GIS-based geotechnical seismic hazard screening tool

Outil de criblage de risques sismiques geotechiques basé sur le SIG

Andrew J. Wilding
URS Corporation

Ronaldo Luna
Missouri University of Science and Technology

ABSTRACT

Geotechnical earthquake engineering hazards have consequences that are difficult to mitigate, especially for infrastructure systems with multiple and distributed components. In the last few decades significant progress has been made to provide more accurate and useful methods to evaluate hazards for complex systems. This research developed a GIS methodology to be used as a "screening tool" to evaluate geotechnical earthquake engineering hazards from a database of borehole data and then display the results on a map. The methodology was customized within the GIS environment to calculate both the liquefaction potential and a ground motion magnification factor from borehole data and ground motion time histories, using well established procedures. The results are then displayed spatially for screening purposes, or manual inspection and analyses by the engineer. A pilot study was conducted for a series of boreholes along the highway system near Poplar Bluff, Missouri, using two different New Madrid seismic events. The results for this pilot study show that this type of screening tool could be advantageous for state and federal agencies responsible for earthquake resilient infrastructure systems.

RÉSUMÉ

Les risques géotechniques lies à la sismicité ont des conséquences difficiles à réduire, particulièrement pour les systèmes d'infrastructure avec des composantes multiples et distribués. Au cour des dernières décennies, des progrès considérables ont été accompli pour fournir des méthodes d'évaluation des risques associés aux systèmes complexes qui sont plus précises et utiles. Cette recherche a développé un outil de criblage de données basé sur le SIG afin d'évaluer les risques géotechniques lies aux séismes. L'outil utilise une base de données de forages, et présente par la suite les résultats sur une carte détaillée. La méthodologie proposée a été adaptée á l'environnement du SIG afin de calculer le potentiel de liquéfaction et un facteur d'amplification de mouvements de terrains, ceci a partir des données de forages et de l'historique des mouvements de terrains en utilisant des procédures bien établies. Les résultats sont présentés spécialement soit pour criblage ou pour inspection manuelle et analyses par l'ingénieur. Une étude pilote a été conduite á partir d'une série de forages le long des infrastructures autoroutières de Poplar Bluff, Missouri, utilisant deux événements sismiques différents de la région de New Madrid. Les résultats de cette étude démontrent que ce type d'outil de criblage pourrait être avantageux pour les états et agences fédérales en charge d'infrastructures résilients aux tremblements de terre.

Keywords : GIS, geotechnical engineering, earthquake engineering, screening tool

1 INTRODUCTION

In geotechnical earthquake engineering, it is common practice to run a site-specific response analysis as a way to obtain the ground motion at the ground surface and near structures. This is generally done using a computer program (e.g. SHAKE2000, DEEPSOIL, etc.) that will propagate the motion from the bedrock and through the soil column to a free field condition. While a site-specific approach is seen as most appropriate, it is time consuming and requires detailed site data and significant knowledge of geotechnical earthquake engineering. Therefore, it would be advantageous to have an application that allows the user to look at sites in a region and quickly asses the general geotechnical hazard potential of each and then decide which would most warrant a site-specific analysis. Incorporating this screening tool into a geographical information system where data could be viewed spatially would add significant usability for decision makers or agencies responsible for earthquake resilient infrastructure systems (Wilding 2008).

To demonstrate the usefulness of this type of application, a methodology was developed to assess potential geotechnical earthquake engineering hazards within a geospatial application, and a prototype version of this application was created to run within ArcGIS by ESRI™. The Spatial Seismic Screening Software (S4) was produced as a prototype screening application to demonstrate the evaluation of both the liquefaction potential and a magnification factor of ground motion within a GIS environment. The S4 application calculates the potential for these hazards from a database of borehole data and ground motion time histories and then displays the results on a map. Once the application was completed, a pilot study was completed to demonstrate the functionality of the application.

