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Development of a GIS-based seismic hazard screening tool

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DEVELOPMENT OF A GIS-BASED

SEISMIC HAZARD SCREENING TOOL

by

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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. One of these advances involves the application of spatial analysis and geographic information systems (GIS), for not only presenting data as maps, but also providing more practical and usable solutions, such as calculating the hazard potential with spatial distribution. This thesis studies the evaluation of geotechnical earthquake engineering hazards within a GIS environment, using borehole-specific data and seismic ground motions. Existing methods and applications used to evaluate these hazards, as well as existing geotechnical database formats are presented and discussed. 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.

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NOMENCLATURE

Symbol	Description
a_{max}	peak horizontal acceleration at the ground surface
C_B	correction factor for borehole diameter
C_E	correction factor for hammer energy
C_N	correction factor for overburden pressure applied to SPT
C_R	correction factor for drilling rod length
C_S	correction factor for split spoon sampler without liners
$CRR_{7.5}$	Cyclic Resistance Ratio for a magnitude 7.5 earthquake
CSR	Cyclic Stress Ratio
d_i	thickness of any layer between 0 and 100 ft
FC	fines content, or the amount passing the #200 sieve in a sieve analysis
FS	Factor of Safety
g	acceleration of gravity
H	thickness of soil column
H_A	thickness of the deposit A
H_B	thickness of the deposit B
H_i	thickness of layer i
$H - z_{mi}$	depth of midpoint of layer i
i	individual soil layer
MF	damped magnification factor
MSF	Magnitude Scaling Factor
M_w	Earthquake Moment Magnitude
N_m	measured standard penetration resistance
$(N_1)_{60}$	corrected standard penetration resistance
r_d	stress reduction coefficient
T	period
T_A	fundamental period of layer A
T_B	fundamental period of layer B

T_0	fundamental period of ground motion
T_s	characteristic site period
V_s	average shear wave velocity of soil column
V_i	average shear wave velocity of soil column for given layer i
v_{si}	shear wave velocity in feet per second
X_i, X_{i+1}	estimated fundamental modeshapes at lower and upper boundary of layer i
z	depth beneath ground surface in meters
β	tuning factor
γ	total unit weight of the soil strata i
ξ	damping ratio
ρ_A	mass density of layer A
ρ_B	mass density of layer B
σ_{vo}	total vertical overburden stress
σ'_{vo}	effective vertical overburden stress
τ_{av}	average horizontal shear stress acting on soil layer during shaking generated by given earthquake
ω	fundamental frequency of the profile
ω_0	fundamental circular frequency of the ground motion
ω_s	characteristic site circular frequency

1. INTRODUCTION

1.1. PROBLEM STATEMENT

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 that will propagate the motion from the bedrock and through the soil column to a free field condition. Examples of these computer programs include SHAKE2000, DEEPSOIL, RASCAL, etc. 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. At the time of publication, no such screening application exists.

The objectives of this research were to:

- Develop a methodology to assess potential geotechnical earthquake engineering hazards within a geospatial application,
- Produce this application as a prototype which calculates the liquefaction potential and the magnification factor based on the predominant period of ground motion and the characteristic site period, and
- Conduct a pilot study to demonstrate the functionality of the application.

1.2. BACKGROUND INFORMATION

Geotechnical earthquake engineering, unlike many engineering professions, is a field that has experienced most of its growth in the past fifty years. Many breakthroughs have occurred, often following large earthquakes, which propel the field forward. The Niigata earthquake of 1964 helped shape the liquefaction potential calculations we use

today. Earthquakes, such as those affecting Mexico City, Leninakan, Armenia, and San Francisco Bay, have helped shape the way ground motion amplification is analyzed (Borcherdt 1994). Many different methods exist for calculating both of these parameters, as well as every other aspect of geotechnical earthquake engineering. Changes are being made constantly to update, enhance, and improve the methods to analyze these issues.

Similarly, Geographical Information Systems (GIS) exist in a fairly young field, with nearly all of the advances (specifically computer technology) also occurring or being incorporated in the past fifty years. Recent advances in GIS include the integration of other stand-alone programs such as spreadsheets and databases for simplified querying, increased compatibility with popular programming languages, and integrated routines. As computers continue to become faster and more powerful, what can be achieved within a GIS environment is unlimited.

The combination of these two fields, however, has been somewhat limited, despite the propensity to create highly useful applications that combine both subject matters. Most applications that do exist have been in the educational sector and have never been introduced into the commercial market. While the advantages of this to the research community are immense, the disadvantage is that very few finished and stream-lined applications that combine geotechnical earthquake engineering with the usefulness of GIS exist. Those applications that do exist, as well as many of the research projects are discussed in Section 2.2.

1.3. SCOPE OF WORK

This thesis involves developing and presenting a methodology to assess potential geotechnical earthquake engineering hazards within a geospatial application, and then developing a prototype version of this application. The application, discussed in much detail later, was developed primarily in Visual Basic to run within ArcGIS by ESRI ™. In doing so, a thorough literature review was conducted encompassing calculations in current engineering practice (including liquefaction potential, characteristic site period, and Fourier spectra), as well as existing geotechnical earthquake engineering applications. Both self-contained programs and those applications embedded in a GIS

environment were reviewed. Also a study of the current state of GIS in geotechnical engineering was conducted. The Spatial Seismic Screening Software (S4) was then 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. The liquefaction potential uses the well established procedures using borehole data and the ground motion to ultimately display a profile of factor of safety vs. depth. The magnification factor compares the predominant period of the bedrock ground motion to the characteristic site period of the soil profile. Once the application was finished, a pilot study was completed to demonstrate the functionality of the application.

1.4. THESIS ORGANIZATION

This thesis is broken down into five distinct sections. These being: Introduction, Review of Existing Literature, Software Design, Pilot Study – Poplar Bluff, Missouri, and Conclusions and Recommendations. The Introduction contains the problem statement, some background information, and the scope of work for the project.

The second section, Review of Existing Literature, is divided into four subsections. The first goes through the calculations used in current engineering practice; first walking through liquefaction potential, then characteristic site period, followed by response spectra and Fourier spectra and finally touching on some of the other parameters (such as the Magnitude Scaling Factor) used in the application. Secondly, GIS in Geotechnical Engineering is discussed. Liquefaction and other seismic hazard mapping are discussed, and similar existing programs and applications in geotechnical engineering are evaluated. Both self-contained programs and those embedded within GIS programs are discussed. The future of GIS along its current path is then speculated and discussed, and remote sensing and the related technology are examined. The third section discusses seismic screening procedures, particularly those related to GIS. Finally, the fourth section focuses on the dissemination of geotechnical data in the form of currently existing geotechnical engineering databases.

The Software Design section focuses on the design and creation of the Spatial Seismic Screening Software (S4) prototype application. It first describes the design methodology and approach, touching on the intended user of the application and the borehole specific engineering profile approach employed. Secondly, the desired inputs and outputs are discussed, and finally the system architecture is described. The visual basic programming, graphic user interfaces, and the ArcGIS interface are all discussed.

The Pilot Study section details the implementation of the aforementioned application to an earthquake hazard susceptibility analysis of the highway structures in the area near Poplar Bluff, Missouri. The specific reasons for selecting this region are discussed and the results are documented.

Finally, the Conclusions and Recommendations section summarizes the major conclusions that were obtained from this study. It also provides recommendations for future work along similar lines as this research and suggests expansions of the discussed application.

2. REVIEW OF EXISTING LITERATURE

2.1. CALCULATIONS IN CURRENT ENGINEERING PRACTICE

As previously stated, variations on methods of computation in geotechnical earthquake engineering are large in number. For this review, three parameters were researched and are discussed: (1) Liquefaction Potential, (2) Characteristic Site Period, and (3) the Fourier and Response Spectra. All of these parameters have many methods of calculation and they are reviewed here.

2.1.1. Liquefaction Potential. Liquefaction is defined as the transformation of a granular material from a solid to a liquefied state as a consequence of increased pore-water pressure and reduced effective stress (Marcuson 1978). Usually this liquefied state is the result of rapid cyclic loading under seismic conditions, which may generate landslides, lateral spreads, sand boils, and bearing capacity failures. These consequences prove not only expensive to remediate, but dangerous as well. Liquefaction potential has been estimated for many years, particularly since the Alaska and Niigata earthquakes of 1964 (Seed and Idriss 1971). In the last couple decades significant changes have been made to provide more accurate estimations. Both field and lab data can be used to estimate the potential for liquefaction. A "simplified procedure" was developed, using field data, for faster, more general calculations, and others have built on to this method to increase its usefulness. Also, significant work has been done in probabilistic based approaches which incorporate local site conditions and regional seismicity.

One of the earliest accepted methods for calculating liquefaction potential, first published by Seed and Idriss (1971) as the "simplified method", is an empirical method based on the performance of similar soils in previous earthquakes. Particularly, the Niigata earthquake of 1964 was studied, and the earthquake-induced demand on the soil was estimated using the cyclic stress ratio (CSR). The CSR was then related to the soil density to assess the triggering of level ground liquefaction. Later, the density parameter was replaced with the SPT blow count, for ease of obtaining data. Next, the Cyclic Resistance Ratio (CRR), or ability of the soil to resist liquefaction, is calculated. By dividing the CRR by the CSR, a factor of safety against liquefaction could be obtained. Similarly, a graph was assembled plotting effective overburden pressure versus standard

penetration resistance and showing the degree of liquefaction for areas on the graph. This chart could then, hypothetically, be used to assess the potential at other sites. A plot of the CSR versus SPT data was also constructed and used in a similar way. While the CSR calculation is similar to the method used in the current "simplified procedure", due to the small quantity of available data used for the empirical relationships, this method produced results with little accuracy.

A second method was based on an evaluation of stress conditions in the field coupled with laboratory determinations of the stress conditions that caused liquefaction in soils. This method involved evaluating the site and determining the magnitude of cyclic stresses induced at different levels in the site soil deposits by seismic shaking. The results were then compared to the cyclic stresses determined in the lab (by tests such as the cyclic simple shear test), for which given confining pressures corresponding to specific depths in the deposit caused liquefaction of the soil. After plotting these two sets of data, an evaluation of liquefaction potential was then based on a comparison of these two curves. While this method provided a more accurate way of estimating the liquefaction potential, it required expensive lab testing procedures and ideal soil samples for lab testing. Given the probability of extracting a perfectly undisturbed saturated sand sample, it is probably much less accurate in real world applications (Cubrinovski and Ishihara 1999).

By the mid 1980's, more widely accepted methods had been established to estimate the liquefaction potential for a given site. Several case studies were being performed and studies of liquefaction potential for specific sites were being completed. By this time, the use of field and lab testing methods had gained increased popularity. A method was proposed by Seed et al. (1983), using either SPT or cone penetration test (CPT) data to estimate the liquefaction potential at a given site. This method, with minor changes, is the method still widely used today. It involves calculating the CSR, correcting the SPT blow count and finally determining whether this value falls within the area designated as potential liquefaction based on empirical data.

Similarly, the CPT test could be used to estimate the liquefaction potential. In many cases the CPT test provides better data for this application because it provides continuous data and different layers can be more easily distinguished. However, at the

time of this publication, SPT data was more available so better correlations were possible due to the large amounts of data. The CPT data is handled very similarly to the SPT data for this estimation. Charts similar to the SPT charts previously mentioned were constructed for the CPT data; however, these are just correlated from the SPT data. While this is a rather simplified description of the work by Seed et al. (1985), it has been kept brief in the interest of newer revisions.

Another method which must be mentioned is the estimation of liquefaction potential using empirical relationships between liquefaction occurrences and cone penetration resistance as developed by Stark and Olson (1995). These relationships are the result of 180 liquefaction and non-liquefaction case histories where CPT tests were performed. These relationships have proved to be very accurate in determining whether liquefaction will occur. Additionally, these relationships have also been developed for both silty and gravelly soils.

While using field data from the SPT or CPT test is the most widely used source of data for estimating the liquefaction potential, other methods are still used and are mentioned here for completeness. Both undrained and drained static triaxial tests, as well as cyclic undrained tests on samples can be used to estimate the cyclic behavior of a soil (Macari et al. 1993). Additionally, shear wave velocities, most often measured by a cone penetrometer, can be used to calculate the liquefaction potential (Andrus et al. 2004).

In 2001 Youd et al. published a paper documenting a revised version of the Seed and Idriss (1971) "simplified procedure". While this method is still derived from empirical data, the amount of information that it can now draw from is immense, making it quite attractive, and the method most commonly used today. Like the original method, the revised "simplified method" requires the calculation of two values: the seismic demand on a soil layer (CSR) and the capacity of the soil to resist liquefaction (CRR). The equation used to calculate the CSR is the same equation proposed in 1971 and factors in the horizontal peak ground acceleration (PGA), the vertical overburden stresses and a stress reduction coefficient based on the depth of the soil layer, as shown in equation 1.

$$CSR = \frac{\tau_{av}}{\sigma'_{vo}} = 0.65\left(\frac{a_{max}}{g}\right)\left(\frac{\sigma_{vo}}{\sigma'_{vo}}\right)r_d \tag{1}$$

where τ_{av} = average horizontal shear stress acting on soil layer during shaking generated by given earthquake

σ'_{vo} = effective overburden pressure

a_{max} = peak horizontal acceleration at the ground surface generated by the earthquake

g = acceleration of gravity

σ_{vo} = total vertical overburden stress

σ'_{vo} = effective vertical overburden stress

r_d = stress reduction coefficient

The CRR is based on measured field data from SPT and CPT tests, in addition to other tests such as the shear wave velocity test (Vs) and the Becker Penetration Test (BPT). Each of these tests has its distinct advantages and disadvantages, depending on the type of soil and the resolution needed. The SPT and CPT methods are preferred since they have the largest database of measurements at sites of liquefaction and no liquefaction. It should be noted that the liquefaction potential calculated using the CPT was more accurate than any other test method, resulting in correct estimations over 85% of the time, according to Youd et al. (2001). However, when CPT testing is employed, some soil sampling should also be done to verify the accuracy of the CPT data. Whichever test data is used, it must be corrected for overburden, slope of ground, efficiency and a number of other similar discrepancies.

$$CRR_{7.5} = \frac{1}{34 - (N_1)_{60}} + \frac{(N_1)_{60}}{135} + \frac{50}{[10 \cdot (N_1)_{60} + 45]^2} - \frac{1}{200} \tag{2}$$

for $(N_1)_{60} < 30$

Once the CSR and CRR are determined, a factor of safety (F.S.) against liquefaction can be calculated and the potential for liquefaction known.

$$FS = \left(\frac{CRR_{7.5}}{CSR}\right)(MSF) \tag{3}$$

where $CRR_{7.5}$ = Cyclic Resistance Ratio for a magnitude 7.5 earthquake
CSR = Cyclic Stress Ratio
MSF = Magnitude Scaling Factor

Two ground motion parameters must also be estimated in order to use the "simplified procedure"; the earthquake magnitude, and the PGA. Estimation of these two parameters is beyond the scope of this paper, but these parameters are expected as input. However, it should be noted that the accuracy of the liquefaction potential is only as good as the estimation of these parameters. Finally, the corrections for fines content and effective overburden stress must be mentioned as they increase the quality of the results significantly. Both corrections are calculated into the CSR value.

The Simplified Procedure is the most straight-forward and widely accepted method used today. However, drawbacks to it do exist. The first, and perhaps most important is the fact that it only applies to relatively clean sands, though liquefaction has been documented in both silts and gravels (Andrews and Martin 2000); (Andrus 1994). Methods for calculating liquefaction potential in these materials do exist, though research in these areas is fairly new, and no generally-accepted method exists for their calculation. For this reason, liquefaction in silts and gravels was omitted from this application. Additionally, due to the quality and lack of data, it is inherently severely limited as an empirical approach. Since most of the methods to assess liquefaction potential were developed post-1960's, data is not readily available from events that occurred pre-1960's. Similarly, the quality of data used to form the equations is always in question. Finally, a lack of a degree of probability provides a limitation to this method. The Chinese Criteria, as presented by Seed and Idriss (1982) can be used as a simple way to identify whether a particular soil is susceptible to liquefaction, and then the appropriate estimation method selected.

Probabilistic evaluation of liquefaction potential is a more recent method for assessing the liquefaction potential. It involves estimating the liquefaction based on the variability of an earthquake occurrence and site parameters. First, the factor of safety for

liquefaction is calculated for a given magnitude earthquake. Next, seismic parameters, as well as site parameter uncertainties are included to produce earthquake-site models. Based on a given moment-magnitude, the probability of liquefaction can be determined for the specific model. By analyzing the same model at different moment magnitudes, a liquefaction potential probability matrix can be constructed, showing probabilities of different severities of liquefaction versus different moment magnitudes for the given site. The benefit of this method is that it incorporates local site conditions and regional seismicity, as well as uncertainties in seismic and site parameters. Much work has recently been done in this area by a number of researchers, including Liao et al. (1988, 1998), Youd and Noble (1997), Toprak et al. (1999) and Hwang and Lee (1991). Results from this method have been compared to results from the simplified method and both yield very similar results. However, while this method may be marginally better, it is still a fairly new concept and is not as refined for ease of use as the "simplified procedure," so it is not presently as common.

The future holds more methods for evaluating liquefaction potential. Recently, significant work has been done in neural network (Goh 2002) and energy-based approaches (Green and Mitchell 2004) that may prove to replace all previous methods. As in many fields of science, with the continual increase of computing speeds, methods that were previously impossible may replace the existing procedures and provide more accuracy. As these methods continue to be improved and new methods are introduced, the quality of liquefaction potential evaluation can only increase.

2.1.2. Characteristic Site Period. Earthquakes in the past fifty years have shown how local soil conditions can dramatically modify the characteristics of ground shaking. (Ohsaki 1969; Seed 1969). Earthquakes such as Mexico City in 1957 (Duke and Leeds 1959), and Loma Prieta in 1989 (Kramer 1996) exemplify this point. Numerous investigators have studied this topic, including Trifunac and Brady (1975) and Seed et al. (1974) and conclusively shown that structures with foundations on deep or soft alluvium can be subject to much larger seismic forces than those founded on rock, with equal peak ground accelerations (Dobry et al. 1976). To quantify this parameter, the fundamental period (or characteristic period) of the soil profile is calculated. Kramer (1996) defines the Characteristic Site Period as the period of vibration corresponding to the lowest

natural frequency. When the characteristic site period of the soil profile is close in period to the predominant period of the input ground motion, harmonic amplification, or resonance of the ground motion may occur, resulting in greater accelerations at the ground surface than what was originally emitted from the source. This is further discussed in Section 2.1.3.

Unlike many, if not most, of the parameters used in geotechnical earthquake engineering, methods of calculation of the characteristic or fundamental period of a soil profile have changed very little in recent history, particularly since the early 1970s. Prior to this time, local site conditions were often ignored or treated as independent of the period of the structure in building codes when calculating the design base shear force for a structure. Since the early 1970s many building codes have adopted a more sophisticated approach which accounts for the fundamental period of the structure as well as the stiffness and depth of the local soil (Dobry et al. 1976). The use of a site period to characterize the site conditions was first introduced into the Chilean code around this time (IAEE 1973; Arias et al. 1969).

