supports the Python and R programming languages, and can access all files within the DesignSafe data repository, called the Data Depot. A key benefit of using a Jupyter notebook within the DesignSafe cyberinfrastructure is that the scripts can be published in the cloud in the Data Depot and easily shared with other researchers (Rathje et al. 2017).

The Jupyter notebooks are developed to interface directly with the U.S. Geological Survey Unified Hazard Tool such that the required ground motion hazard information can be pulled directly from the USGS website (https://earthquake.usgs.gov/hazards/interactive/). As displayed in **Figure 2**, the first set of input information required for the sliding displacement hazard assessment includes the coordinates of the site (i.e. Latitude and Longitude as decimal fractions), site class, and USGS Source (i.e. NSHM 2008 or 2014). These parameters are used to obtain the seismic deaggregation data for various return periods (i.e., hazard levels). Here, return periods are selected between 1 year and 20,000 years inclusive. These return periods must correspond with those available from the USGS Unified Hazard Tool.

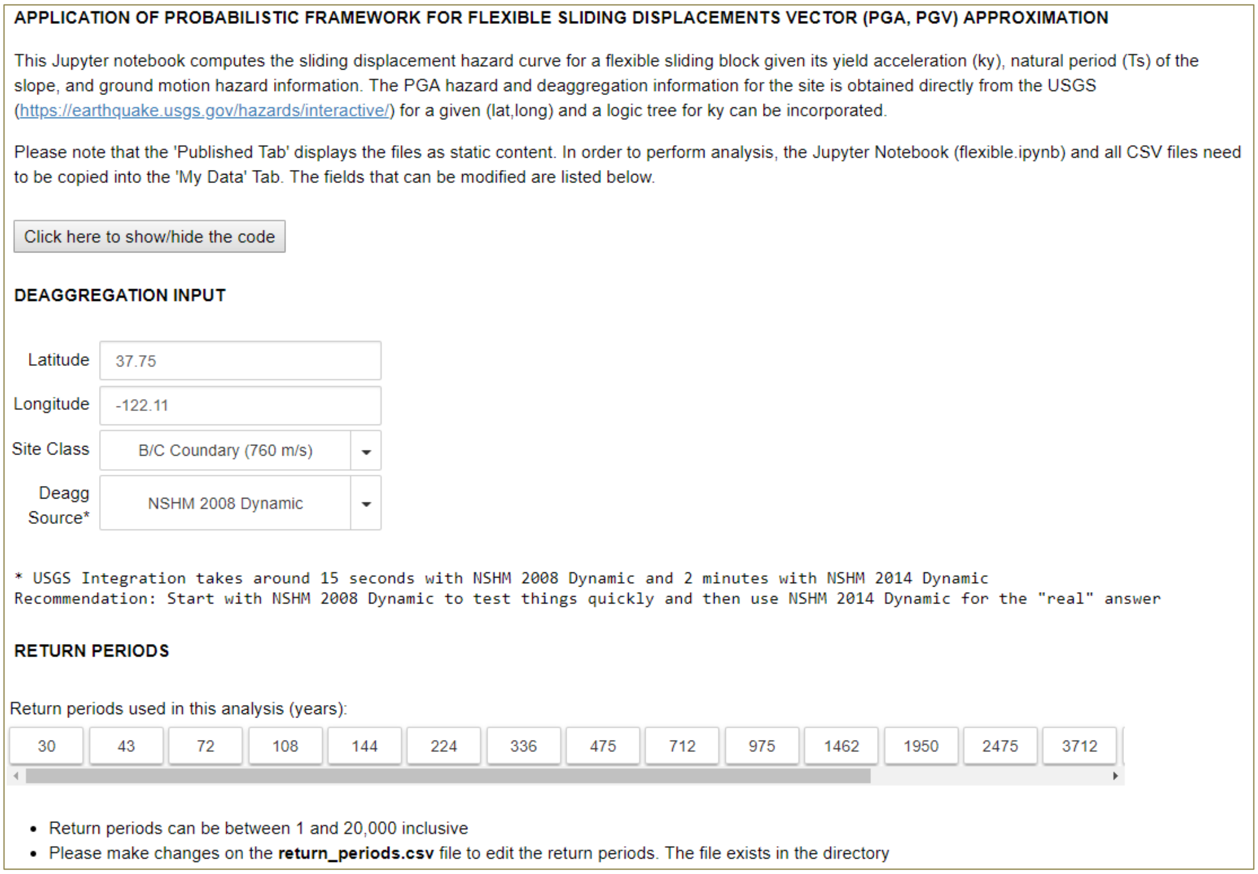


Figure 2. Screenshot of input parameters required to programmatically access the USGS deaggregation data