2 SOFTWARE DESIGN

To demonstrate the two selected seismic hazard analyses in a spatial screening application, a prototype tool (software application) named the Spatial Seismic Screening Software or S4 was created to operate within the ArcGIS 8.3 Desktop software group by ESRI. Before development of the software application could begin, several decisions had to be made as to the desired nature and purpose of the software. It was decided that, as the application would be designed as a screening tool to quickly identify seismically problematic areas, the intended user of this application would be an engineer or researcher with limited background knowledge of seismology and earthquake engineering. This may include a geological engineer or entry-level geotechnical engineer with

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limited seismological experience, or a geologist or seismologist with little engineering background. Similarly, due to its ability to quickly analyze complex distributed systems, this application may be of particular interest to engineers or geologists affiliated with state or federal agencies responsible for earthquake resilient infrastructure systems. As with the selection of the intended user, determination of the scale and resolution of the input and output, as well as the actual desired input and output parameters were critical to the design of the application, since the scale and detail that the application operates within greatly dictates the design and format for this application. After reviewing the seismic hazard analyses and considering the chosen user and their intended use, it was decided to pursue an application that utilizes engineering profiles from individual boreholes, and their associated measured data. Though there were many reasons for this decision, those of primary importance included accuracy and resolution of data without the need for averaging, independence of scale, practicality and ease of use.

To develop an application which operates within the ArcGIS 8.3 Desktop environment, three main categories of features are needed. The first of these is programming in Visual Basic for Applications (VBA), which is utilized by the ArcGIS environment to produce the code used to compute the actual algorithms and handle the data, as well as to call external 3rd party software routines (tools). Secondly, the graphical user interfaces, also developed within VBA, are what the user sees and uses to interact with the software. Finally, the ArcGIS interface allows the data and the VBA code to interact with the spatial environment for input and output purposes.

Once the scope of the application was determined, it became necessary to determine which methods of computation would be utilized for the seismic hazard analyses. For this application, two main seismic hazards are analyzed; (1) the magnification factor as a comparison of the predominant period of ground motion and the characteristic site period of the soil profile, and (2) the liquefaction potential as a factor of safety. Figure 1 summarizes the main features of the prototype application.

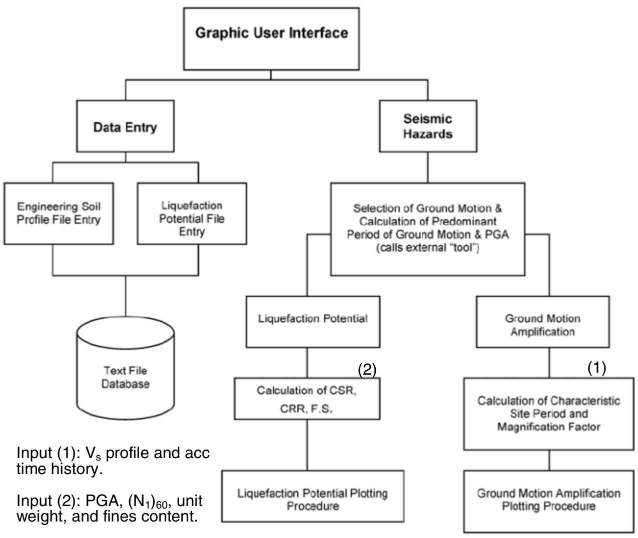

Figure 1. System architecture for prototype application (S4).

To compute the magnification factor, the soil column was treated as a linear elastic single-degree-of-freedom system and compared to the input ground motion with 5% damping (Kramer 1996). This required the computation of several parameters, including the characteristic site period and the predominant period of the ground motion. For computation of the characteristic site period, the standard equation for the site period, as derived by numerous investigators (Reid 1908; Jacobsen 1930) was employed. The site period calculation requires the input of the average shear wave velocity for the soil column. This value was calculated from measured shear wave velocities, using the method outlined in the International Building Code (2000), which uses a weighted average to calculate a single average shear wave velocity for the entire soil column. To calculate the predominant period of the input ground motion, a small, external executable program, FFTPowerSpec was modified from existing code developed by Ordonez (2008) and included within the application. FFTPowerSpec computes the Fourier power spectra using a Fast Fourier Transform, and exports a Fourier power spectrum. The predominant period, the period at which the peak value of the Fourier power spectrum is located, can then be retrieved programmatically. Once both the characteristic site period and the predominant period of the input ground motion are computed, the magnification factor can be calculated as a function of the tuning factor (the ratio of the site period to the predominant period). Each of these methods is based on well established procedures from within the geotechnical earthquake engineering field; however, their integration into a GIS-based application has not been previously undertaken.