Dobry et al. (1976) published a study of simplified procedures for estimating the fundamental period of a linear or equivalent linear model of a soil profile. In this report, fundamental periods for seventy-six representative soil profiles were estimated using seven different methods and the results were compared with the exact values from closed form or computer solutions. Soil deposits were modeled as a one-dimensional, elastic beam on rigid rock. Cases analyzed included a) shear wave velocities increasing with depth, b) shear modulus increasing (or decreasing) with depth, c) two-layer profiles, and d) an overconsolidated layer over a soil with modulus increasing with depth. Closed form solutions were computed for simple cases while many of the complex actual soil profiles were solved with a computer. For complex stratigraphies, the Rayleigh Procedure (Biggs 1964) was used. This procedure is an iterative method obtained by equalizing the total maximum kinetic and potential energies of the system when vibrating freely in the fundamental mode.

Since computation by the Rayleigh method will usually require the use of a computer, several approximate methods were compiled to calculate the fundamental site period by hand. In total, seven methods were analyzed and compared to the results

previously computed by closed form solutions or the Rayleigh method. These methods are summarized in Table 2.1.

Table 2.1. Summary of Calculation Methods for Fundamental Period

#	Method of Calculation	Reference
1	Weighted average of velocities of layers	Madera (1971); Schnabel et al. (1973)
2	Weighted average of moduli of layers	Ambraseys (1959); Idriss (1966)
3	Sum of periods of layers	Shima (1962); Zeevaert (1972); Okamoto (1973)
4	Selection of equivalent wave velocity at depth 0.63H	Dobry et al. (1971)
5	Equation based on linear first modal shape	Dobry et al. (1976)
6	Successive use of two-layer solution	Madera (1971); Chen (1971); Urzua (1974)
7	Simplified version of the Rayleigh procedure	Dobry et al. (1976)

Five of these methods were previously developed by other researchers, while methods (5) and (7) were developed during the study by Dobry et al. (1976).

Once each method was analyzed, the degree of error for each method could be known. Methods (6) and (7) were by far the most accurate when compared to exact values. These methods resulted in errors of less than 10% for the period of all profiles and were recommended for practical use. However, these methods, while simple compared to the Rayleigh method, are still fairly complex to compute by hand. A programmable calculator is recommended for method (7). Methods (1) through (5) are simpler procedures that can be calculated by hand, but were much less accurate in at least some of the cases, resulting in maximum errors of about 50%. Method (1) was the most accurate of these five, providing accurate results (maximum error less than 20%) except where there was a distinct drop in shear wave velocities with depth. This scenario again

returned errors of up to about 50%. This method was found acceptable except where mentioned above, and may be desirable due to its simplicity. Methods (1), (6), and (7) are described in more detail below.

Each of the above methods is based on the same basic formula for a uniform layer, which has been derived by numerous investigators (Reid 1908; Jacobsen 1930). This equation in its simplest form can be represented as

$$T = \frac{4H}{V} \tag{4}$$

where T = period
      H = thickness of soil column
      V = average shear wave velocity of soil column

For a uniform layer, this equation may be used in its exact form. However, a non-uniform or multi-layer stratigraphy requires the use of a more inclusive method.

In method (1) above, a rather simplified approach is taken to approximate the fundamental site period, using a weighted average of the velocities of each layer. For each layer, the velocity is weighted as a function of the thickness (H_i) of the layer. Then, a final single weighted velocity is used in the period formula. This can be represented in equation form as

$$V = \frac{1}{H_i} \sum_{i=1}^{n} V_i H_i \tag{5}$$

where V_i = average shear wave velocity of soil column for given
           layer i
      H_i = thickness of soil column for given layer i

$$T \approx T_1 = \frac{4H}{V} \tag{6}$$

where H = thickness of soil column
      V = average shear wave velocity of soil column

As previously stated, this equation generally gives results within 20% of the actual value when compared with exact results from the Rayleigh procedure. Results for this method were generally higher than actual values, representing longer periods for ground motion. This method is probably adequate for most cases when a simple calculation is needed (i.e. quick checks or screening procedures). However, for profiles with a distinct drop in shear wave velocities with depth, errors can be on the order of 50%.

Method (6) (above), employs a significantly more complicated approach than method (1) above, though it is still simple enough to be carried out by hand calculations. This method utilizes the successive use of a two layer system to approximate the fundamental period for a series of layers. To accomplish this, the first two layers are treated as a two layer system on rock, and a representative period is calculated using the equation

$$T = \frac{\rho_B H_B T_A}{\rho_A H_A T_B} \tag{7}$$

$$
\begin{aligned}
where \quad & \rho_B & &= \text{mass density of layer B} \\
& H_B & &= \text{thickness of the deposit B} \\
& T_A & &= \text{fundamental period of layer A} \\
& \rho_A & &= \text{mass density of layer A} \\
& H_A & &= \text{thickness of the deposit A} \\
& T_B & &= \text{fundamental period of layer B}
\end{aligned}
$$

This combined period is then treated as a new unique layer and the same process is completed using this layer and the layer below it (the third real layer) as a two-layer system on rock. This procedure is repeated for each layer, until the bottom of the stratigraphy is reached. This method proved to return very good results, within 10% of the exact value for all of the test cases.

Method (7) is the most complicated of the seven methods analyzed, but since it is a simplified version of the Rayleigh procedure, it is still much simpler to calculate than the Rayleigh procedure itself. However, it is recommended that a programmable calculator or computer is utilized for the calculations, as they are generally too intense to

be practical for hand calculations. This method utilizes the Rayleigh equation simplified by replacing integrals with constant average values for each layer. This method can be described by the equations

$$X_{i+1} = X_i + \frac{H - z_{mi}}{V_i^2} H_i \tag{8}$$

$$\omega^2 = \frac{4 \sum\limits_{i=1}^{n} \dfrac{(H - z_{mi})^2}{V_i^2} H_i}{\sum\limits_{i=1}^{n} (X_i + X_{i+1})^2 H_i} \tag{9}$$

where X_i, X_{i+1} = estimated fundamental modeshapes at lower and upper
              boundary of layer *i*
    H_i = thickness of layer i
    H - z_{mi} = depth of midpoint of layer i
    V_i = shear-wave velocity
    ω = fundamental frequency of the profile

In this method, the properties for each layer are entered into a calculator or spreadsheet, an estimate of the fundamental mode shape is calculated, and the contributions of each layer are summed into the numerator and denominator of the above equation. Like method (6), this method proved to return very accurate results, within 10% of the exact value for all of the test cases, however, it is probably still too complicated to use for day-to-day estimates.

As can be seen in the above equations, it is necessary to determine the shear wave velocity profile for a soil column before calculating the period of that column. However, a detailed discussion of means of estimating shear wave velocities is beyond the scope of this thesis, as is a discussion of the pros and cons of each method. It should be noted, however, that several methods may be used to obtain these values. These methods include surface shear wave surveys, such as the Spectral Analysis of Surface Waves Method (SASW), borehole shear wave surveys such as downhole or crosshole testing methods, and cone shear wave velocity surveys, utilizing a seismic cone penetrometer (Bauer 2004). These methods are commonly accepted in standard engineering practice.

Additionally, studies have been completed correlating shear wave velocities to more readily available (and more frequently tested) values such as the standard penetration resistance (Andrus et al. 2001). Correlations such as these are available for the researcher or industry professional in the absence of direct measured shear wave velocity data.

Since the 1970s, the generally accepted method for calculating the site period has changed only slightly. The International Building Code (2000) which can be viewed as the current working industry standard, shows the procedure for calculating the average shear wave velocity as

$$V = \frac{\sum_{i=1}^{n} d_i}{\sum_{i=1}^{n} \frac{d_i}{v_{si}}} \tag{11}$$

$$\sum_{i=1}^{n} d_i = 100 \, feet \tag{12}$$

where d_i = the thickness of any layer between 0 and 100 ft
       v_{si} = the shear wave velocity in feet per second

This equation is then input into the original formula to determine the fundamental site period. As stated, this method is now the generally accepted method or industry standard.

2.1.3. Response Spectra and Fourier Spectra. Like the previously mentioned parameters, the response spectra and the Fourier spectra have various uses and methods of calculation within geotechnical earthquake engineering.

2.1.3.1 Response spectra. Currently in geotechnical earthquake engineering, it is standard practice to perform a site-specific dynamic response analysis for any site which may encounter strong ground motions. This analysis usually entails calculating natural site periods, assessing ground motion amplification, evaluating the liquefaction potential, calculating the seismic stability of any slopes and embankments and providing a response spectrum for design. (GovindaRaju et al. 2001) It is this last parameter, the calculation of response spectra that may seem the most abstract and difficult to grasp.

Mathematically, a response spectrum can be defined as a plot of the maximum response of a series of oscillators to an excitation or vibration, with some degree of damping. For transient vibrations (such as strong ground motions), the peak response is reported. (Kappos 2002). For seismic analyses, structures and soil columns usually can be approximated as single degree of freedom oscillators, making the use of response spectrum very applicable. In this way, if the fundamental frequency of the soil column or structure is known, the peak response of the structure (or column) can be estimated by picking the corresponding value from the spectrum plot. If a structure or soil column has similar frequencies to the ground motion, harmonic amplification can occur resulting in increased damage. This was especially evident in the 1985 Mexico City earthquake where "double-resonance" occurred when the bedrock ground motions were amplified by the soft lacustrine soils, and the soil motions were amplified by the mid-rise concrete structures. (Kramer 1996).

In geotechnical earthquake engineering, response spectra are usually estimated by computer based applications such as SHAKE2000 or WESHAKE or nonlinear analysis programs such as DEEPSOIL or DESRA (USACOE 1999). Both of these programs compute the one-dimensional analysis of site response. Both will compute the equivalent linear response, while DEEPSOIL will also compute the one-dimensional non-linear response. The theory behind the computations used within these programs is beyond the scope of this document. However, it should be noted that both use complex calculations based on the upward propagation of shear waves from an underlying rock formation. (Ordonez 2006), (Hashash 2005). While use of programs like these are standard practice in geotechnical earthquake engineering, their use is time consuming and somewhat involved to master.

In 1982, Newmark and Hall developed what they referred to as the "idealized" seismic response spectrum based on response spectra developed from many ground motion sources. This was later developed into a design spectrum for use in structural design. A damping value of 5% is generally used, to avoid infinite response results. Many building codes specify design response spectra for seismic design originally based on this Newmark and Hall (1982) method. (Building Seismic Safety Council 2000,

International Code Council, Inc. 2000). Researchers such as Borcherdt (1994) have adapted this initial procedure and streamlined it for use within these codes.

As previously stated, significant seismic damage may result to buildings if the building response is in harmony with components of the ground motion. Similarly, if the fundamental site period is in harmony with the soil column, harmonic ground motion amplification may occur, usually resulting in more damage at the ground surface. This relationship can be described via a magnification factor, where resonance occurs when the ratio of the site period to the predominant period of the ground motion, or the ratio of the structure period to the site period, approach one. At this point, resonance occurs, as the periods are in harmony with each other, resulting in harmonic amplification.

2.1.3.2 Fourier spectra. Mathematically, a Fourier transform is defined as a linear operator that describes how the amplitudes of the waves that contribute to a given wave group vary with frequency (Beiser 1995). In geotechnical earthquake engineering, the Fourier amplitude spectrum of a strong ground motion shows the frequency distribution of the relative amplitudes of that ground motion. In this way, frequencies that compose large components of the ground motion are seen more easily as the breakdown of energy is plotted versus the frequency (or period) (Kramer 1996). This resultant spectra can then be compared to the natural frequency (or period) of a soil column or structure to assess the magnification of the ground motion.

The Fourier transform and use of the Fourier spectra is in no way unique to the field of geotechnical earthquake engineering. Fourier series are commonly used in electrical engineering, signal processing and acoustics, optics and other vibration analyses and taught in many university calculus classes. Numerous Fast Fourier Transforms (FFT) have also been developed for ease of calculating the response spectra by means of estimation. (Press et al. 1992).

A strength and weakness of the Fourier spectra in geotechnical earthquake engineering is its independence of the properties of the soil column. The fact that the spectra is in intrinsic value of the ground motion, allows for somewhat simple computation and comparison to the natural frequency of a soil column or a structure to judge the magnification of that interaction. However, this same identity of the spectra makes it less useful than response spectra because it does not account for the response of

the soil column. The ease of computation with a FFT application lends itself well to seismic screening procedures or quick estimation of seismically problematic areas.

In addition to the Fourier spectra, another related and often used spectrum in geotechnical earthquake engineering is the Fourier power spectrum. These spectra are calculated from the Fourier spectra and illustrate how the strength of a quantity varies with frequency (or period) (Kramer 1996). In shape and period, the Fourier power spectra are nearly identical to the Fourier (amplitude) spectra. However, the amplitude and units of amplitude are in power (acceleration squared) instead of acceleration. For this reason, the predominant period value obtained from a Fourier spectrum will equal the value obtained from a Fourier power spectrum.

Another use of the Fourier spectra within geotechnical earthquake engineering is for the estimation of seismic intensity (Modified Mercalli Intensity).   Sokolov (2002) has developed various empirical relationships to estimate the seismic intensity of a seismic event using Fourier amplitude spectra of the ground acceleration. This research was based on over 1000 strong ground motion records, and implies that the seismic intensity is a function of the ground motion amplitudes in the frequency range of 0.4 to 13 Hz.

In addition to using an FFT to determine the predominant period of the ground motion, other procedures have been developed for determination of the frequency content of earthquake ground motions. Rathje et al. (1998) described the use and calculation of both the mean period (Tm) and the smoothed spectral predominant period (T0) which can be used for determination of the magnification factor. These parameters, along with the predominant period were compared in that publication and each method was found to have advantages and disadvantages.

2.1.4. Magnitude Scaling Factors. For magnitude scaling factors (MSF), several different methods of calculation exist. Youd et al. (2001) describe eight different methods to calculate the MSF, each with distinct differences. For the most accurate results, they recommend utilizing a combination of calculations for engineering practice. Specifically, they recommend using the revised Idriss (Youd et al. 2001) method for a low bound for M_w values of less than 7.5, and the Andrus and Stokoe (1997) method as a high bound for the same magnitude. These upper bound values were found to be consistent with several of the other methods. For M_w values greater than 7.5, the revised

Idriss method was again suggested as the preferred calculation. As very little liquefaction data exists for earthquakes with magnitudes greater than 7.5, it is difficult to judge which is the best method for these values of M_w. This combination of methods was designed to provide a range of values, and allow the engineer to make judgments based on the risk involved. While this works well in general engineering practice, it is not very efficient for providing a general value in a programming environment. For this reason, the revised Idriss method can be used as a single conservative method for all situations, as it is the preferred method for the upper range of magnitudes, as well as the lower bound for the lower magnitudes. This equation, as proposed by Idriss (Youd et al. 2001) is shown below.

$$MSF = \frac{10^{2.24}}{M_w^{2.56}}$$
(13)

where M_w = Earthquake Moment Magnitude

For magnitudes higher than 7.5, it should provide a value as accurate as any other method, while at values of less than 7.5, it will provide a slightly conservative value. In these lower magnitude values, the MSF values obtained from the revised Idriss (Youd et al. 2001) method range from roughly 79% of the Andrus and Stokoe (1997) value for a moment magnitude of 5.5 to 95% of the Andrus and Stokoe (1997) method at a moment magnitude of 7.0. So, while the revised Idriss (Youd et al. 2001) method provides a more conservative result, it maintains similar values to those from the other preferred method.

2.2. GIS IN GEOTECHNICAL EARTHQUAKE ENGINEERING

GIS has many applications within geotechnical earthquake engineering. Among these are liquefaction and other seismic hazard mapping, and actual geotechnical earthquake engineering applications that run within or along side of GIS environments. These are discussed here. Additionally, there are several screening procedures that exist as general guidelines for conducting seismic hazard analyses that are very applicable for

this topic. These are also reviewed within this section. Finally, a short discussion is included about the future of GIS in geotechnical earthquake engineering.

   2.2.1. Liquefaction Hazard Mapping. Mapping has become a standard approach for identifying liquefaction potential within the geotechnical earthquake engineering community. These maps are generally produced in the following steps: the evaluation of factors of safety at field test locations, calculation of the liquefaction potential at each location, and the contouring of this data to produce a spatial representation (Liu and Chen 2006). These steps are a general description of the approach to producing a liquefaction hazard map, though countless researchers have devised new methods and alternate procedures to produce results. A few of these projects are discussed below.

   Piya (2004) developed a borehole-based geological database for the assessment of liquefaction hazards in the Kathmandu Valley. This research sought to develop a database to contain the over 350 deep and shallow boreholes that had been drilled in the area and from them, construct a GIS-produced liquefaction hazard map based on both qualitative and quantitative methods. No single detailed database had been previously built for this data. The database stores all of the information from the original boreholes including lithological descriptions, N-values, and other geological information within Microsoft Excel 2000 and Microsoft Access files, and allows it to be displayed within a GIS environment. Both ILWIS and Rockworks99 were utilized for the GIS-based portions of the research. The final product of this research was the construction of a GIS-produced liquefaction hazard map for the Kathmandu Valley. A reusable stand-alone application or GIS based sub-routine (extension) to perform this task was not created as part of this research.

   Realizing that most liquefaction hazard maps are regional in scale, and based primarily on geologic units identified by their age and depositional environment, Baise et al. (2006), performed research to produce liquefaction hazard maps based not solely on regional geology, but using the regional geology in conjunction with local data from soil samples with calculated liquefaction properties. Generally, in traditional liquefaction hazard mapping, select soil properties from standard penetration tests, cone penetration tests, shear wave velocities and a plethora of other tests are used to generalize the

geologic unit and assign some degree of liquefaction potential, which is then displayed as a region of some degree of liquefaction potential. While in a local liquefaction study, the specific soil data is used to quantify the liquefaction potential directly. The goal of their project was to produce liquefaction hazard maps based on both regional and local data and be able to locate zones of liquefiable materials within a geologic deposit. A three-step procedure is outlined within this project to produce these maps, which include statistical characterization of the distribution, spatial characterization of the population and global and local characterizations. Statistical models were then used to determine zones of interest, which were displayed spatially within a GIS interface. A case study was performed for an area around Cambridge Massachusetts, to illustrate the method.

Liu and Chen (2006) proposed utilizing cone penetration test measurements to more economically produce liquefaction hazard maps, as the resolution and even availability of maps are limited by exploration costs. Liu and Chen advocate using CPT data as a more economical means of collecting data, and interpolating or extrapolating between the data to estimate/update data at unsampled locations, which could then be displayed within a GIS application. Much of their project was related to the rationale of interpolation and extrapolation techniques

While the vast majority of liquefaction hazard maps are developed two-dimensionally, Baise et al. (2006) developed a customized three-dimensional geographic information system for viewing and analyzing liquefaction potential across a site as an alternative to traditional two-dimensional GIS based maps. This model incorporates sample specific soil data in addition to soil stratigraphy. A demonstration was presented utilizing this model for an area around Berkeley, Alameda, and Oakland, California. Three dimensional liquefaction hazard mapping had been researched earlier by Luna and Frost (1998). Baise et al. updated this study by utilizing the probability methods based on Bayesian updating as proposed by Moss et al. (2005), and developed a custom 3-D GIS to display the data.