The notebooks first programmatically receive JavaScript Object Notation (JSON) of parseable seismic deaggregation data for various return periods and next convert raw deaggregation data (i.e., percent contribution for each magnitude (M), distance (R), and epsilon scenario) into a matrix of M and R bins by summing up the hazard contributions of all events in the same bin. The matrix of M and R bins is set in the notebook but can be revised by the user. The PGA for each return period from the seismic deaggregation data are used to plot the ground motion hazard curve (**Figure 3**). These PGA also are used as the PGA bins for which $P\left[PGA_i, PGV_j\right]$ are computed.

The next set of input required for the sliding displacement hazard assessment for rigid sliding masses is the PGV bins (in cm/s units) for which $P\left[PGA_i, PGV_j\right]$ are calculated, the correlation coefficient between PGA and PGV ($\rho_{PGA,PGV}$), and the logic tree parameters for epistemic uncertainty. The logic tree simply includes k_y branches and their associated weights. The required input parameters for flexible sliding masses are PGV bins, the k_{max} bins (in g units) and $k_{vel\text{-}max}$ bins for which $P[k_{max\,m}, k-vel_{max\,n}]$ are calculated, the correlation coefficients between PGA and PGV ($\rho_{PGA,PGV}$) and between $k_{max\,m}$ and $k-vel_{max\,n}$ ($\rho_{kmax,k-velmax}$), and logic tree for epistemic uncertainty in k_y, T_s, and the mean period of the earthquake motion, T_m.

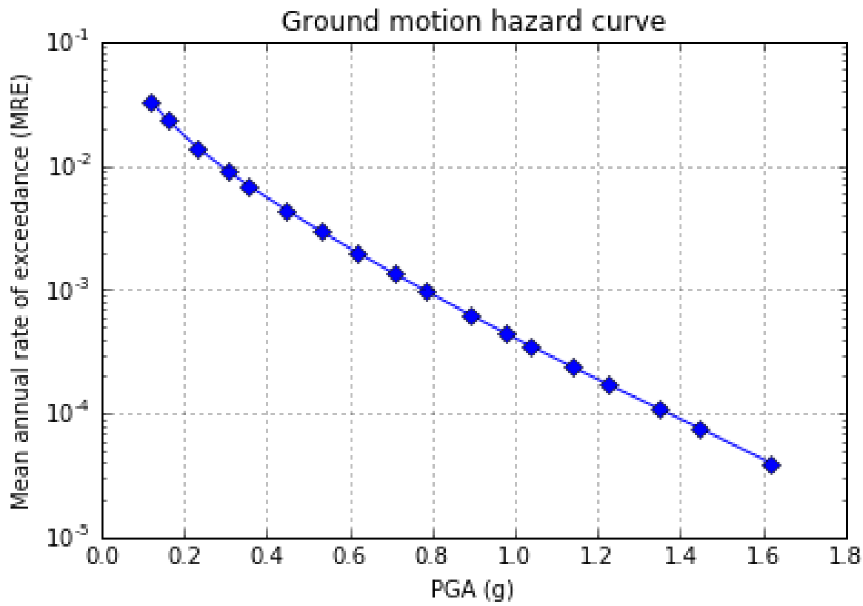


Figure 3. Ground motion hazard curve derived from data accessed from the USGS Unified Hazard Tool