For the liquefaction potential computations, the revised "Simplified Procedure" (Youd et al. 2001) was selected as the desired method. This method, one of the most widely accepted methods used today, involves calculating the Cyclic Resistance Ratio (as a function of the in-situ Standard Penetration Test blowcount for this application), and the Cyclic Stress Ratio (primarily a function of the peak horizontal acceleration at the ground surface and the vertical overburden). The factor of safety against liquefaction at a given location and depth is computed as the ratio of these two values.

Once the preferred computation methods were ascertained, it was necessary to determine how to integrate them into an application to be computed and displayed programmatically. Input was easily handled using user-created text-based files, created through the use of VB input forms. Displaying the output in a usable format was a slightly more difficult task. The magnification factor calculations resulted in a single magnification factor value for each borehole location. This was simply displayed on the output map as a circle at the location of each feature with a graduated size and color corresponding to preset magnitudes of magnification. With this type of display, those features with high magnification factors are plotted on the map with very large or large red circles, those with magnification factors near 1.0 are plotted with medium to small sized yellow or green circles, and those that do not experience any magnification are plotted with very small blue circles. With this plotting procedure, seismically problematic areas can be located on the map very quickly. Additionally, for added functionality, a routine was added within the output screen to allow the user to compare the calculated site period to the period of a hypothetical structure in order to compute the magnification factor between those periods as well.

Displaying the liquefaction potential results was slightly more complicated as the revised "Simplified Procedure" produces results in three dimensions (X and Y directions in plan versus depth), while a typical GIS is only capable of plotting in two dimensions (Carroll 1998). To plot the results in the X-Y plane, a procedure was developed to find the lowest F.S. value for each feature and plot a circle at the location of that feature with a graduated size and color, similarly to the previous procedure. To view the data in the third dimension, a simple plotting procedure was developed where a corresponding plot of the F.S. data versus depth graph could be generated by selecting a borehole feature. With this procedure, borehole locations which experienced only thin, isolated liquefiable layers could be distinguished from those locations with more significant liquefiable zones.

3 PILOT STUDY – POPLAR BLUFF, MISSOURI

Upon completion of the S4 application, it was desired to conduct a pilot study to demonstrate the functionality of the program. For the pilot study, a site in the central United States, around the city of Poplar Bluff, Missouri was chosen, as it met several required criteria. Southeast Missouri, particularly the area immediately surrounding the city of Poplar Bluff, presents a unique geological setting with two distinct geologic units. Both residual clays with shallow bedrock, as well as deep alluvial sands from the Mississippi embayment exist within the city (Grohskopf 1955). Additionally, the close proximity to the New Madrid Seismic Zone (NMSZ) and the history of seismic activity help justify the area for use in this study. Finally, the Poplar Bluff area was recognized as a suitable site for this pilot study because of the large amount of available subsurface data. Both research-derived (Anderson et al. 2005), as well as department of transportation (Anderson et al. 2000, Luna et al. 2001) subsurface data, including field and laboratory data, were made available for this study.

Two synthetic ground motions were developed to test the S4 application resulting in two acceleration time histories. Since there are no recorded strong ground motions in the NMSZ, synthetic ground motions were obtained from the USGS stochastic seismogram simulations. The two ground motions were selected with the intent of showing a difference in earthquake magnitude. The first synthetic ground motion was for a low magnitude event with a 20% probability of exceedance in 50 years event (return period = 224 yr). The second synthetic ground motion was a less probable event with a 2% probability of exceedance in 50 years event (return period = 2475 yr). These resulted in magnitudes 6.1 (PGA of 0.074g) and 7.2 (PGA = 0.527g), respectively (U.S. Geological Survey 2006). Figure 2 presents the time history, power spectrum and magnification factor computed for the 2% PE in 50 yrs ground motion.

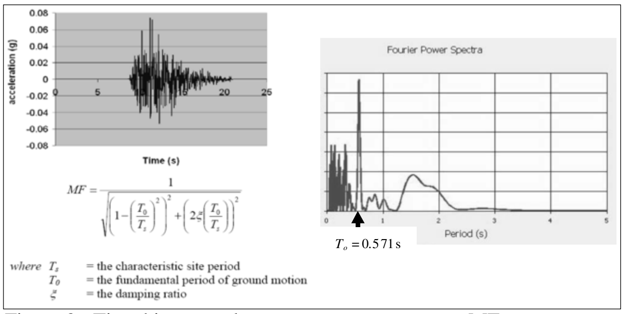

Figure 2. Time history and power spectra to compute MF.