Additionally, countless single-use GIS analyses have been completed for various specific locations around the world including, but not limited to, county-wide hazards assessment in South Carolina (Cutter et al. 1997), identifying faults and epicenters in Montana (Kennelly and Stickney 2000), liquefaction mapping in Ventura County,

California (Hitchcock et al. 2002), utilizing GIS and SHAKE for microzonation of Armenia, Colombia (Slob et al. 2002), seismic slope stability zonation around Lanzhou City, China (Wang et al. 2004), and liquefaction susceptibility mapping in Saint Louis, Missouri (Pearce and Baldwin 2005).

Finally three other projects should be mentioned which developed GIS based applications to analyze and map seismic hazards. Both Luna and Frost (1995) and Carroll (1998) worked to develop applications for the evaluation and mapping of seismic hazards with a primary focus on liquefaction hazard analysis, while Rockaway et al. (1997) developed an application to map and analyze hazards for both liquefaction and ground motion amplification. The first of these applications (Luna and Frost 1995) was developed to calculate liquefaction potential within a spatial analysis system. It utilized the simplified method of calculating liquefaction potential from SPT blowcounts or CPT soundings, and the liquefaction potential index (LPI) as proposed by Iwasaki et al. (1978) to reflect the severity of a given incidence of liquefaction at the ground surface, using probabilistic and deterministic calculation methods. These results were then analyzed spatially in a GIS environment. Arc/Info 6.1.2 by ESRI was chosen as the geographical information system for this application and a pilot study was conducted for the Treasure Island site in the San Francisco Bay area. This research, while it produced an application (GIS-QUAKE, and later Spatial LIQUEFAC) (Carrol et al. 1997), was not site-independent, and was somewhat cumbersome for the non-GIS-analyst to perform routines due to complexity of the Arc Macro language.

To streamline these difficulties, this research was built on and was recreated as the software application SLIQ v1.0 (Carroll 1998). SLIQ was designed as an application to perform site and scale independent spatial liquefaction analyses, again utilizing the LPI, within a GIS environment, while being easy to install and easy to use for the general researcher. In addition to predicting the occurrence of liquefaction, estimates of liquefaction-induced vertical settlements were also calculated. For this application, ArcView 3.0 by ESRI was utilized, and SLIQ was created as an installable extension for use within the GIS package. Again this project utilized the Treasure Island site in the San Francisco Bay area for its pilot study. This application proved to be one of the first

installable applications for spatial seismic hazard mapping and analyses within a GIS environment.

Also, of particular interest are Rockaway et al. (1995) and Rockaway et al. (1997), who built upon the work by Luna and Frost (1995) and developed an application for analysis procedures and mapping of seismic hazards within a GIS environment for the Evansville, Indiana area. This research developed the computer system GIS-QUAKE to perform liquefaction and ground motion analysis routines with site-specific information. While a database of borehole specific information with x, y, and z, coordinates was used within GIS-QUAKE for the calculation of the hazard potentials, the results were not presented as borehole specific results, but rather as averaged zonation maps of the region. The LPI was again utilized within this program to present three-dimensional liquefaction results as a two-dimensional representation at the ground surface. The SHAKE91 software package was used to compute ground motion amplification results, as it was considered the industry standard at the time. Hazard maps of the Evansville, Indiana area were produced for these two geotechnical earthquake engineering hazards as the results of this project.

2.2.2. Other Seismic Hazard Mapping. While not as common as liquefaction hazard mapping, numerous other seismic hazards commonly utilize spatial displays as well. Soil amplification maps, slope failures and landslides and ground response maps are just a few of the seismic attributes represented in this way.

Wakamatsu et al. (2004) developed a GIS-based geomorphic map for nationwide hazard assessment in Japan, including the mapping of site amplification of seismic motion, soil liquefaction, slope failure and landslides, and flooding. The spatial data includes soil type, geologic age, surface geometries, and relative relief, and like the hazard mapping described above, displays the information spatially within a GIS environment. The main focus was on liquefaction and liquefaction hazard zonation was performed for the entire country. Planned future additions to this project include the addition of three-dimensional capabilities.

It should also be mentioned that national seismic hazard maps have been created for the entire United States, including Alaska and Hawaii, by the United States Geological Survey. These maps include peak ground accelerations and spectral response

at 0.2, 0.3, and 1.0 second periods at 10%, 5%, and 2% probabilities of exceedance in 50 years (Frankel et al. 2000). These maps are the basis for seismic design in the International Building Code (International Code Council, Inc., 2000).

2.2.3. GIS-Based Applications for Geotechnical Earthquake Engineering.

While GIS applications are used fairly extensively within geotechnical earthquake engineering for producing hazard maps, very few applications exist to manipulate and analyze seismic data, be they stand-alone applications or extensions of existing GIS software. However, this is not to say that they are non-existent. Most of the GIS-based geotechnical earthquake engineering applications that exist have either come from private industry as retail products, or more frequently from the academic research community, with the greater number coming from the latter.

One such application is the program NDCGIS, a GIS based program designed to process seismic data to monitor and differentiate between earthquakes and nuclear test explosions in Israel (Leonard et al. 2002). The Israeli National Data Center (NDC) monitors all regional seismic ground motions to detect illegal nuclear tests, in order to deploy international investigation teams. To manage and monitor these large quantities of seismological data, NDCGIS was developed as an integrated object-oriented seismological-GIS tool to support the NDC. NDCGIS was developed to run as an AutoCADMap based application on a PC equipped with Windows 95, and utilizes preexisting routines (from previous unrelated research) which perform tasks such as hypocenter location, signal processing, phase picking, and source identification by pattern recognition, among others. An ORACLE database operating under a SUN/Unix operating system was set up for the task of storing the vast amounts of seismological data. Standard base maps and querying abilities are also included in the application. NDCGIS appears to provide a logical step towards implementing a GIS approach to political policy and decision making.

Garagon Dogru et al. (2004) conducted a research project to develop a web-based seismic GIS application. The goal of the project was to develop and implement an internet-based geographic information system to provide access to seismic spatial datasets for within Turkey, which could then be viewed, queried, and analyzed as a software-independent system without purchasing or installing personal GIS software.

Referenced data included vector data representing current earthquakes, historical earthquakes, earthquake record stations, fault lines, GPS stations, displacements by GPS, city boundaries, city centers, county boundaries, lakes, rivers and roads. As the research was primarily focused on the creation and execution of the actual web-based application, the seismic analyses were not developed in detail. The aspects of earthquake engineering were primarily used as examples of the type of data that could be contained and manipulated within the environment, and displayed the applications capacity for data distribution. The project presented pertinent points on web-based applications and how they may become the future of GIS use.

Additionally, HAZUS-MH, developed by FEMA for natural hazard loss estimation has become used within the earthquake engineering community (FEMA 2003). HAZUS-MH calculates the exposures for selected areas, characterizes the level intensity of the hazard for the area and then estimates the loss for the area. HAZUS-MH not only estimates losses due to seismic activity, but as the MH stands for multiple hazards, loss estimates can be completed for other hazards as well, including floods and hurricanes. It should be noted that HAZUS-MH can provide loss estimates based on both liquefaction and ground motion amplification hazards (among other seismic hazards), however the methods for computation of these hazard probabilities are based on regional analyses, and are generally not site nor borehole specific. HAZUS-MH runs within the ArcView GIS environment by ESRI.

Other research analyzing seismic hazards within a GIS environment has been performed by Seker et al. (1998), Werner (2000), O'Rourke et al. (2001), Mansoor et al. (2004), Macari et al. (1997), and Tun et al. (2004).

2.2.4. The Future of GIS and Seismic Hazards. While no one can accurately predict the future, it seems there are certain technologies that will become very useful within the overlapping fields of seismic hazard analyses and GIS applications in the near future. One of these technologies is remote sensing for use with GIS. Remote sensing has been around for some time and is used extensively for general mapping applications. Applications within geotechnical earthquake engineering which utilize GIS and remote sensing currently tend to focus on damage assessment and include inventorying buildings and critical structures such as building foundations and embankments after seismic events

(Bell and Westerlund 1999) and analyzing seismic vulnerability based on estimated locations of population (Zavala and Chuvieco 2003).

Additionally, the inclusion of three dimensional computer modeling is changing the way that seismic hazards are analyzed. Three-dimensional stratigraphy models as discussed by Luna and Frost (1998) and developed by Baise et al. (2006) not only change the way we calculate seismic hazard potentials, they change the way we look at earthquakes and the soils that are impacted in general.

These two technologies are just a glimpse of what will be the future of geotechnical earthquake engineering. New methods of calculation, empirical relationships, and research break-throughs continue to be published almost constantly.

2.3. SCREENING PROCEDURES

Though not directly related to GIS and mapping, a very comprehensive screening guide has been developed for rapid assessment of liquefaction hazard at highway bridge sites by Youd (1998, 1999), which could somewhat easily be integrated into a spatial application. This guide, designed for highway engineers with geotechnical knowledge, but lacking seismic hazard knowledge, acts as a step-by-step process for assessing liquefaction risks for a large number of highway bridges. Hazards covered include liquefaction, ground displacement potential, and assessment of how likely bridges are to be damaged. The screening process starts with the least complicated and least time-consuming analyses to eliminate low risk structures, and subsequently narrows the spectrum of bridges by using progressively more in-depth and data intensive analyses to identify those structures most at risk. In this way, only those structures found to have moderate to high risk are further analyzed and those found to have low risk drop out of the analysis. This allows the most time to be spent on the structures requiring the most analyses; an important fact, as most of the analyses are designed to be computed by hand. For structures without sufficient geotechnical information, a procedure is detailed to prioritize locations for further testing.

For the actual liquefaction analysis, the simplified procedure for liquefaction hazard estimation is employed, utilizing either SPT or CPT data for calculation of the

cyclic resistance ratio. In addition to standard liquefaction calculations, recommendations for slope instability due to liquefaction are discussed and various static equilibrium procedures are mentioned, lateral spread displacements are covered and the method proposed by Bartlett and Youd (1995) is given as the preferred procedure, and the analysis of ground settlement is discussed using the Tokimatsu and Seed (1987) procedure. Finally, bearing capacity failures due to liquefaction are discussed, including methods to estimate residual strength bearing capacity. These analyses allow a rapid assessment to be conducted for highway bridges or any other group of structures or locations where significant subsurface data exists.

Similarly, a procedure developed by the U.S. military for the screening of structures for seismic hazards is outlined within TM 5-809-10-2/NAVFAC P-355.2/AFM 88-3 (Departments of the Army, the Navy, and the Air Force 1988). While not as computation specific as the procedure described above, this document presents a methodology for evaluating existing structures (buildings) using a rapid seismic analysis. Designed solely as a screening procedure, not an in depth investigation, this method is presented as a means to quickly assess the seismic risk at a much lower cost than would be accrued by an in-depth analysis. This method relies heavily on a preliminary evaluation which utilizes a document review, a site inspection, an approximation of the building's capacity to resist seismic forces, and damage approximations. From there various structural assessments are detailed, based on geotechnical approximations of the ground motion. Again, as above, this procedure eliminates those structures with small amounts of risk and focuses on the high risk structures so that detailed structural analyses can be minimized.

2.4. DISSEMINATION OF GEOTECHNICAL DATA

One of the newer aspects of geotechnical engineering is the electronic dissemination of geotechnical data. With the influx of computers in the field and in engineering labs, and the growth and development of global computer networks, electronic interchange, storage, and manipulation of data has become not only a convenience, but nearly a necessity. However, as this aspect of geotechnical engineering

is still in its adolescence (if not its infancy), no universally accepted method or standard has been accepted by the geotechnical engineering community. Numerous groups and individuals have developed formats to fill the need for such a standard, many out of necessity, others as proprietary systems for commercial use, and still others out of the desire to disseminate data more freely. Though no standard or format has emerged on the forefront of the field, several of the proposed formats appear to have significant merit and are being accepted widely, if not universally. The most pertinent of these formats are discussed below.

On a small scale, numerous standards have been produced by groups such as the NEESgrid (Ratzeberger 2004), the US Army Waterways Experiment Station (WES) (McPhail 2001), and the American Society of Testing Methods (ASTM). ASTM Standard D 6453 – 99 describes a format of computerized exchange of soil and rock test data, between different users and agencies. It claims that as there is no consistency in data storage formats, a standard was needed and devised. The goal of the ASTM standard was to produce a less time-consuming and less expensive method of exchanging computerized test data files among organizations (American Society for Testing and Materials 2007a). Included in the standard are a definition of the principal data elements considered important, and preparation of a text based data storage system from which larger databases may be prepared. Specific rules for data formatting and organization are detailed throughout the document. Additionally, example distribution files are included.

The primary reason for the creation of standards such as those mentioned above is for inclusion within a geotechnical database. While basic computer based geotechnical databases have existed since the late 1970s (Toll et al. 2001), much has changed since that time. In the late 1980s developers began using Database Management Systems to create geotechnical databases in the form of exchange standards. In 1992, the Association of Geotechnical Specialists, in the United Kingdom created an exchange standard for geotechnical data. This standard was widely adopted within the UK and as time progressed, throughout the world. The AGS standard is composed of ASCII (text) files arranged in a single file structure. This structure is divided into data groups which in turn are composed of fields which house the actual data. A data dictionary is employed to list and define the fields for each data group. In this way, spreadsheets or

text editors may be used to manipulate the data. Site data, field data, and lab data are all contained within the AGS format. (Toll et al. 2001).

The AGS file format has gained a significant following, though with time, the format has been shown to have many limitations. A restrictive programming language, the lack of a logical structure, and the use of a single file for an entire project are thought by opponents to limit the file format so as to be undesirable (McPhail 2001). Additionally, as the database was designed for use by consultants and contractors, it does not fulfill the needs of many in the research community (Benoit and Satyanarayana 2001)

The United States Universities Council on Geotechnical Engineering Research (USUCGER) with their research program, the National Geotechnical Experimentation Sites (NGES), has developed a standard of geotechnical data exchange based on the AGS method (McPhail 2001). The goal of the NGES was to produce a central data repository for dissemination of the data acquired at the NGES sites. The creators of the NGES file format created a more complex version of the AGS standard to fulfill the research needs of its users, while maintaining usability. The NGES format was originally developed in and accessed Dbase, which ran within the DOS operating system. Later a Windows query module was developed to interface with the original file. Recently, the NGES database was restructured to run via an Internet interface and use a relational database that runs on a UNIX based server. A Java application is employed by the end user to access and manipulate the data in text form. Like the AGS format, the NGES format houses site data, in situ test data, specimen data, and lab test data. This data is arranged in a relational database, so there is little duplication of data, and the speed of querying and data access is maximized. (Benoit and Satyanarayana 2001)

The final standard discussed here was developed recently by the Consortium of Organizations for Strong-Motion Observation Systems (COSMOS) in 2004 and supported by the Pacific Earthquake Engineering Research Center (PEER) Lifelines Program (LL). Based on the NGES data standard (which, as previously stated, was based in turn on the AGS standard), the COSMOS standard was created as a universally accepted standard to fulfill the needs of the research community as well as the commercial engineering community. (Swift 2004)

Unlike the aforementioned data standards and file formats, the COSMOS standard utilizes the Extensible Markup Language or XML. XML is defined as a World Wide Web Consortium-recommended general-purpose markup language that supports a wide variety of applications (W3C XML Core Working Group 2000). XML was created in 1998 by the World Wide Web Consortium (W3C) as a format to facilitate data sharing between various platforms and languages, with primary focus on data sharing via the internet.

XML provides a tree-based structure for data storage that is text-based. Data in an XML file can be viewed and read as plain text with data interspersed that describes the hierarchy of the tree structure, and the attributes of the data itself. Since the data is visible in a text format, these files can easily be edited with text editors such as Notepad, Wordpad, TextEdit or most word processors. Additionally, though XML files are text based, many software packages can now display the data as more complicated formats. XML files are platform independent and can be imported into a variety of programs including GIS, Spreadsheet, and CADD programs. (W3C XML Core Working Group 2000). XML has been suggested for use in geotechnical databases numerous times previously; however the COSMOS database has been the first to release it to widespread use. (McPhail 2001, Bardet et al. 2003)

At first glance the XML data structure of the COSMOS standard resembles an inverted tree structure, however upon closer examination it can be seen to be much more complex, with circular relationships for many of the entities. Utilizing these relationships, data from the site, field, and lab is stored with minimal space and is able to be queried and accessed much more quickly than a database utilizing redundant data. (Benoit et al. 2004)

Like the NGES database, the COSMOS database is accessed via the internet, and data is downloaded from a remote server. The COSMOS database takes this further by also employing the use of a GIS map interface to spatially locate the data. (Turner et al. 2004) Additionally, COSMOS has adopted a data format for strong ground motion data, to standardize the dissemination of this data as well. (COSMOS 2001)

Much time, thought, and effort has been put into the COSMOS database, including survey input from potential users. (Turner et al. 2004) However, it is yet to be

seen whether this very complex standard will be universally adopted by the geotechnical engineering community. Electronic dissemination of geotechnical data is undoubtedly one of the newer aspects of geotechnical engineering. With the increase of computers in use within the geotechnical engineering profession, digital file dissemination has become the standard, even if no standard for dissemination exists. However, with numerous standards in existence, no standard has been universally accepted by the geotechnical engineering community.

3. SOFTWARE DESIGN

To demonstrate the previously mentioned seismic hazard analyses in a spatial screening application, a prototype tool (software application) named the Spatial Seismic Screening Software or S4 was created. It was decided that the tool would include calculations of liquefaction potential in the form of factors of safety against liquefaction and it would calculate the site resonance between the ground motion and the characteristic site period in the form of a magnification factor. Furthermore, it was decided that the ArcGIS 8.3 Desktop software group by ESRI would be used as the base GIS software platform.

Before development of the software application could begin, a methodology and approach for the design of the application needs to be contemplated. This involved analyzing both the anticipated user of the application, and the scale and resolution of the input and output. Next the desired inputs and outputs themselves were defined and the system architecture was then determined for the visual basic programming, graphical user interfaces and the ArcGIS interface. Once these were completed, the engineering algorithms for both the magnification factor of ground motion and liquefaction potential could be analyzed. Finally, the limitations inherent to the application were documented. This process is discussed in the following sections.

3.1. DESIGN METHODOLOGY AND APPROACH

To create a tool that quickly screens a site for seismic hazards, two key elements need to be considered. First, the anticipated user of the tool needs to be considered as their level of experience greatly shapes the tool, possibly more than any other aspect. Someone with very little experience in geotechnical earthquake engineering will require a tool much different than an engineering seismologist with many years of experience. With that in mind, a decision had to be made as to whom this application would be designed for.