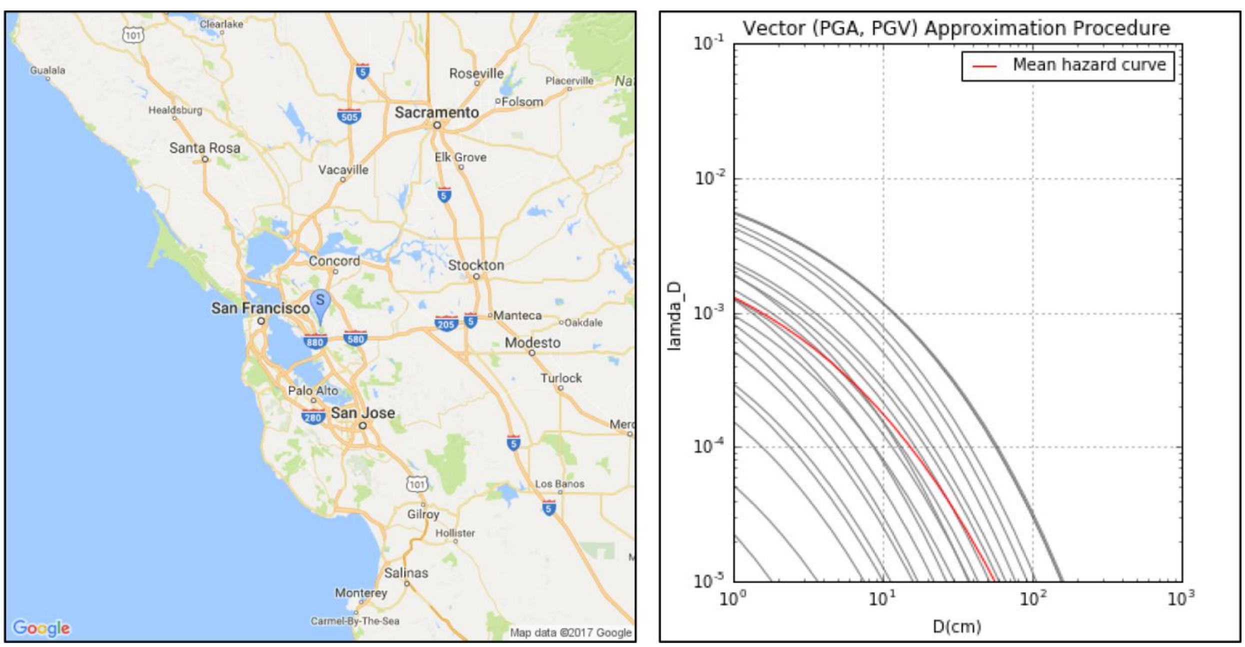


Figure 4. Example Jupyter notebook outputs; (a) site map and (b) displacement hazard curves

After providing the site location and various inputs described above, the Jupyter notebook output consists of a map showing the site location, which is rendered using the Google Maps URL Scheme, and the computed displacement hazard curves. Examples are shown in **Figure 4**. The displacement hazard curves for each branch of the logic tree are shown in gray and the mean hazard curve computed using the logic tree weights is shown in red. The displacement hazard curves also are saved as a CSV file. The user has the option to change the name of this output CSV file before the analysis.

The developed Jupyter notebooks for rigid and flexible sliding masses are publicly accessible within the Published section of the Data Depot of DesignSafe (Saygili et al. 2018a, b). The notebooks and associated files can be copied to the user's My Data space and used to perform analyses for a specific location and site-specific properties. Use of these Jupyter notebooks should be cited as Saygili et al. (2018a, b).

CONCLUSIONS

This paper describes the Jupyter notebooks developed for the probabilistic assessment of the seismic displacement of slopes. The Jupyter notebooks are developed for both rigid and flexible sliding masses, and they are written to interface directly with the U.S. Geological Survey Unified Hazard Tool such that the required ground motion hazard information can be pulled directly from the U.S. Geological Survey website. These cloud-based Jupyter notebooks are available to the public as a published dataset within the Data Depot of DesignSafe. One of the major advantages of the Jupyter notebooks over the conventional static object/files is that they allow the data as well as the scripts to be easily shared and edited among researchers. The Jupyter notebooks permit users to perform analyses for new site locations with a set of new parameters and permit users to modify the processing scripts to suit their specific needs.

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