For the first of the two analyses performed for the pilot study, a relatively small earthquake corresponding to a 224 year return interval was entered. The magnification factor was calculated for 22 locations using the characteristic site period, T_0, based on shear wave velocity data. Several locations showed signs of significant magnification potential. All twenty-two locations produced magnification factors higher than 1.0, though several were very near this value. Fourteen of the processed boreholes/sounding locations contained magnification factor results higher than 1.25. Figure 3 shows the S4 magnification factor output in relation to the surficial geology of the region (Missouri Department of Natural Resources 2003). It becomes apparent that all of the borehole locations with high magnification factors (greater than 1.25) fall within the alluvial lowland region around Poplar Bluff.

For further screening, the values of the characteristic site periods and magnification factors can be viewed for each of these boreholes within the S4 application. As previously mentioned, it is also possible to input a structure period of vibration to calculate the magnification factor from resonance between the characteristic site period and the period of the structure. For each of these boreholes, a hypothetical period for a multispan continuous concrete bridge, of 0.5 seconds (Nielson & DesRoches 2005) was used as a default. Each of the analyzed locations that showed potential for magnification of ground motion also showed at least some potential for further magnification by resonance with the structure. These locations could present a serious problem in the event of a ground motion with similar period to the one utilized in this study.

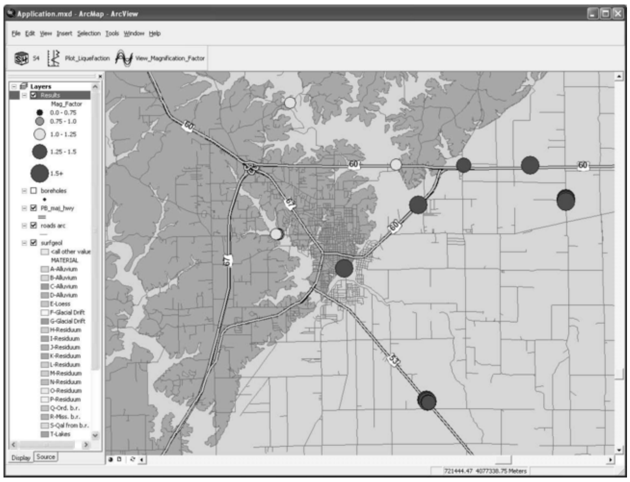

Figure 3. S4 Ground Motion Magnification Factor Results for 224 Year Mean Return Period Ground Motion.

Liquefaction potential results were also calculated based on this PGA and the input moment magnitude for each of the 85 boreholes in the surrounding area. The majority of the factors of safety against liquefaction were above 1.5 for this input ground motion, though factors of safety for seven of the remaining borehole locations plot in the range of 1.25 to 1.5, and the remaining seven borehole locations have factors of safety within the range of 1.0 to 1.25. Figure 4 shows the liquefaction potential F.S. in relation to the surficial geology map and the locations with relatively low factors of safety (F.S. = 1.0 – 1.25) fall within the alluvial lowland region. This is to be expected due to the sandy composition of the alluvium deposits in this lowland region.

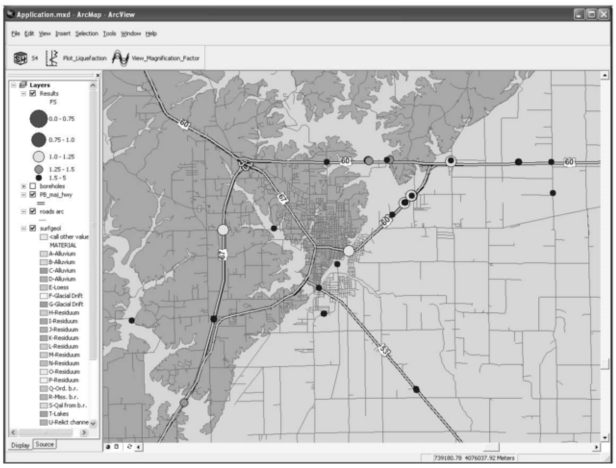

Figure 4. S4 Liquefaction Potential Results for 224 Year Mean Return Time Ground Motion.