The second item of consideration was the scale and detail that the tool would operate within. The type of calculation that could be computed based on regional

geologic deposits with averaged soil parameters would differ significantly from those that could be analyzed for specific layers with measured soil properties within a given geotechnical borehole. Likewise, input files, output formats and user interfaces would be quite dissimilar for these two examples.

3.1.1. The User. As previously stated, this application is not meant to be the final result of a site-specific analysis. It is meant to be a screening tool to quickly identify seismically problematic areas. While an in-depth site specific analysis requires a fairly thorough knowledge of seismology and earthquake engineering, locating the problematic areas is a much simpler task. Hopefully this application will make this task even more easily achievable. The intended user of this application is an engineer or researcher with limited background knowledge of seismology and earthquake engineering. They may be a geological engineer or entry-level geotechnical engineer with limited seismological experience, or a geologist or seismologist with little engineering background. Similarly, a structural engineer with little geotechnical engineering background may find it useful. Finally, 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.

The geotechnical and earthquake engineer were also kept in mind during the development of this prototype application. As previously mentioned, while ideally, it would be most advantageous to perform a 1-D response analysis (SHAKE or similar) for every seismically questionable point in a given project area, this would be cumbersome, time consuming, and expensive for the average engineer or researcher. Instead it makes much more sense to narrow the scope, by locating the most seismically susceptible points in the area, and running an in-depth analysis on these few points. In this case, several parameters are reported that may prove useful for a site-specific analysis. This information, while perhaps more in depth than the average foundation engineer or geologist would need, is helpful for an in-depth analysis.

Whoever the user, a limited knowledge of GIS as well as geotechnical and earthquake engineering is required. Knowledge of the inputs and outputs as well as the ability to manipulate the spatial data is imperative. As in all computer applications, the

quality of the output is highly, if not completely, dependant on the quality of the input. Therefore, a certain knowledge of the nature of this data is obviously required.

        3.1.2. The Engineering Profile Approach. The scale and detail that the tool operates within greatly dictates the 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. There were three main reasons for this decision. These are: a) accuracy and resolution of data, b) independence of scale, and c) practicality. With this method, a user may select an individual borehole with field and lab gathered data, and compute results for that borehole.

        By using a borehole specific engineering profile approach, data can be entered in raw form, in the same format that it is recorded in the field or the lab, with no loss of accuracy or resolution by combination of data. No averaging of data is required to create zones or regions, or even lithology, as each borehole is independent of each other borehole. Typically, when zones of "similar" soil properties are created among multiple boreholes, small anomalous regions can be lost within the larger regions. With this method, if one borehole contains materials with lower strengths, results will be calculated for those strengths, and not lost in a somewhat higher "average". Additionally, with the borehole method, nearly unlimited numbers of soil layers are permitted for a borehole, with disregard to the number of layers in adjacent boreholes. Again, this lithology requires no averaging or zoning. The engineering profile borehole specific approach also makes spatially referencing data very simple. An X and Y coordinate is assigned to each borehole and a depth value is assigned for each soil parameter, so no spatial averaging is required for the geotechnical data. Finally, should a simpler input be desired, several boreholes can be averaged and entered into the application as a single composite borehole.

        Secondly, by utilizing the engineering profile approach, the results and the input are independent of scale. The user can select as large or as small of an area as desired and enter as many or as few boreholes as desired. This also allows for the use of a nearly infinite number of sites and different purposes of analysis. If a local analysis of just a few boreholes is desired, an analysis can be completed for just that site. However, if the

user would like to look at a larger region, such as a small city, that can also be completed, and analyzed by the user. Where this may present a problem is in areas with vastly differing subsurface conditions. However, in this instance, the user may elect to "zoom-in" and increase the scale and analyze a specific area in more detail. By presenting the application with independence of scale, this is an available option, where with large regions of identical soils data, it would not be. Finally, it should be noted that without an application such as this, analyzing all of the available boreholes for a large region would be a very time consuming task.

The third and final reason for utilizing the borehole approach is practicality. Typically in engineering practice, an engineer, geologist, or scientist wishing to analyze a seismic hazard will obtain borehole information from fieldwork and calculate the desired parameter from these values by hand or using a spreadsheet. For this reason, the borehole approach is very practical for entering and manipulating data. The user can obtain their data and enter "as-is" without taking the time to correlate or average (as previously mentioned), and required calculated data (e.g., vertical overburden stress) can be included with the borehole at the associated depths. Additionally, many if not most of the calculations for computing these parameters are based on field-measured values such as SPT (Youd et al. 2001), or shear wave velocity (International Building Code 2000). By using borehole specific data, the calculations to determine the desired parameters are very straightforward.

As described, the desired scale and detail greatly dictates the format for this application. A decision was made to use a borehole specific approach for data storage, handling and manipulation. Three elements were considered which aided in this decision, namely, a) accuracy and resolution of data, b) independence of scale, and c) practicality. With this method, a user may select an individual borehole with field and lab data, and compute results for that borehole. Additionally, data is recorded as collected and stored for each particular borehole.

3.2. SYSTEM ARCHITECTURE

The system architecture describes the organization of the application and how different aspects of it relate to each other. To examine the system as a whole, it is easiest to break it into subsystems, or groups of features or routines that share common elements. In this way, the entire architecture can be broken into a tree structure diagram to view its components.

While a system may be divided into subsystems and displayed by function, by category, or any number of similarities that link the items in a subsystem together, the application described in this document is most easily diagramed when organized by the way the application progresses or flows. While not the same as a dataflow diagram, the modified tree structure diagram, shown in Figure 3.1, displays the complete system broken up into subsystems by the way the user progresses through the program, and the way the program progresses independent of the user. It should be noted that while this diagram may not follow a common architecture format, the composition of this application makes it more easily understandable in this configuration.

The initial element of the structure is the Graphical User Interface (GUI). This interface allows the user to interact with the application in a visual manner. Beyond the GUI are two main branches which the user may choose to progress through. Theses are a) data entry, b) seismic hazards. Contained in the data entry branch are the procedures for entering data and the geotechnical database itself. The seismic hazards branch contains two smaller subsystems, a) liquefaction potential, and b) ground motion magnification factor (or site resonance). The liquefaction potential branch contains the calculations for the parameters that are used to obtain a factor of safety against liquefaction. Finally, the ground motion magnification factor branch contains the computations of those items used to calculate the site resonance.

To build the elements of the system architecture, three main categories of features are needed. The first of these is programming in Visual Basic for Applications (VBA), which is utilized to produce the code used to compute the actual algorithms and handle the data as well as to call the external 3rd party software routine (tool). Secondly, the graphical user interfaces 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
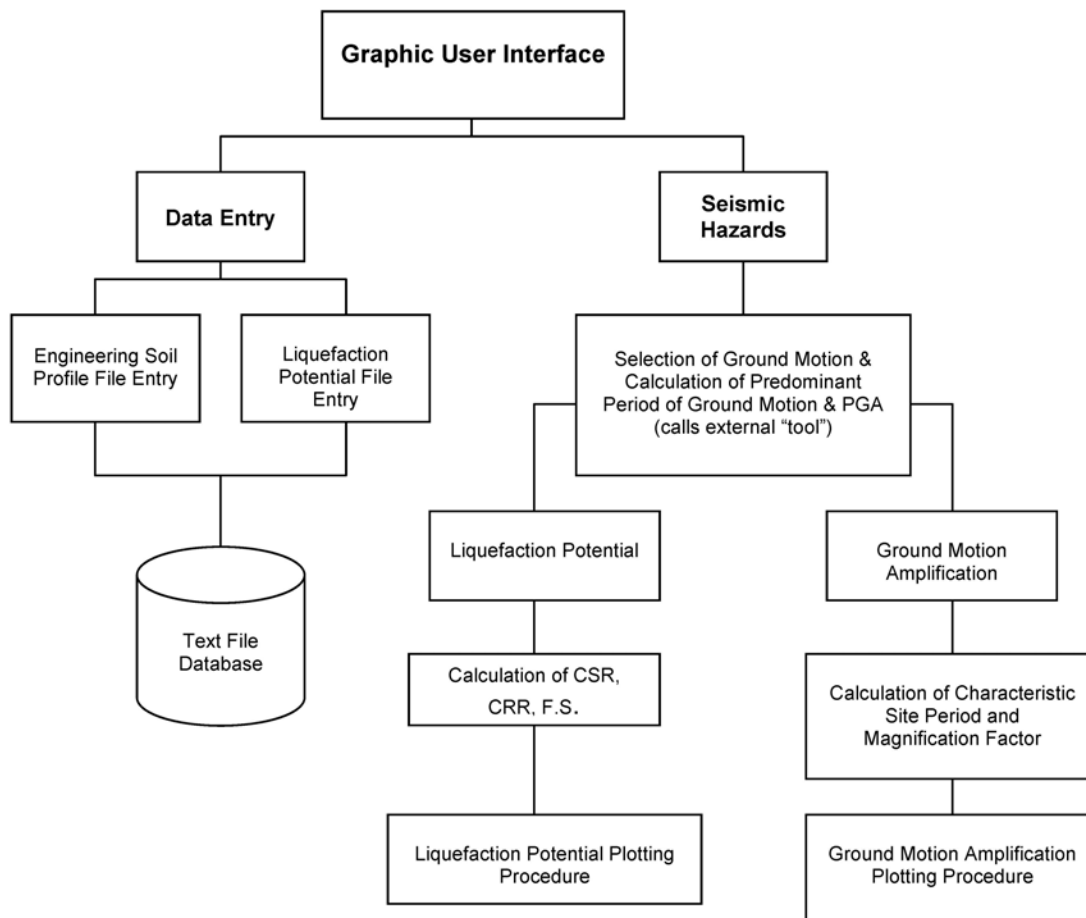
Figure 3.1. System Architecture for Prototype Application of the Spatial Seismic Screening Software (S4)

spatial environment for input and output purposes. Each of these three categories is discussed below. The user should refer to the Appendix, the Guide for Future Development for a more complete description of the application's operation.

       3.2.1. Visual Basic Programming. The major aspects of this application were created by programming within Visual Basic for Applications (VBA) or in a few cases, Visual Basic 6.0 (VB6). VBA is a "slimmed-down" derivative version of VB6 included with many Microsoft programs and many third-party products such as ArcGIS and AutoCAD (Microsoft Corporation 2008). ("Visual Basic" and the acronym VB will be used to describe both VBA and VB6 unless otherwise noted.)

Visual Basic is an event driven visual programming language from Microsoft
Corporation, which facilitates application development by use of controls on user forms,
actions for those forms and conventional code (Microsoft Corporation 2008).
Visual Basic contains an integral graphical user interface (GUI) consisting of user forms
with input boxes, drop-down combination boxes, buttons, etc. User forms compose most
of the "visual" aspects of code written in VB. Within the forms and code, design
components called controls are used to perform many of the tasks within VB in
conjunction with basic "if statements", "for loops", and simple arithmetic calculations
(Dictor 1999). Conventional text file handling is another important aspect of VB (as in
any other programming language) that was used extensively in the development of S4.
Finally, Visual Basic also allows the developer to run external third party programs using
a shell command.

3.2.2. Graphical User Interfaces. While Visual Basic uses controls and code to
access and manipulate data, the Graphical User Interface (GUI) is what allows interaction
between the user and this data. Visual Basic employs various types of elements and
controls to create GUIs, primarily in the form of dialog boxes and forms.

Dialog boxes are simple, preformatted graphic interface elements with "pop-up"
capabilities. There are several types of dialog boxes including message boxes which
deliver a text message to the user, input boxes which gather text based input from the
user, yes no boxes which retrieve a Boolean input from the user, and several others. An
example message box is shown in Figure 3.2.
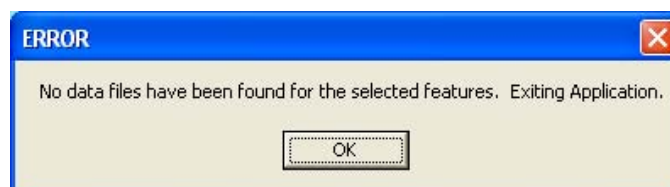
Figure 3.2. Example Visual Basic Message Box

User forms serve many of the same purposes as dialog boxes within VB; however, forms can be used for much more complicated tasks than the simple dialog boxes. In addition to the ability to have pop-up capabilities to alert the user, request input, or display output, forms may contain multiple input or output items, images, graphs, charts or even videos. Forms are the building blocks for a GUI and are constructed with the mouse using drag and drop techniques. An example VB form is shown in Figure 3.3.
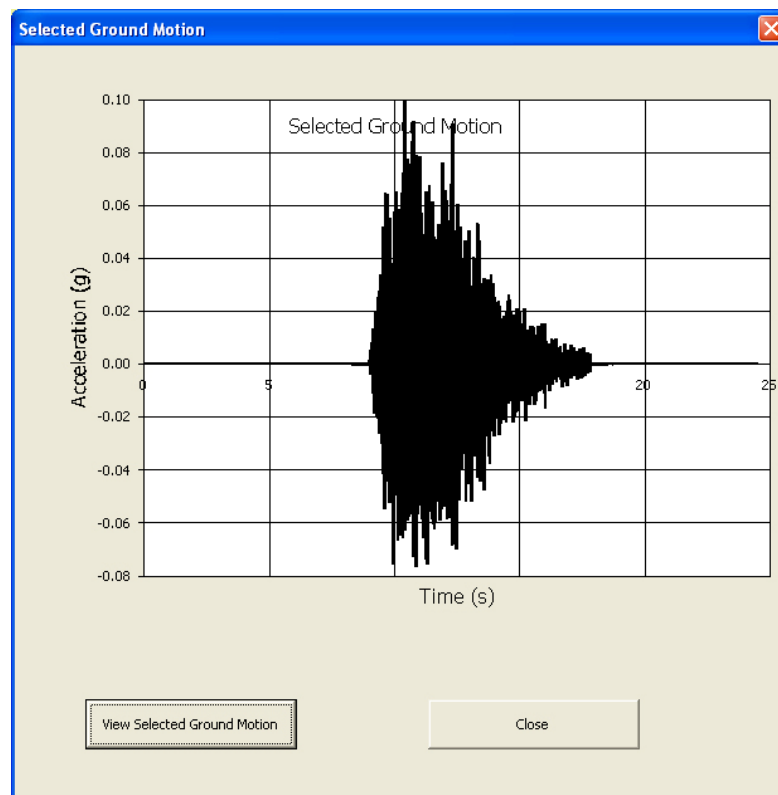
Figure 3.3. Example Visual Basic User Form

Commands are executed from VB forms by way of user initiated, mouse events. Virtually any mouse operation can be set to trigger a command. Additionally, commands can also be executed without using forms at all, but utilizing other aspects of the GUI. For example, in S4, after an analysis is complete, simply clicking on a borehole location

executes a procedure to display a graph. This is just one example of how user forms compose the essential elements of the GUI.

Graphical user interfaces within VB are composed primarily of dialog boxes and user forms. While dialog boxes are uncomplicated and can be used to effectively gather or transmit simple information to the user, user forms are much better suited for anything but the most simple of tasks. However, the use of both is warranted to interact between the VB code and the user. The final element which uses elements of both the VB programming and the GUI is the GIS interface. While the GUI exists for the user to interact with the VB programming, the ArcGIS interface allows the VB programming to interact with the spatial aspects of the application.

3.2.3. ArcGIS Interface. As previously described, the Visual Basic code performs the actions of the application, and the graphical user interface allows interaction between the user and these commands. The final component of the application, which uses aspects of both the VB code and the GUI, and in turn interacts with both, is the geographic information system (GIS) interface.

As previously mentioned, ArcGIS 8.3 by ESRI was chosen as the platform for which to demonstrate this application. ArcGIS is a geographic information system that allows the representation of geographic data and provides tools for creating, analyzing, and manipulating it (ESRI 2001). While ArcGIS is often referred to as a software package or program, it is actually a complete line of GIS software packages. Among these software products are ArcView (the product chosen for this application), ArcInfo, and ArcEditor. Each of these programs can be used to accomplish similar tasks, though higher levels of functionality are included respectively. Each of the three can be used to access the ArcGIS desktop, which provides functionality through three smaller programs. These programs are ArcMap, ArcCatalog, and ArcToolbox. ArcMap, as the central unit of the ArcGIS desktop, allows the user to interactively view and process spatial data. The subject tool of this research, S4, was designed to operate within ArcMap.

ArcMap provides not only a visual backdrop, but serves as the working environment for this application. The two previously discussed components, the VB programming and the GUI, work interactively with ArcMap to accomplish the tasks required of the application. The primary component of ArcMap is the Data View. The

Data View appears as a digital map, which houses the icons for each borehole in the S4 application. To the left of the Data View is the legend, which contains a list of the data layers currently loaded within the Data View. Various toolbars can be found along the top, bottom and sides of the Data View, which allow the user to accomplish various tasks, including data entry, data manipulation, and special queries. A sample screen shot of the ArcMap layout is shown in Figure 3.4.
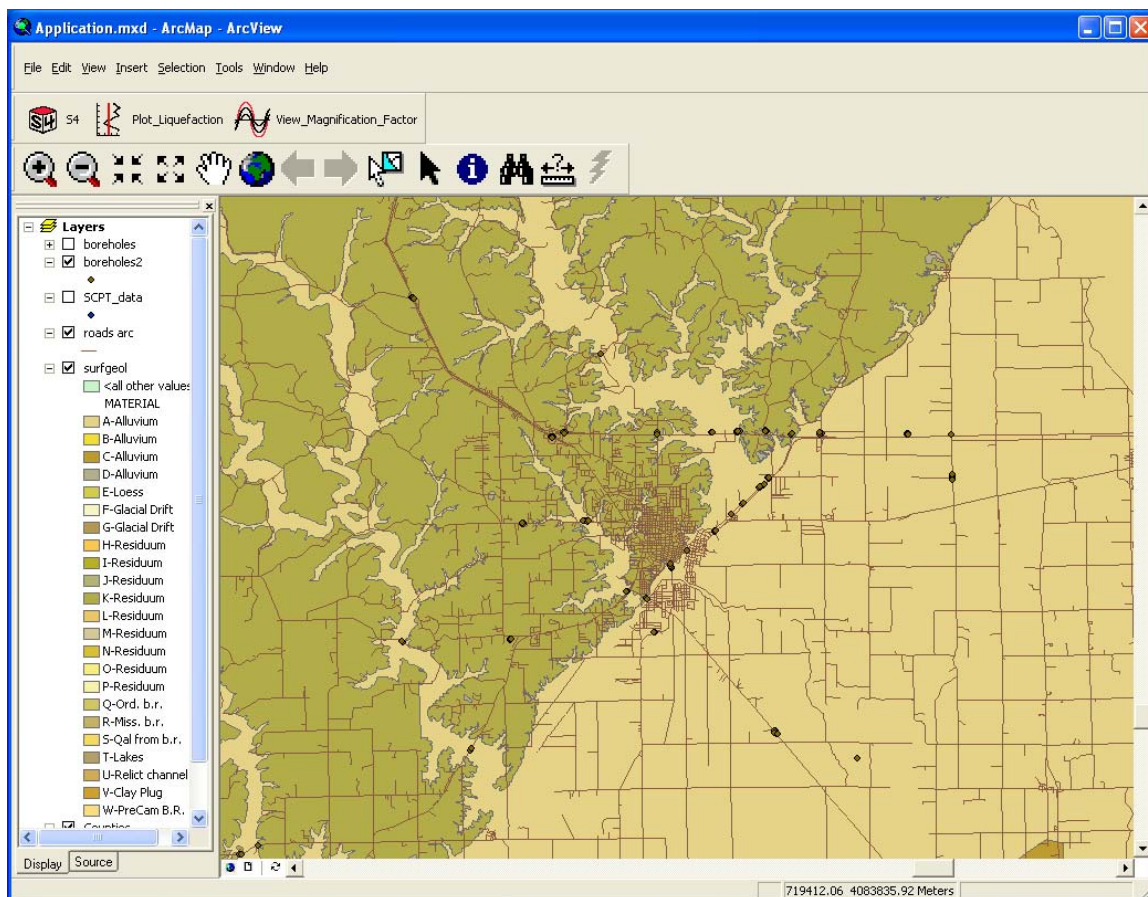

Figure 3.4. Screenshot of ArcMap Data View

To initiate the S4 application, borehole features are selected within ArcMap and a button is clicked from the toolbar. This initiates the previously discussed VB procedures, which in turn invoke the GUI features.

Development with Visual Basic within ArcGIS is completed within one of two methods. Macros are generally used for small applications (and were utilized for S4), while extensions can be compiled and distributed as executables for larger applications. Within each method, the development follows the same procedures.

In Visual Basic, as discussed, controls are used to accomplish the tasks required of the application. In order to work with ArcGIS, a specific type of controls, called ArcObjects are used by VB. ArcObjects is a component based object modeling development platform that works with Visual Basic (Zeiler 2001). By using ArcObjects, procedures can be programmed to manipulate data with ArcMap, and that work seamlessly with the VB procedures and the GUI. Some examples of ArcObjects functions include plotting data spatially, querying or changing spatial attribute table data, and calculating spatial attributes such as area. In the S4 application, ArcObjects are used to, among other things, change the size and color of the borehole icons based on the factor of safety against liquefaction. To the general user however, this procedure is invisible as ArcObjects are used solely by the developer to produce this type of procedures. A guide for future development of the S4 application is included in Appendix A.

As discussed above, the system architecture of the S4 application is made up of three different categories of features that work together to accomplish the desired tasks. These categories are a) programming within Visual Basic, b) graphical user interfaces, and c) the ArcGIS interface. While each of these categories is distinctly different, the interfaces between categories can blend together almost seamlessly to produce an application that is both streamlined, user-friendly and promotes the ease of data flow throughout the application.

As is shown in Figure 3.5, the data flow within the S4 application occurs between the individual elements of the software in numerous ways. At the center of the application is the GIS application, which acts as a hub for the rest of the data flow. As shown in the diagram, two-way data flow occurs between the GIS application and the liquefaction potential procedure and the site resonance procedure, primarily by interaction through the graphic user interface. Additionally, two-way data flow occurs between the GIS application and the spatial data utilized by the application, in the form of

user selections and visual display of data. Data is also transferred from the GIS to the data entry procedure when this option is selected within the user interface. Data from the data entry procedure is then written to the geotechnical database. The geotechnical database also experiences two-way data flow between both the liquefaction potential procedure and the site resonance procedure. Both of these procedures rely on data from the geotechnical database to perform the calculations within each respective procedure, and each procedure produces a geotechnical output file which resides in the database. Likewise, two-way dataflow occurs between each procedure and the seismic data, as each procedure reads an input time history, and produces calculated seismic parameter values. Finally, both the liquefaction potential procedure and the site resonance procedure write data to the spatial data after computation is complete, so one-way data flow is shown between these elements.
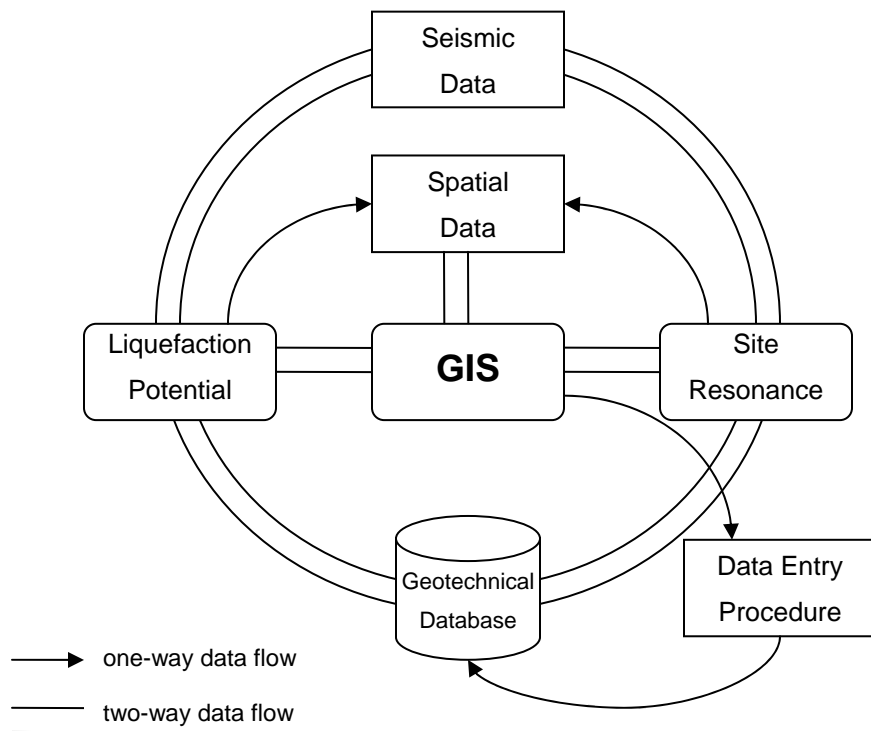
Figure 3.5 Data Flow Diagram for the S4 Application

3.3. GEOTECHNICAL ENGINEERING ALGORITHMS

An algorithm can be defined as "A finite set of unambiguous instructions performed in a prescribed sequence to achieve a goal, especially a mathematical rule or procedure used to compute a desired result" (Leinedelien 2005). For this application, two principal geotechnical algorithms were developed to calculate two fundamental seismic hazard parameters. These algorithm objectives are: (1) the magnification factor caused by resonance between the predominant period of a ground motion (derived by a Fourier power spectra) and the characteristic site period of a soil column (also known as the site resonance) and (2) the liquefaction potential, calculated as a factor of safety against liquefaction potential. Additionally, as "stepping stones" within these algorithms, the calculation of various parameters were required, including cyclic stress ratio, cyclic resistance ratio, characteristic site period, magnitude scaling factor and several others. Both of these categories are described, step-by-step, below, along with the general interaction procedure.

3.3.1. Algorithms for Magnification Factor. The calculations required to compute the magnification factor require several separate computations, which are performed independently. The principal computations required to determine the site resonance are a) the determination of the predominant period of the input ground motion (T_P), b) the characteristic site period of the input soil column (T_s), and c) the determination of the resultant magnification factor.

As discussed in Section 2, there are many available methods to calculate each of these parameters, and many ways to represent the results of these calculations. The pros and cons of these methods were discussed in Section 2, and suitable methods for each computation were selected for this application. To compute the predominant period, T_P, of the input ground motion, an external program was used to calculate the Fourier power spectra of the input ground motion, using a Fast Fourier Transform (FFT). To compute the characteristic site period, T_S, the current working industry standard, as proposed in the 2000 International Building Code (International Code Council, Inc. 2000) was selected. This method utilizes a weighted average of the measured shear wave velocity of a soil column to compute the characteristic site period. And finally, to determine the

magnification factor, a simple frequency-based magnification equation, as discussed by Kramer (1996), was converted into a time-based equation and utilized for this procedure. Once an input file (as discussed later in Section 3.4) is complete for at least one borehole, results for site ground motion magnification factor may be computed. Initially, the user is required to select the features (boreholes), within the Data View, for which they would like computations completed. Next a value for the moment magnitude of the ground motion must be supplied by the user. An input ground motion must then be selected and the user is given the option to view a plot of the selected ground motion, and then to choose a different ground motion if desired. This allows the user to view their file options for ground motions before running the actual computations. Once a ground motion is selected, the application calculates the Fourier power spectra of the ground motion and reports the predominant period of the ground motion. The application then loops through the selected features and calculates the magnification factor for each of the selected features, using the methods described below. A flowchart of this procedure is shown in Figure 3.6.

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). FFTPowerSpec computes the Fourier power spectra using a Fast Fourier Transform (FFT), and exports a Fourier power spectrum.

To use FFTPowerSpec, a simple text-based acceleration history input file (with time step equal to 0.02 seconds) is called by the application from a user selection, via a batch file. The program then exports a text file containing the Fourier power spectra (period and power in g^2). Next the visual basic code loops through the output power values to determine the peak value, and then locates its corresponding period. This value is later compared to the characteristic site period.

The first step in calculating the characteristic site period is determining the weighted shear wave velocity of the soil column (International Code Council, Inc. 2000). This is computed by use of equation 14.
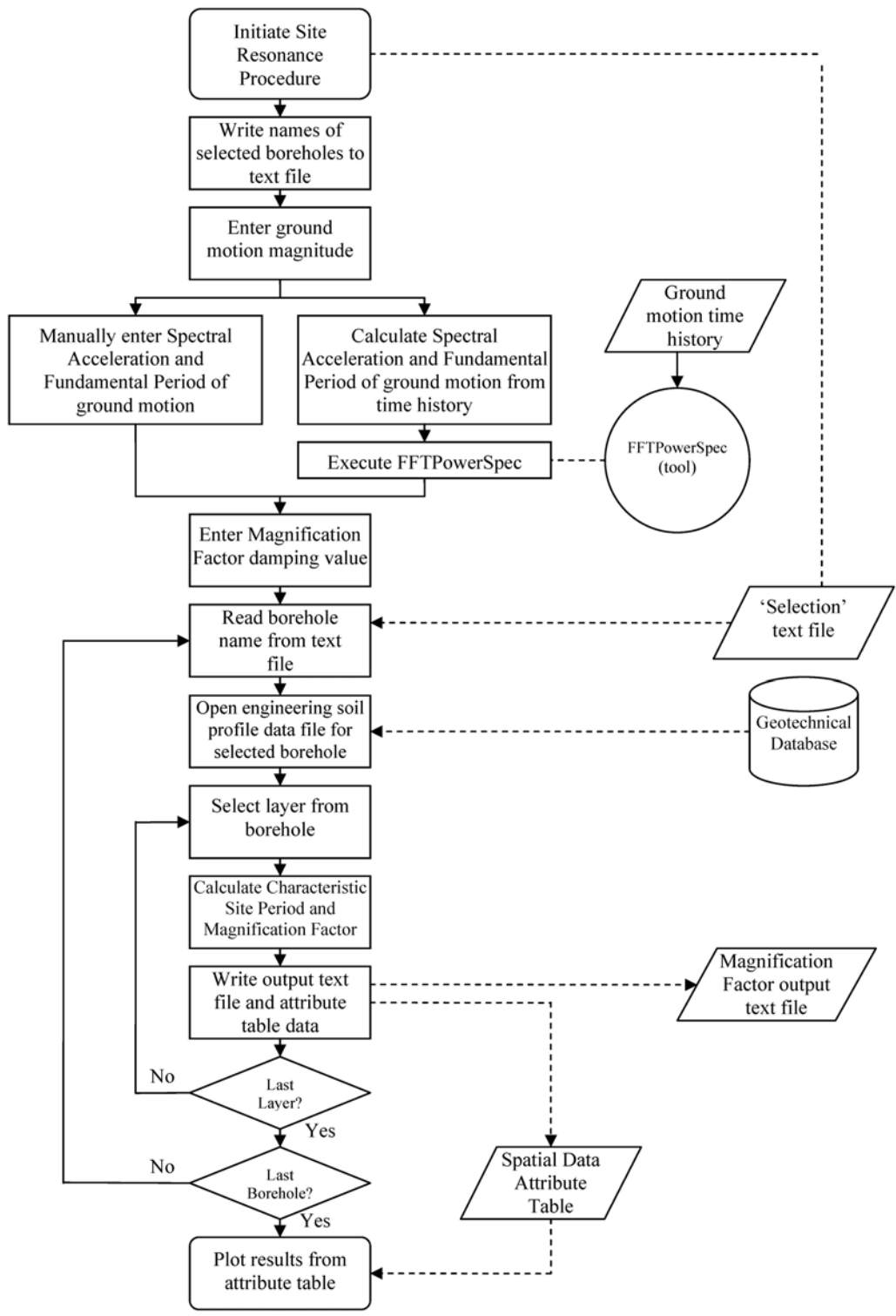
Figure 3.6. Flowchart for S4 Magnification Factor of Ground Motion Procedure

$$V_s = \frac{\sum\limits_{i=1}^{n} d_i}{\sum\limits_{i=1}^{n} \dfrac{d_i}{v_{si}}} \tag{14}$$

$$\sum\limits_{i=1}^{n} d_i = 100 \, feet$$

where d_i = the thickness of any layer between 0 and 100 ft
v_{si} = the shear wave velocity in feet per second

By utilizing this method, a single averaged shear wave velocity value may be obtained for the entire soil column, weighted for the thickness of each layer.

This weighted average of shear wave velocities is then input into the basic period formula as derived by numerous researchers (Reid 1908; Jacobsen 1930), and as shown in equation 15.

$$T = \frac{4H}{V_S} \tag{15}$$

where H = thickness of soil column
V_S = average shear wave velocity of soil column

Once both the predominant frequency of the ground motion and the characteristic site period are calculated, they may be compared using a magnification factor. The magnification factor (MF) is a standard function frequently used in physics and any vibration analysis (Kramer 1996). It can be calculated as

$$MF = \frac{1}{(1 - \beta^2)} \tag{16}$$

where β, the tuning factor is defined as:

$$\beta = \frac{\omega_s}{\omega_0} \qquad (17)$$

where ω_s = the characteristic site circular frequency
  ω_0 = the fundamental circular frequency of the ground motion

Since period is equal to the inverse of frequency, both the fundamental frequency and the site frequency may be converted to periods by taking the inverse of each. This results in the equation:

$$MF = \frac{1}{\left[1 - \left(\frac{\left(\frac{1}{T_s} \right)}{\left(\frac{1}{T_0} \right)} \right)^2 \right]} \qquad (18)$$

where T_s = the characteristic site period
  T_0 = the fundamental period of ground motion

Simplifying this equation gives:

$$MF = \frac{1}{\left[1 - \left(\frac{T_0}{T_s} \right)^2 \right]} \qquad (19)$$

In this form, period values may be used to produce the same magnification factor graph as that produced by the frequency values. (Kramer 1996)

When using the undamped equation (as can be seen in Figure 3.7) which is not realistic, as the tuning factor approaches unity the standard magnification factor approaches infinity. This type of equation does not work well in a programming
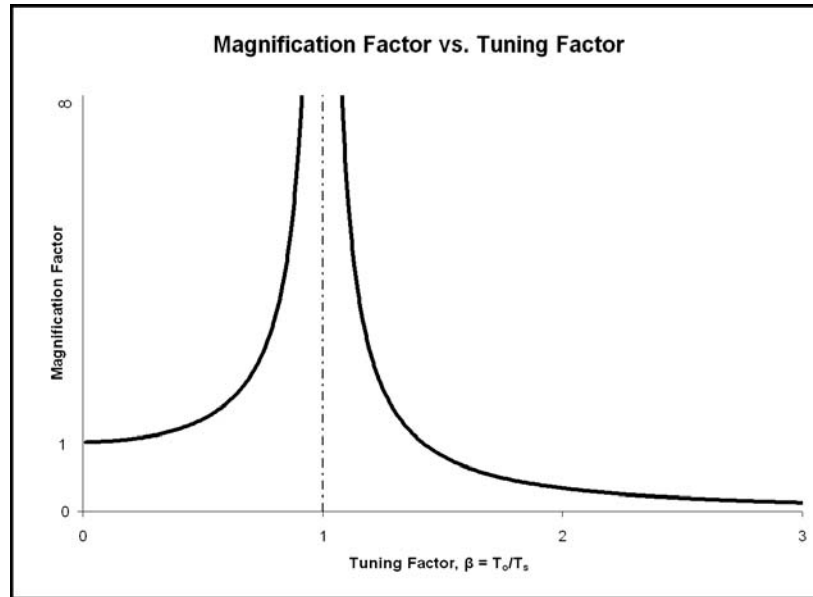
Figure 3.7. Magnification Factor

environment, so a damped magnification factor equation must be used to prevent dividing by zero in the application in the case of the characteristic site period being equal to the fundamental period of ground motion.

The damped magnification factor is given by the equation (Kramer 1996):

$$MF = \frac{1}{\sqrt{\left(1-\left(\frac{T_0}{T_s}\right)^2\right)^2 + \left(2\xi\left(\frac{T_0}{T_s}\right)\right)^2}} \tag{20}$$

where T_s = the characteristic site period
       T_0 = the fundamental period of ground motion
       ξ = the damping ratio

A plot of the magnification factor for various damping ratios is shown in Figure 3.8. Within the S4 application, the damping factor for the equation above is entered as a user input at runtime.
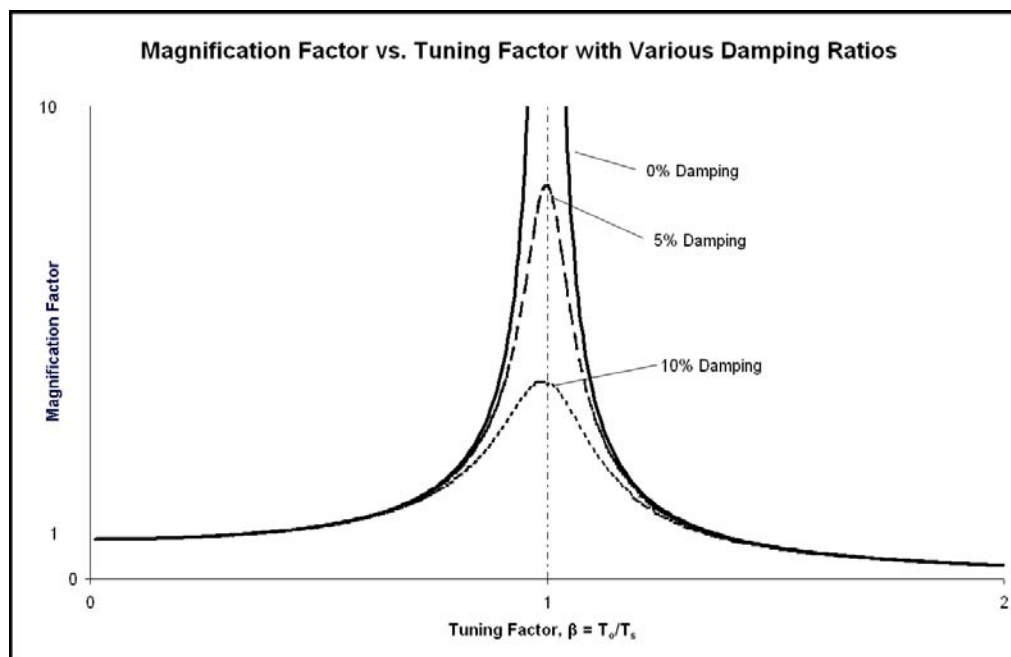
Figure 3.8. Magnification Factor with Various Damping Ratios

By programmatically comparing the predominant period of the ground motion with the characteristic site period, the degree of magnification is determined. To plot the results on the map in the Data View, a procedure is executed to plot a circle at the location of each feature in a new layer with a graduated size and color corresponding to preset magnitudes of magnification. The sizes, colors, and corresponding values for these graduated circles are given in Table 3.1. 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.