The screening tool also has the ability to interact with the user to display additional information with depth. By double clicking on the map results at the desired location, a distribution of F.S. with depth is displayed in a new window (Figure 5). Previous GIS applications have focused on presenting the liquefaction potential index (LPI) to develop maps (Luna and Frost 1998). But since this application is just a screening tool, the engineering user can examine where this lowest factor of safety is located within the soil profile and relative to the structure being evaluated. This is particularly advantageous to detect very low FS layers that are not reflected by the averaging method of the LPI.

$$FS = \left(\frac{CRR_{7.5}}{CSR}\right)(MSF)$$

Where,

$CRR_{7.5}$ = Cyclic Resistance Ratio for M=7.5
CSR = Cyclic Stress Ratio
MSF = Magnitude Scaling Factor

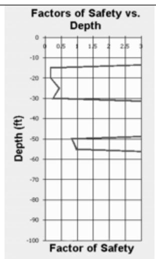

Figure 5. Distribution of FS with depth at a specific location.

In contrast to the previous analysis, a second analysis was completed for a different, strong ground motion, corresponding to a 2475 mean return time earthquake. Despite the difference in the magnitude of the input ground motion used in the two analyses, the predominant periods of the motion were very similar, so the results from the calculation of the magnification factor proved to be very similar for both analyses.

The liquefaction potential was then calculated based on a PGA of 0.527g and the input moment magnitude for each of the 85 boreholes in the surrounding area. Figure 6 shows the liquefaction potential results as plotted within the S4 application. Upon viewing these results in relation to the surficial geology of the region, it again becomes evident that borehole locations, and thus structures, that fall within the alluvial regions are at a distinct risk for liquefaction.

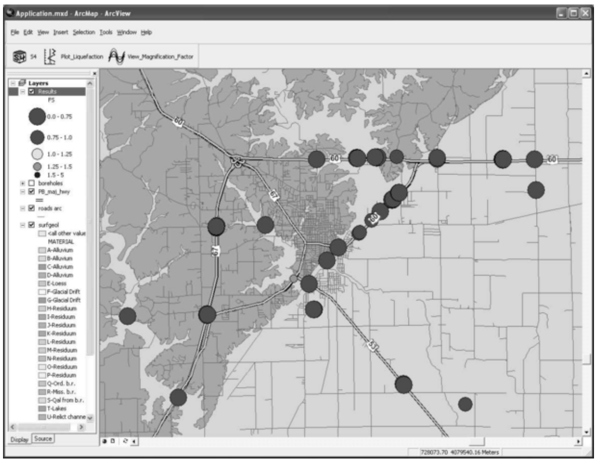

Figure 6. S4 Liquefaction Potential Results for 2475 Year Mean Return Period Ground Motion

Based on the results of an S4 analysis, a transportation department or other agency responsible for earthquake resilient infrastructure systems could view the analyzed structures and determine which are at risk for damage from an earthquake. Specifically, those structures that exhibit low factors of safety against liquefaction and exhibit high magnification factors are the most vulnerable. For the cases analyzed in this pilot study, for a large earthquake, all structures founded in the alluvial lowland region were found to be at risk for both hazards analyzed. The agency could then focus their in-depth analyses on the alluvial lowland region. The rest of the structures could be prioritized for further in-depth analyses based on the combination of liquefaction and magnification factor results.

4 CONCLUSIONS

This study demonstrates the use of the S4 application as a screening tool for two specific seismic hazards, magnification and liquefaction. As shown in the pilot study, this application works well with data distributed spatially across a project site or small city. For this reason, the methodology developed, and specifically the S4 application should prove advantageous as a screening tool for state and federal agencies responsible for earthquake resilient infrastructure systems.

It should be noted that the methodology presented herein was intended to enable simple and fundamental concepts of geotechnical earthquake engineering in a framework that allows for the analysis of spatially distributed data within a GIS. The methods used have little merit when compared to what can be accomplished in a site-specific geotechnical analysis when a ground motion is propagated mechanistically through the profile. However, seldom is the site-specific level of analyses performed for infrastructure systems that contain small components, like county bridges in a highway system or lift stations in a water/sewer distribution. Hence, the application of this methodology has some merit and should be limited as an engineering screening tool.

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