3.3.2. Liquefaction Potential Algorithms. As discussed in Section 2, there are many available methods for calculating the liquefaction potential of a given soil, and many ways to represent the results of these calculations. The pros and cons of these methods were discussed in Section 2 and the revised "Simplified Method" for calculating liquefaction potential, most recently proposed by Youd et al. (2001), was shown to be the

Table 3.1. Display Format for Magnification Factor Results

Magnification Factor	Display Color	Display Circle Size (Relative Size)
0.0 - 0.75	Blue	8 point (Very Small)
0.75 - 1.0	Green	12 point (Small)
1.0 - 1.25	Yellow	16 point (Medium)
1.25 - 1.5	Red	20 point (Large)
1.5+	Red	25 point (Very Large)

most straight-forward and widely accepted method used today.

The revised "simplified method" requires the calculation of two values: the seismic demand on a soil layer or Cyclic Stress Ratio (CSR) and the capacity of the soil to resist liquefaction or Cyclic Resistance Ratio (CRR). Simply stated, dividing the CRR by the CSR results in the computation of a factor of safety against liquefaction. This factor of safety can then be corrected for different earthquake magnitudes by the use of a Magnitude Scaling factor (MSF).

The first step in calculating the liquefaction potential is collecting and accessing the subsurface data needed for the calculations. As discussed later in Section 3.4, a text-based input file format is needed for this purpose. This desired input file format is sample-oriented, with a separate text line for each sample depth, containing corresponding soil parameter values. A separate input file of this type is created for each borehole location, either entered manually by the user, or created semi-automatically via the engineering profile input procedure.

Once an input file is complete for at least one borehole, results for liquefaction potential may be calculated. Like with the characteristic site period and site resonance calculations, the user is required to select the features (boreholes) on the map within the Data View for which they would like computations completed. As before, an input ground motion must be selected and a value for the moment magnitude entered. The application then loops through the selected features and calculates the liquefaction potential in the form of a factor of safety against liquefaction (within another loop) for each sample depth below the groundwater table, for each of the selected features. A flowchart of this procedure is shown in Figure 3.9.
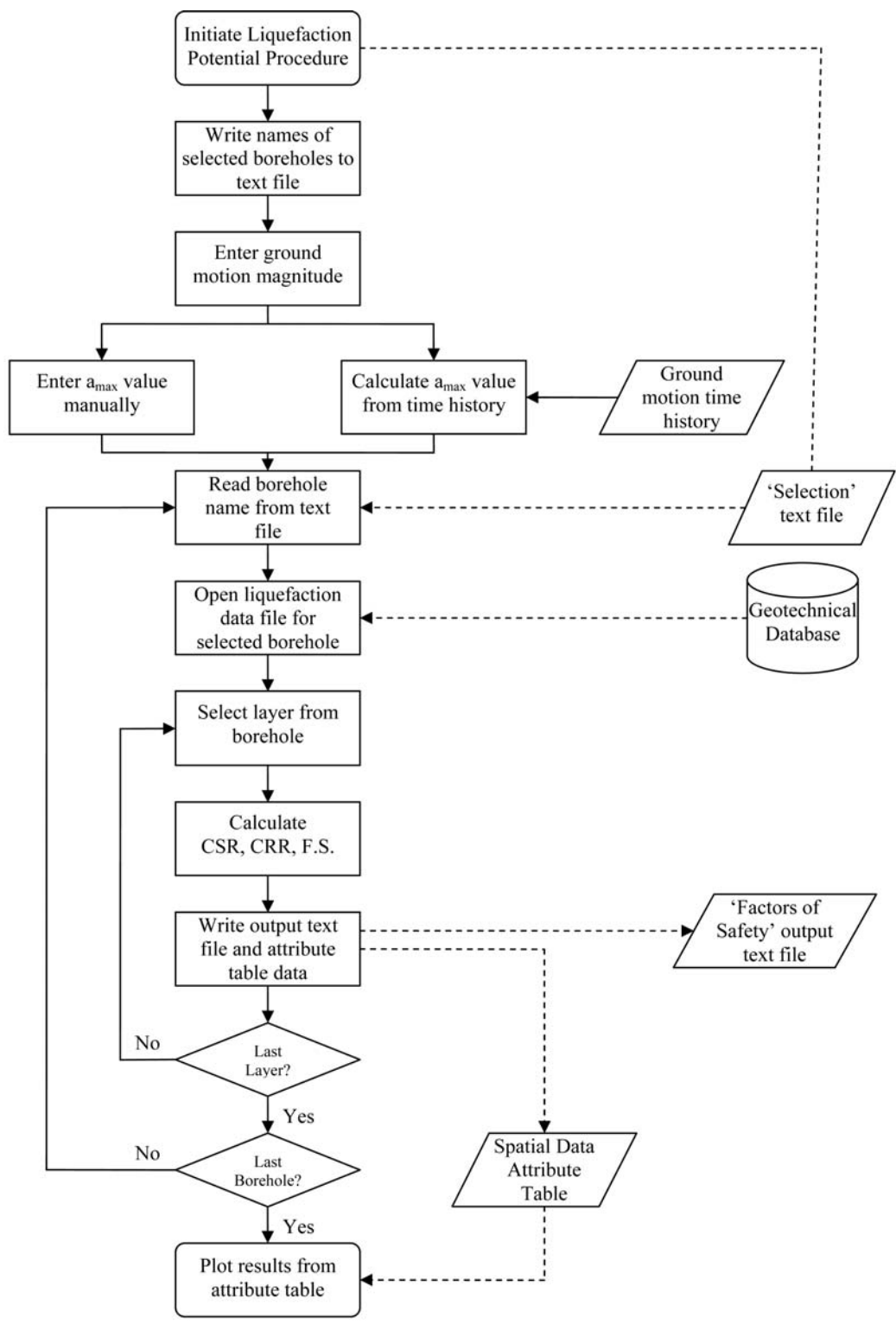
Figure 3.9. Flowchart for S4 Liquefaction Potential Procedure

To calculate the liquefaction potential in the form of a factor of safety against liquefaction, both the CSR and the CRR must be calculated from input file values read into a dynamic array. However, before these values are calculated, the application first checks to see if the specified layer is above the groundwater table. If the layer is above the groundwater table, it is ignored and the application proceeds to the next layer. Once the first layer beneath the groundwater table is encountered, the CSR and CRR are calculated for this layer and each successive layer. The equation used to calculate the CSR, as proposed by Youd et al. (2001) factors in the horizontal maximum acceleration (a_{max}), the vertical overburden stresses and a stress reduction coefficient based on the depth of the soil layer, as shown in equation 21.

$$CSR = 0.65\left(\frac{a_{max}}{g}\right)\left(\frac{\sigma_{vo}}{\sigma'_{vo}}\right)r_d \tag{21}$$

$$\begin{aligned}
where \quad a_{max} \quad &= \text{peak horizontal acceleration at the ground surface} \\
&\quad \text{generated by the earthquake} \\
g \quad &= \text{acceleration of gravity} \\
\sigma_{vo} \quad &= \text{total vertical overburden stress} \\
\sigma'_{vo} \quad &= \text{effective vertical overburden stress} \\
r_d \quad &= \text{stress reduction coefficient}
\end{aligned}$$

The stress reduction coefficient above is calculated based on sample or layer depth as proposed by Youd et al. (2001) and shown in equation 22.

$$r_d = \frac{(1.000 - 0.4113z^{0.5} + 0.04052z + 0.001753z^{1.5})}{(1.000 - 0.4177z^{0.5} \_ 0.05729z - 0.006205z^{1.5} + 0.001210z^2)} \tag{22}$$

$$where \quad z \quad = \text{depth beneath ground surface in meters}$$

In this application, the CRR is based on corrected Standard Penetration Test values. This test data must be corrected for overburden, sampling variables, hammer efficiency and a number of other similar discrepancies. These corrections are completed in the data input stage and discussed in Section 3.4. One correction to the SPT blowcount is computed at the time of program execution, as it differs for each sample. The

correction for fines content is applied as proposed by Youd et al. (2001) and shown in equation 23.

$$(N_1)_{cs} = \alpha + \beta(N_1)_{60} \tag{23}$$

where $(N_1)_{60}$ = corrected standard penetration resistance
α and β = coefficients determined from the following relationships:

$$\alpha = 0 \text{ for FC} \leq 5\% \tag{23a}$$

$$\alpha = \exp[1.76 - (190/FC^2)] \text{ for } 5\% < FC < 35\% \tag{23b}$$

$$\alpha = 5.0 \text{ for FC} \geq 35\% \tag{23c}$$

$$\beta = 1.0 \text{ for FC} \leq 5\% \tag{23d}$$

$$\beta = [0.99 + (FC^{1.5}/1,000)] \text{ for } 5\% < FC < 35\% \tag{23e}$$

$$\beta = 1.2 \text{ for FC} \geq 35\% \tag{23f}$$

where FC = fines content, or the amount passing the #200 sieve in a sieve analysis

Once this correction is applied, the application can calculate the CRR. The CRR equation as proposed by Youd et al. (2001) is given in equation 24.

$$CRR_{7.5} = \frac{1}{34 - (N_1)_{60}} + \frac{(N_1)_{60}}{135} + \frac{50}{[10 \cdot (N_1)_{60} + 45]^2} - \frac{1}{200} \tag{24}$$

for $(N_1)_{60} < 30$
where $(N_1)_{60}$ = Corrected SPT Blow Count

The final major calculation for determining the liquefaction potential is the computation of the magnitude scaling factor (MSF). The above equations for CSR and CRR were determined for earthquakes of moment magnitude 7.5. Of course, in the real world, ground motions occur with varying intensities, so a scaling factor is required to calibrate the factor of safety against liquefaction to the magnitude of the input ground motion. For this purpose, the MSF equation as proposed by Idriss and documented by

Youd et al. (2001) was determined to be the most suitable. A discussion of this determination can be found in Section 2.

The MSF equation, as proposed by Idriss (1995) is calculated as follows:

$$MSF = \frac{10^{2.24}}{M_w^{2.56}} \tag{25}$$

where M_w = Earthquake Moment Magnitude

Once the CSR, CRR, and MSF are determined, a factor of safety (F.S.) against liquefaction, as proposed by Youd et al. (2001), can be calculated and the potential for liquefaction recorded at that depth.

$$FS = \left(\frac{CRR_{7.5}}{CSR} \right)(MSF) \tag{26}$$

where $CRR_{7.5}$ = Cyclic Resistance Ratio for a magnitude 7.5 earthquake

CSR = Cyclic Stress Ratio

MSF = Magnitude Scaling Factor

This calculation is then repeated within a loop for each line of data (each representing a unique depth and SPT value), and the results are written to a unique output file for each borehole. This output file contains two columns of data, containing the factor of safety (F.S.) values and the associated depth for that F.S.

This entire procedure is then again repeated within a loop for each selected feature, and a unique output file is generated, containing F.S. data versus depth for each borehole.

One of the biggest issues with calculating the liquefaction potential in a GIS is that while the revised "Simplified Procedure" produces results in three dimensions (X and Y directions in plan versus depth), a typical GIS is only capable of plotting in two

dimensions (Carroll 1998). To plot the results in the X-Y plane, a procedure is executed to find the lowest F.S. value for each feature and plot a circle at the location of that feature in a new layer with a graduated size and color corresponding to preset ranges, similarly to the previous procedure. This sizes, colors, and corresponding values for these graduated circles are given in Table 3.2. With this type of display, those features with very low F.S. results are plotted with very large or large red circles, those with F.S. values slightly above 1.0 are plotted with medium sized yellow circles, and those with high F.S. values are plotted with small or very small green or blue circles. To view the data in the third dimension, a simple plotting procedure was developed. A corresponding plot of the F.S. data versus depth graph can be generated by simply clicking on a borehole feature. This plot is shown in Figure 3.10.

Table 3.2. Display Format for Liquefaction Potential Results

Factor of safety	Display Color	Display Circle Size (Relative Size)
1.5 - 5	Blue	8 point (Very Small)
1.25 - 1.5	Green	12 point (Small)
1.0 - 1.25	Yellow	16 point (Medium)
0.75 - 1.0	Red	20 point (Large)
0.0 - 0.75	Red	25 point (Very Large)

With this series of procedures, from a user standpoint, a typical liquefaction potential screening procedure may proceed as follows: The user enters boreholes and subsurface data for each borehole. The user then selects these desired boreholes and the liquefaction procedure is initiated. An input ground motion and a moment magnitude value is selected by the user, and the liquefaction potential is calculated. The lowest F.S. value for each borehole is displayed by a series of graduated circles each corresponding to one of the selected boreholes. The user can then click on each of the boreholes with the lowest F.S. and view the plot of F.S. versus depth to determine whether each location requires further analysis (i.e. a site specific analysis).
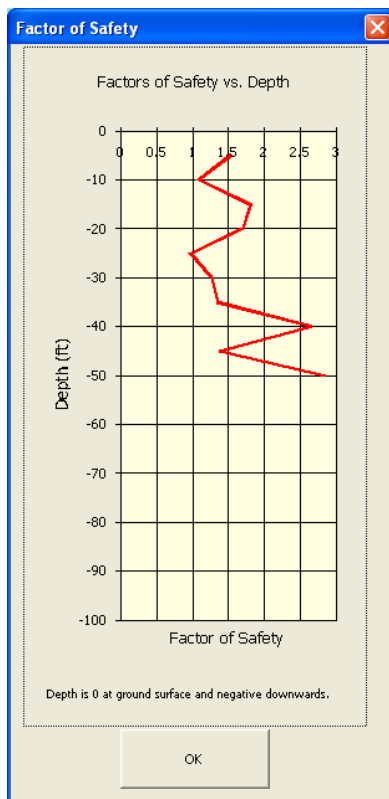
Figure 3.10. Plot of Factor of Safety versus Depth

3.4. DESIRED INPUTS AND OUTPUTS

The first step in the actual calculation of the parameters for estimating the magnification factor of ground motion, or site resonance, was the generation of a text file format for use in each of the calculations. Initially, two items were considered when determining what information was required for an input file. The first consideration was the desire to allow the user input of an engineering profile, which is standard for most engineering computer applications. Secondly it was determined which input parameters were minimally required for calculation of the different required computations. These required parameters were determined to be: a) depth to top of soil layer, b) depth to bottom of soil layer, c) shear wave velocity, and d) the peak ground acceleration. An input ground motion in time-history format was also required for which to calculate the predominant period. Additionally, several other parameters were deemed to be worthwhile additions to the input file, to allow the creation of an engineering profile, and as the format of the data file is hard-coded into the program, in the event that future

modifications to the application required more information for additional features. Finally, a few parameters were added to the input file for convenience including the borehole name, and a count of the number of lines of data.

      The final data types included in the engineering soil profile input file are: a) borehole name, b) depth to piezometric surface, c) line number, d) depth to top of layer, e) depth to bottom of layer, f) unit weight of soil, g) USCS classification, h) fines content, i) shear wave velocity, j) undrained shear strength, and k) internal angle of friction. (The internal angle of friction is not utilized at this time, but is included for future development). The peak ground acceleration would be imported from the input ground motion at the time of execution.

      The engineering soil profile input text file format was given the extension "*.epf" for <u>E</u>ngineering <u>P</u>rofile <u>F</u>ile. An example of this file format is shown in Figure 3.11.

```
Boring Name
US60_A3799E41+5535L

Water Table Depth

5

Line, Top Depth, Bottom Depth, Gamma, USCS, FC, Vs, Su, Phi
1,0,5,125,SW,10,800,0,33
2,5,10,128,SM,25,800,0,33
3,10,15,125,SP,0,900,0,34
4,15,20,125,SP,0,950,0,34
5,20,25,127,SM,15,1000,0,33
6,25,30,120,CL,95,1000,1200,0
7,30,35,120,CL,95,1250,1250,0
8,35,40,125,SP,2,1000,0,34
9,40,45,125,SP,1,1000,0,34
10,45,50,125,SP,4,1000,0,34
```

Figure 3.11. Engineering Soil Profile Input Text File

      A data entry procedure was developed to aid in the creation of these files. Initially, a dialog is displayed requesting the user to enter the number of layers for which

they would like to enter data. After entering this number, the user is then able to populate input cells, within a dialog, within a loop to create the text file. This input screen is shown in Figure 3.12.

Figure 3.12. Engineering Soil Profile File Data Entry Screen

This input screen is displayed once for each layer the user has elected to enter. Each of these layers corresponds to one line in the data file. A second data entry procedure is available as an option from the engineering soil profile data entry procedure. This procedure is also used to enter data for the liquefaction potential data file, and is discussed in more detail, later in this section.

Similar to the input file created for the characteristic site period, a text file format was generated for use in the calculation of the liquefaction potential. Initially, it was determined which input parameters were minimally required for calculation of liquefaction potential at a discrete depth using the revised "Simplified Procedure" (Youd et al. 2001). These were determined to be: a) depth, b) effective vertical overburden stress, c) total vertical overburden stress, d) the corrected SPT blowcount (for SPT based calculations), e) Unified Soil Classification System (USCS) soil classification f) the peak ground acceleration, and g) the moment magnitude of the input ground motion. Additionally, several other parameters were deemed to be worthwhile additions to the input file, in the event that future modifications to the application required more information for additional features. Also, it was determined that some of the parameters could be calculated from other parameters if additional information was provided. For

example, effective vertical overburden stress could be calculated from the total vertical overburden stress if the depth to the piezometric surface was included. In this way, the user was no longer required to enter the effective vertical overburden stress, resulting in easier input, and more information was included in the input file in the form of more diverse data. Finally, a few parameters were again added to the input file for convenience including the borehole name and a count of the number of lines of data.

The final data types included in the liquefaction input file are: a) borehole name, b) depth to piezometric surface, c) line number, d) depth to sample, e) unit weight of soil, f) total vertical overburden stress, g) corrected SPT blowcounts for sample, h) USCS classification, i) fines content, and j) shear wave velocity. It was determined to omit the value for the moment magnitude from the input file, as it would flow more smoothly to enter this value as an input at the time of computation. In this respect, this value could be changed readily to analyze a number of different ground motion situations. The peak ground acceleration would be imported from the input ground motion at the time of execution.

Similar to the engineering profile file, the liquefaction input text file format was given the extension "*.lpf" for Liquefaction Potential File. An example of this file format is shown in Figure 3.13.
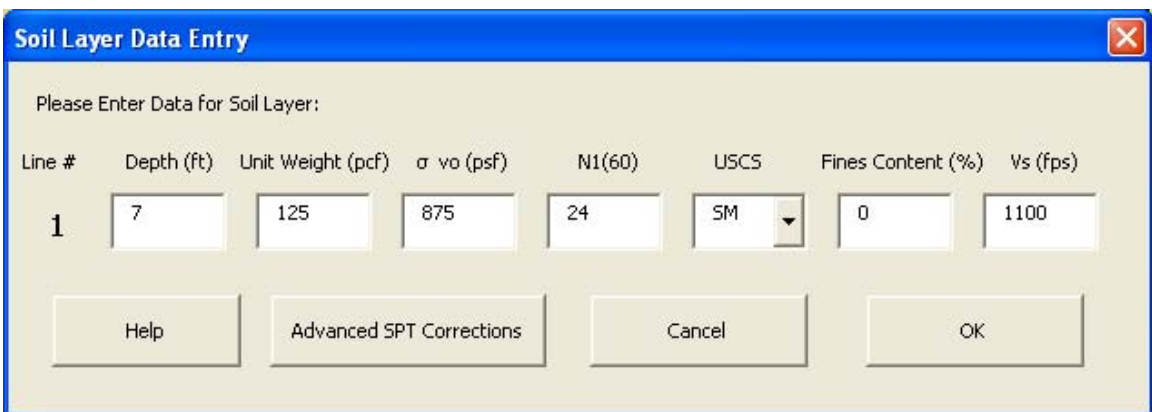
Like with the engineering soil profile procedure, a data entry screen was developed to ease the creation of these files. After entering a number of lines for which to enter data, the user is then able to populate input boxes within a loop to create the text file. This input screen is shown in Figure 3.14.
Additionally, a small sub routine was also included within the data entry dialog for liquefaction potential to calculate the corrected SPT blowcount values from the raw SPT values using the required correction factors. These factors include corrections for vertical overburden stress, drilling and sampling equipment, borehole diameter, and rod length, and are entered in an input form, which is pre-populated with suggested values for each factor. Suggested values for correction factors for different conditions can be viewed by clicking on the help menu within this dialog. These values are shown below in Table 3.3.

Figure 3.13. Liquefaction Potential Input Text File

Figure 3.14. Liquefaction Potential File Data Entry Screen

Table 3.3. Correction Factors for SPT Blowcount Values (after Robertson and Wride 1998 (modified from Skempton 1986))

Correction Factor	Correction Application	Drilling or Sampling Variable	Correction Value
C_N	Overburden Pressure	-	$(P_a/\sigma'_{vo})^{0.5}$
		-	$C_N \leq 1.7$.
C_E	Hammer Energy Ratio	Donut hammer	0.5 - 1.0
		Safety hammer	0.7 - 1.2
		Automatic-trip Donut-type hammer	0.8 - 1.3
C_B	Borehole Diameter	65 - 115 mm	1.0
		150 mm	1.05
		200 mm	1.15
C_R	Rod Length	< 3 m	0.75
		3-4 m	0.8
		4-6 m	0.85
		6-10 m	0.95
		10-30 m	1.0
C_S	Sampler	Standard sampler	1.0
		Sampler without liners	1.1 - 1.3
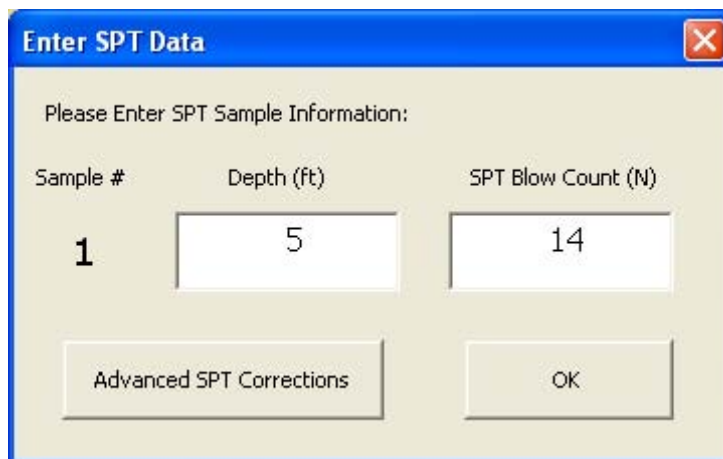
These correction factors are applied as shown in equation 27.

$$(N_1)_{60} = N_m C_N C_E C_B C_R C_S \tag{27}$$

where N_m = measured standard penetration resistance
C_N = correction factor for overburden pressure applied to SPT
C_E = correction factor for hammer energy
C_B = correction factor for borehole diameter
C_R = correction factor for drilling rod length
C_S = correction factor for split spoon sampler without liners

This equation allows SPT N-values contained in the input file to be corrected. Another correction to the SPT N-value is completed for the fines content of the subject soil. However, this correction is made during the program execution, as was discussed within Section 3.3.

It needs to be noted that unlike the input file used for calculation of the characteristic site period and site resonance, which allows the user to input an engineering profile, the input file for liquefaction potential is strictly sample oriented. A separate line is written for each SPT sample that is desired for liquefaction potential calculation, independent of any specific layer properties. The equation format for the "Simplified Procedure" works very easily with this type of "sample-based" input file. This format, however, makes it impossible to calculate the vertical overburden stress programmatically (without additional input), which is why it is required as a user pre-calculated input. For this reason, a second data entry procedure was developed for the liquefaction potential input file, which works in conjunction with the characteristic site period and site resonance input file generation procedure. While entering the engineering profile for characteristic site period and site resonance calculations, the user is given the option to also create an input file for liquefaction potential calculation. If this option is selected, after completion of the engineering profile data entry, an input box is displayed within a loop to enter the desired number of SPT sample blowcount values, along with associated depths. This data entry screen is shown in Figure 3.15.

Figure 3.15. Entry Screen for Liquefaction Data

Additionally, in this procedure, the total vertical overburden stress is calculated based on the depth of the sample and the data entered for the engineering profile input file. While this calculation is relatively simple with hand calculations, performing it programmatically is somewhat more of a challenge. The basic formula for calculating the total vertical overburden stress value (Coduto 1998) is

$$\sigma_{vo} = \sum_{i=1}^{n} \gamma_i \cdot H_i \qquad (28)$$

$$\begin{aligned}
&\textit{where } \sigma_{vo} && = \text{total vertical overburden stress} \\
&\quad\ i && = \text{individual soil layer} \\
&\quad\ \gamma && = \text{total unit weight of the soil strata } i \\
&\quad\ H_i && = \text{thickness of the soil strata } i
\end{aligned}$$

To execute this in the code, a loop was written to cycle through each line in the engineering profile input file. For each line, an "if statement" is executed to determine whether the depth of the sample falls within that layer. If the depth does not fall within the layer, the thickness of the layer is calculated and multiplied by the total unit weight. When the layer is encountered which contains the depth of the sample, the thickness of the layer above the sample depth is calculated and again multiplied by the total unit weight. A summation is then done of these resultant values to produce the total overburden stress.

The remaining values included in the liquefaction potential input file are imported or calculated from the previously entered characteristic site period and magnification factor input file, and the "*.lpf" file is created programmatically. If the same data is entered, both procedures will produce identical input files for liquefaction potential calculations.

In this way, a borehole "database" was constructed, with two text files for each borehole. This approach provides seamless interaction to the user and the small size of *.txt files allows the storage of data for many boreholes without becoming cumbersome. Additionally, at this time the design excluded any outside programs or applications (including database packages) that were not readily available to the user, or that could not

be included in the software package. This could be changed in future developments of this software.

Finally, it should be noted that a macro and procedure were developed to work within Microsoft Excel to import data from a project specific database into the format used in this application. This macro was designed specifically for this project database, so it has little applicability outside of this project. For this reason this macro is discussed in the section detailing the geotechnical data for the pilot study (Section 4.2) and not in this section. However it is mentioned here, as this was another contributing factor in the decision to utilize a text file based "database".

3.5. LIMITATIONS

Several known limitations exist within the S4 application, with some of the limitations being found in the methods of calculations, while others are found in input and output formats. Still other limitations are found in the quality requirements of the input data. Finally, as this is a prototype application, countless small omissions, dead ends, and programming errors will undoubtedly surface as the prototype program is analyzed. However, due to the nature of a prototype, these can be expected and will not be discussed here.

In regard to the liquefaction potential calculations, the revised simplified procedure for liquefaction potential estimation was chosen as it is the most straightforward and widely accepted method used today. However, as discussed in Section 2, drawbacks and limitations to it do exist. Perhaps the most important limitation is that it only applies to relatively clean sands, though liquefaction has been documented in both silts and gravels (Andrews and Martin 2000); (Andrus 1994). Due to a lack of generally accepted methods for calculation of liquefaction in these materials, these procedures were omitted from this application. The reasoning behind this decision is discussed in more detail in Section 2.

Also, to most accurately perform a liquefaction analysis, it is necessary to attenuate the bedrock ground motion for the site through the soil column to each depth where a liquefaction potential calculation is desired. With this method, each depth

analyzed may have a slightly different value for a_{max} due to amplification or deamplification of the motion by the soil column.   However, for the S4 application a single value of a_{max} is used for all liquefaction calculations within a given analysis. While this is only an approximate method for calculating the liquefaction potential, it serves as a simplified method to screen a site for locations with high liquefaction potential.

Within the magnification factor computations, several limitations also exist. The foremost is the assumptions made in the calculation of the Fourier power spectra and the predominant period of the ground motion. This method of analysis, though useful and easily implemented, is a somewhat crude representation of the frequency content of the ground motion (Kramer 1996). It has been noted and should be noted again that this application is not a replacement for a site-specific ground response analysis. Specific commercial software packages are available for these types of analyses and should be used for such. The future addition of a true site-specific ground response functionality to the S4 application would be a very worthwhile modification.

An additional limitation found in the magnification factor computations, specifically within the characteristic site period calculations, can significantly affect the analysis results. The characteristic site period is only calculated based on the user-entered layers, so if a borehole was not extended to bedrock, and estimations were not made for the remaining depth, the calculated period will be computed incorrectly. For example, if bedrock exists at 100 feet for a given soil profile, but the soil boring at this location was only drilled to a depth of 50 feet, soil layers would only typically be entered to a depth of 50 feet. The S4 application would then calculate the characteristic site period based on the available 50 feet of data. This could result in a site period grossly different than the actual period based on a 100-foot layer. To account for this in S4 (for boreholes that were not extended to bedrock), it is required to enter an additional estimated layer that extends from the bottom of the measured layers to bedrock.

Though scale independent, the S4 application is also limited by the scale of the analysis. A given seismic scenario is only relevant for the area for which it was developed. In most cases, this is a point located a certain distance and direction from the contributing sources. Locations within a small area will experience similar ground

motion scenarios in a given earthquake, though as the size of the area increases, the scenarios for each point will begin to differ as the ground motion attenuates differently with distance. Therefore, it is impossible to perform an analysis on an entire state, or even county, as the distance and direction from the ground motion source will vary significantly across this area. For this reason it is recommended that S4 analyses be limited to areas encompassing project sites, towns or at most, small cities. Areas larger than this will introduce significant enough errors so as to be unusable if a single ground motion scenario is used. Larger areas may be analyzed by discretizing them into smaller projects and analyzing them with different ground motion scenarios.

Data formatting for the S4 application is very particular and all data must be in the required format if the application is to execute. If one digit is out of place, it could result in a catastrophic crash of the application. For this reason if data is entered manually without the use of the input dialogs, detailed checking of this input data is a necessity before executing the application.

Additionally, the FFTPowerSpec program, and the S4 application in general, will currently only support the input of acceleration time histories having a time step of 0.02 seconds. A single value was required to be hard-coded into the FFTPowerSpec tool, so the value of 0.02 seconds was chosen, as: a) it is a generally recognized standard time step for acceleration time histories, and b) it is a larger time step than most other accepted intervals, so data with a smaller time increment can easily be converted to this standard by removing data points in a spreadsheet. It would be advantageous to have the time step input as a dynamic variable in future versions of the S4 application.

One of the most obvious limitations deals with the subject of quality of input data for any "black box" computer program. In these applications, the quality of the output is highly, if not completely, dependant on the quality of the input. Within both the liquefaction potential and the ground motion magnification factor computations of the S4 application, the accuracy of the results is only as good as the estimation of the input parameters. To put it simply and borrow from the old adage, "garbage in = garbage out."

Finally, the methodology presented for the S4 application was chosen to demonstrate simple and fundamental concepts of geotechnical earthquake engineering in a framework that allows for the analysis of spatially distributed data within a GIS. These

methods are somewhat simplified and have little merit when compared to what can be accomplished in a site-specific geotechnical analysis when ground motion amplification and liquefaction analyses are performed. However, spatially distributed data is rarely used for the site-specific level of analyses of a complex infrastructure system. Therefore, the application of this methodology should be limited as a preliminary screening tool.

3.6. SUMMARY

This section discussed the development of the Spatial Seismic Screening Software (S4) application, which was designed to rapidly screen for two specific seismic hazards (liquefaction and magnification factor) within the ArcGIS environment. Before development could begin, a design methodology and approach were contemplated, with the desired user and the scale and resolution of the project being the primary considerations. Once these items were determined, the required input and output parameters were established, and file formats for their storage were devised. The system architecture was considered next and three aspects, namely the Visual Basic programming, the graphical user interface, and the ArcGIS interface were individually assessed. The engineering algorithms for determination of liquefaction and the magnification factor were then determined, and the means of calculation analyzed. Finally the limitations of the program were considered, both within the inner workings of the application and in the input data. Through this process, it was possible to develop a working prototype of the S4 application that can be modified in the future to produce a distributable geotechnical earthquake engineering tool.

4. PILOT STUDY – POPLAR BLUFF, MISSOURI

4.1. SELECTION OF LOCATION – POPLAR BLUFF, MISSOURI

For the pilot study, a location was desired where several conditions could be met. The site selection criteria included the following: a) the ability to test various geological conditions within a regional setting, b) the location of a seismic source within close proximity to produce a significant ground motion, and c) the availability of enough subsurface geotechnical data in both quantity and type. From experience with concurrent geotechnical research projects (Anderson et al. 2005, Anderson et al. 2000), a site in southeast Missouri, around the city of Poplar Bluff, was recognized as meeting these criteria.

Poplar Bluff, Missouri is located in the southeast corner of Missouri, at the intersections of U.S. Route 67 and U.S. Route 60, as shown in Figure 4.1. 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). The regional geology of the Poplar Bluff area is discussed in more detail in Section 4.2.1.

The close proximity to the New Madrid Seismic Zone and the history of seismic activity help justify the area for use in this study. While the most recent sizable earthquakes occurred in 1811, 1812, and 1895, smaller earthquakes have affected the area on a frequent basis since then (Center for Earthquake Research and Information 2008). The regional seismicity of the area is discussed in more detail in Section 4.2.2.

As stated above, the Poplar Bluff area was recognized as a suitable site for this pilot study, due to the large amount of available subsurface data. In recent years the University of Missouri – Rolla has conducted other research projects in the area with numerous types of field and lab testing. (Anderson et al. 2005) Available subsurface investigation data consists of mud rotary drilling data with standard penetration data and groundwater depths, cone penetrometer data and select geophysical testing. Additionally, a large number of lab tests were completed including water contents, Atterberg limits,
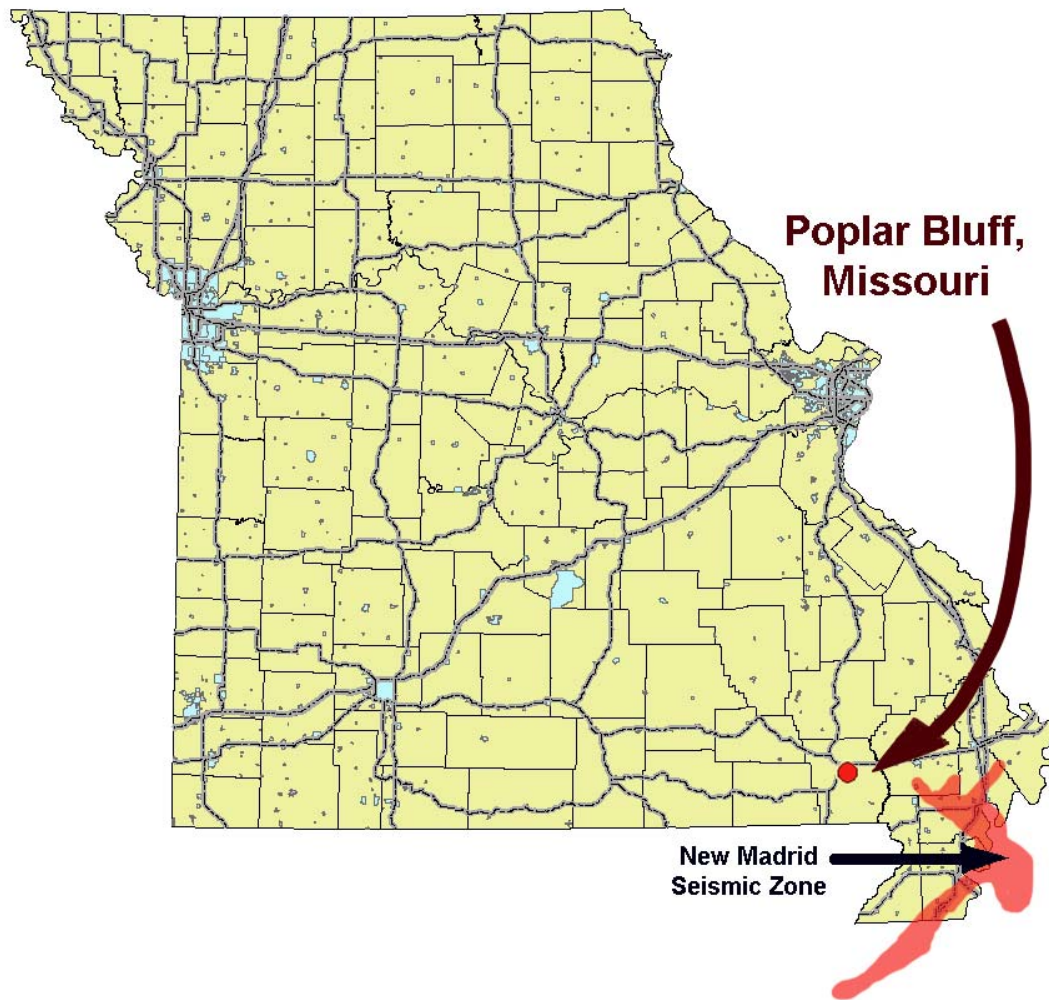
Figure 4.1. Poplar Bluff, Missouri Location Map

grain size analyses, and numerous dynamic soil tests. This data was made available for this study. Finally, in addition to the above data, the Missouri Department of Transportation (MoDOT) borehole logs for highway structures in the area were available from the "Database of Borehole and Other Geotechnical Data for Highway Structures" (Anderson et al. 2000, Luna et al. 2001). This data is generally localized around the existing highway bridges in the area, which makes it ideal for this study. The intended purpose of this study was to create a screening tool to identify potential seismic hazards, as would be applicable for agencies responsible for earthquake resilient infrastructure

systems, so geotechnical data around these structures is quite important. The geotechnical data used for this project is discussed in more detail in Section 4.3.

4.1.1. Regional Geology. Poplar Bluff, Missouri lies at a geological boundary with the Mississippi Embayment to the southeast and the Ozark Escarpment to the northwest. The topography of the area can be divided into a lowland and upland area. These areas are clearly distinguishable on a geologic map of the area, as shown in Figure 4.2.

The lowland area, located in the southeast of Poplar Bluff, Missouri, in the Advance Lowland, is relatively flat reflecting its position in the Mississippi Embayment. Subsurface materials are aggraded colluvial and alluvial deposits generally consisting of Quaternary sands, silts and clays, which are typical of an embayment condition. Ordovician dolomite bedrock exists at a depth of around 100 ft in the immediate area, though can be as deep as 2500 feet at the southeast edge of the Mississippi Embayment in the extreme southeast corner of the state (Grohskopf 1955).

The upland area, in the northwest of the city is part of the Ozark Escarpment and is considered a dissected uplands. The subsurface materials in the uplands are residual in nature and are composed primarily of clays and silts with sands and gravels. These materials are underlain by relatively shallow Ordovician Dolomites, and the region is structurally controlled by the Ozark Uplift and the Saint Francis Mountains to the northwest. Bedrock depth in the escarpment area is sometimes as shallow as a few feet, but generally less than 100 feet (Grohskopf 1955).

4.1.2. Regional Seismicity. The regional seismicity of Poplar Bluff, Missouri is defined by its close proximity to the New Madrid Seismic Zone (NMSZ), one of the most seismically active fault zones in the central and eastern United States. The NMSZ, which lies approximately thirty miles from Poplar Bluff (at its closest point), has produced three of the largest earthquakes ever to occur in an interior tectonic plate. These quakes, occurring between December 1811 and February 1812, caused church bells to ring over 1500 miles away in Boston, Massachusetts, and were felt in much of the northeastern United States and Canada (Stover and Coffman 1993), and as far away as the southeast Atlantic coastal area. More than 200 smaller aftershocks occurred between the third large earthquake and March of the next year. (Nuttli 1990). These three large earthquakes rank

Figure 4.2. Geologic Map of Poplar Bluff, Missouri (modified from Anderson et al. 2005)

as the highest magnitude earthquakes to have occurred in North America since its settlement by Europeans (Nuttli 1973).

Due to the lack of seismic instrumentation and the small population density of the region at the time, the exact locations of the epicenters for these earthquakes are unknown. However, Nuttli (1973) has estimated locations for the epicenters of these ground motions from damage reports and written eye-witness accounts, and estimated the body-wave magnitudes (m_b) of these ground motions by comparing these records to similar reports from more recent measured events. Nuttli places these events along what is commonly referred to as the New Madrid Fault, though is actually a complex of faults extending about 150 miles from Marked Tree, Arkansas, to Metropolis, Illinois in a rough lineation approximately fifty miles wide (Nuttli 1990). This complex of faults passes very near the town of New Madrid, Missouri. Nuttli (1982) reported his estimation of the specific epicenter locations for these earthquakes are 36º N, 90º W for the earthquake of December 16, 1811, 36.3º N, 89.6º W for the earthquake of January 23, 1812, and 36.5º N, 89.6º W for the earthquake of February 7, 1812. His analyses of body-wave magnitudes provided values of 7.2, 7.1, and 7.4 for each of the three ground motions in December 1811, January 1812, and February 1812, respectively. More recently, independent studies by Wheeler and Perkins (2000) and Atkinson et al. (2000) have suggested the moment magnitudes (Mw) of the quakes to be on the order of 7.6 or 7.7±0.5. Since the 1811 – 1812 earthquakes, two other large ground motions have shaken the area. These occurred in January of 1843 and October of 1895, and had surface wave magnitudes of approximately 6.3 and 6.7 respectively (Nuttli 1990).

Seismic hazards in the region still exist today, as current monitoring of seismicity shows that this zone is still very active, with numerous small magnitude earthquakes occurring each year in the geographic vicinity of the three large earthquakes of 1811 and 1812 (Center for Earthquake Research and Information 2008). These ground motions generally originate from a source at a depth of between two and twelve miles, within bedrock buried under over a mile of sediment (Nuttli 1990). Hundreds of small magnitude earthquakes have been recorded in the region in recent years as shown in Figure 4.3, occurring, on average, once every 48 hours. The locations of these earthquakes can be divided into three main linear trends extending into Missouri,
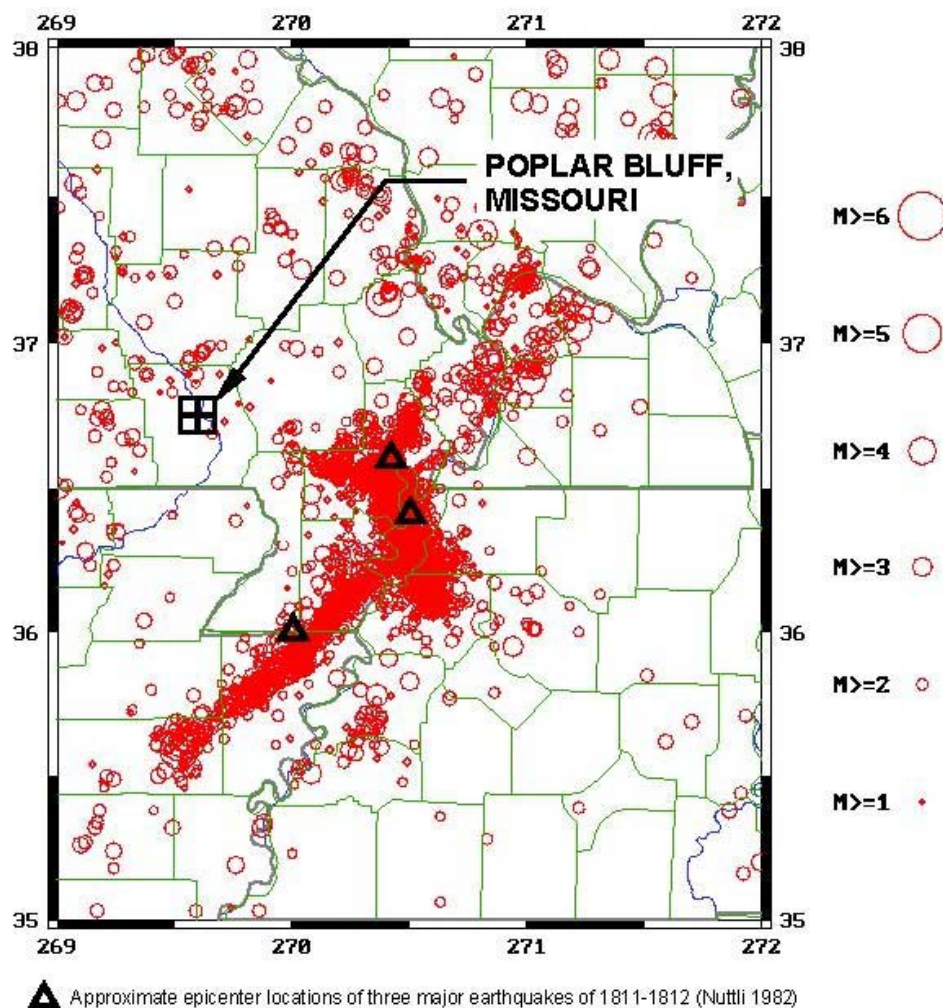
Figure 4.3. Earthquake Epicenters from January 1974 through January 2008, New Madrid Seismic Zone (Modified from www.ceri.memphis.edu 2008)

Arkansas, and Tennessee. The first of these lineations strikes southeast from the town of New Madrid into northwestern Tennessee. The second fault is longer and runs southwest from the Missouri bootheel for approximately 60 miles into northeastern Arkansas, to the town of Marked Tree. The third fault is less apparent but appears to trend northward from the first fault into the southwestern tip of Illinois (Johnston 1982). Different interpretations of these faults describe both strike-slip and reverse deformations (Herrmann and Canas 1978; Nicholson et al. 1984; O'Connell et al. 1982).

4.2. GEOTECHNICAL DATA

Due to involvement in other research projects, the Poplar Bluff area was recognized as a suitable site for this pilot study, due to the large amount of available subsurface data. In recent years researchers at the University of Missouri – Rolla have conducted concurrent research projects in the area and performed significant field sampling and field and laboratory testing (Anderson et al. 2005). This data was made available for this study. In addition to the above data, a statewide database of Missouri Department of Transportation (MoDOT) borehole logs was made available. This database was created for another research project (which assessed earthquake hazards along designated vehicle access routes) and was comprised of boreholes drilled for construction of transportation structures (Anderson et al. 2000). This data is generally localized around the existing highway bridges in the area, which makes it ideal for this study. This database contains a large number of boreholes in the Poplar Bluff area.

4.2.1. Research Based Geotechnical Data. In 2005, a report was published by Anderson et al. titled "Comprehensive Shear-Wave Velocity Study in the Poplar Bluff Area, Southeast Missouri". The objective of this report was to evaluate the utility of two types of geophysical testing (Crosshole Shear Wave Velocity and Multi-channel Analysis of Surface Waves), Ultrasonic Pulse Laboratory Tests and seismic cone penetrometers for determining the shear wave velocity of soils so as to assess the amplification/ deamplification of soil motions in a seismic event. While the end product of that project is fairly unrelated to this project, the steps taken to get to that result are greatly applicable. These steps include extensive field testing in the area immediately surrounding Poplar Bluff, Missouri.

In the spring and summer of 2004, six boreholes were drilled by the MoDOT Soils and Geology drilling crew under the direction of UMR personnel near Poplar Bluff, Missouri to support the above mentioned research project. These locations are shown in Figure 4.4. Standard penetration test soil samples and undisturbed Shelby tube samples were taken to characterize the subsurface materials. In addition to traditional soil borings, geophysical tests in the form of Crosshole (CH) shear wave velocity tests and Multi-channel Analysis of Surface-Wave (MASW) tests, as well as seismic piezocone tests were completed at the sites around Poplar Bluff. These tests were done to correlate

Figure 4.4. UMR Test Hole Locations, Poplar Bluff, Missouri (modified from Anderson et al. 2005)

the different methods to determine the shear wave velocity of soils. These tests provide shear wave velocity profiles used in the pilot study.

Geotechnical boreholes and lab testing from the uplands area revealed soils comprised of various mixtures of residual reddish-brown clays, silts and sands, with layers of gravel. Blowcounts ranged from 10 to 72 blows per foot for the various materials. Rock was encountered in only one hole, borehole BHUMR-1, at a depth of 60 feet. Boreholes BHUMR-2 and CHUMR-1 were drilled to depths of 101.5 and 151.5 feet respectively without encountering rock. Water contents in this region varied from 9 to 53 percent and Atterberg limit tests show most of the soils as being classified as low plasticity. Only one set of shear wave velocity tests was completed in the upland region, due to the difficulty of pushing a cone in the gravelly residuum. The single set of five tests completed generally ranged from approximately 150 to 1000 ft/sec in the upper 20 feet and increased roughly linearly downwards to approximately 3000 ft/sec at 100 feet.

Geotechnical boreholes and lab testing in the lowland or alluvial region revealed typical alluvial stratigraphies composed primarily of sands and gravels. Sands were generally clean, gray, and fine to medium in grain size, though layers with some lignite particles, clay, silt or gravel were not uncommon. Blowcounts ranged from 3 to 71 blows per foot for the various materials. Rock was encountered in only one hole, borehole CHUMR-3, at a depth of 113.75 feet. Boreholes BHUMR-5 and BHUMR-6 were drilled to depths of 110.0 and 115.0 feet respectively without encountering rock. Water contents in this region varied from 12 to 33 percent, and Atterberg limit tests show the few clayey soils tested as being classified as low plasticity. Shear wave velocity tests varied greatly based on the type of test, but values generally ranged between 200 and 1000 ft/sec in the upper 60 feet and were roughly 1000 ft/sec below that to the depths explored. Shear wave velocity profiles from 22 separate seismic cone penetration tests were input and used for this study.

4.2.2. Missouri Department of Transportation Geotechnical Data. In 2000, a report was published by Anderson et al. titled "Earthquake Hazard Assessment Along Designated Emergency Vehicle Access Routes". The objectives of this report were to evaluate earthquake hazards at two locations along designated emergency access routes, and to produce a database of subsurface geotechnical data for use in geographic

information systems to aid in hazard evaluations. While the specific earthquake evaluation of the two locations covered in this report are outside of the Poplar Bluff area, the database produced for that project contains extensive subsurface information that can be used within this project. This database was constructed with the purpose of producing a GIS compatible database using the data provided by MoDOT and UMR and focused along two designated vehicle emergency access routes in the state of Missouri (Luna et al. 2001). Additional features were included to expand the database in the future to include other boring data as required.

The database is organized in a hierarchical structure with the highest tier being the structure ID. For each structure ID, there may be several boreholes, and for each borehole are several tables of geotechnical data that pertains to that borehole. Typical data for a given borehole may include highway structure ID, X and Y coordinates, elevation, station, offset, soil layer depths, ground water level, grain size data, material descriptions, SPT N-values, water contents, phi angle, cohesion, Atterberg limits, unit weight, void ratios, shear moduli, and a collection of other geotechnical values.

Within the MoDOT database, over 400 boreholes, associated with roughly 59 unique structures fall within the general proximity of Poplar Bluff, Missouri. Due to the large number of boreholes, it is difficult to make generalizations as to geotechnical properties (stratigraphy, index properties, etc.), though values generally agree with those discussed in the previous section for the upland and lowland regions.

To be able to use this data within the S4 application, the Microsoft Access-based database was exported and manually manipulated using Microsoft Excel to produce input text files for each borehole. It should be noted that these changes were made to the input data only and not set as defaults within the program. In most cases, the most conservative estimation was used when required data was absent. Each individual borehole was compiled using the following assumptions:

- If different water contents, phi angles or unit weights existed for soil samples recovered from a single sol layer, all non-zero values were averaged to produce a composite value for that layer.

- If multiple depths to the water table were included for a given borehole, the shallowest depth to the water table was used, as it was the most

conservative value. For boreholes without depths to water table, a default value of zero feet was input to maintain conservatism.

- Unified Soil Classification System (USCS) values were assigned to the listed soils as appropriately as possible. Due to a distinct lack of laboratory data, determining the USCS classification was highly subjective in many cases. Classifications were based on the three listed material types and the available lab data. In all cases, if a material was "borderline" between two USCS classifications, USCS classifications with lower fines contents were chosen over a similar description (so as to be more conservative for the liquefaction potential calculations).

- As very few values existed for measured total unit weight, the existing total unit weight values for the Poplar Bluff area were averaged to produce a composite value of 124.69 pounds per cubic foot. Based on this value, a value of 125 pounds per cubic foot was used for calculation of the total vertical overburden stress for boreholes where unit weight values were not available. For boreholes which contained measured unit weight values, the actual values were used for calculation of the total vertical overburden stress.

- Records missing essential pertinent information (i.e. borehole location, material types, or sample data) were deleted.

- As very little of the available subsurface geotechnical data contained numerical grain size data, assumptions needed to be made for the fines content of each soil. Where measured values for the percent passing the number 200 sieve were available, these numbers were used. Where this data was unavailable, conservative assumptions were made based on the USCS classification system (American Society for Testing and Materials 2007b). The most conservative estimation of fines content for calculating liquefaction potential is, by definition, the lowest possible fines content for a given soil classification.   The determined values for the liquefiable USCS soil types are given in Table 4.1 below.

Table 4.1. Assumed Fines Contents for Given Soil Classifications

USCS Symbol	Assumed Fines Content (%)
SW	0
SP	0
SW-SM	5
SP-SM	5
SP-SC	5
SM	12
ML	50

Due to lack of data, once the geotechnical data was processed, only roughly 85 of these boreholes were usable for this study from the original group of over 400. This number, however, proved sufficient for demonstration of the S4 application.

It should be noted that no formal borehole quality assessment was completed on the data analyzed for this study. Recent research has illustrated the need for a quality assessment of the data used for a particular study, particularly if the data was not originally collected for that study (Deaton et al. 2001). Generally, for a given project, those factors which contribute to a loss in quality of geotechnical data are considered and overcome by the initial engineer working with the data. However, upon use by subsequent parties, these limitations are rarely known or considered. In addition, D'Andria et al. (1995) noted that when two projects have different objectives, their assessments of geotechnical data quality may be significantly different as well, even when using similar quality measurement criteria. As most of the data used in this study was collected for design and construction of highway structures, it is not optimized for use in a geotechnical seismic analysis. However, it has sufficient quality to adequately demonstrate the functionality of the S4 application.

4.2.3. Seismic Scenarios. For this pilot study, two different ground motion scenarios were developed to test the S4 application. Since no recorded strong ground motions exist for the NMSZ, synthetic ground motions were obtained for use in the analyses. The two desired scenarios correspond to a mean return period of 224 year

(20% probability of exceedance in 50 years) and 2475 year (2% probability of exceedance in 50 years) earthquake for the study location. These two scenarios were selected with the intent of showing the difference in results for earthquakes of two different magnitudes. From a qualitative standpoint, the 224 year earthquake represents a fairly small earthquake where minimal earthquake hazards are likely to occur, while the 2475 year earthquake represents a fairly large earthquake where geotechnical hazards are very likely. (In standard engineering analyses, it is more common to perform analyses for 108 year and 2475 year earthquakes, however from preliminary analyses it was determined that results from the 108 year input ground motion showed very minimal hazard potential and were not ideal for demonstrating the capabilities of the S4 application).

To determine the values of moment magnitude and peak ground acceleration for the desired scenarios, the United States Geological Survey Earthquake Hazards Program website was used to produce deaggregations of the ground motions at the desired return intervals. These resultant ground motion scenarios from the deaggregations were a magnitude 6.1 earthquake with a peak ground acceleration (PGA) of 0.074g, and a magnitude 7.2 earthquake with a PGA of 0.527g, corresponding to a 224 year and 2475 year return period earthquake, respectively. (United States Geological Survey 2006a). These values are the seismic hazard for the given probability of exceedance, deaggregated by magnitude, epicentral distance, and epsilon (ground motion uncertainty), for the peak ground acceleration. Hazards are separated into moment classes (or bins) of 0.5 magnitude and distance classes (bins) of 10 km width (United States Geological Survey 2006b). From these deaggregations, the individual contributions of numerous sources can be combined to produce a probable mean magnitude and peak ground acceleration for the given site. Graphical plots for these deaggregations are shown in Figures 4.5 and 4.6.

In addition to the graphical deaggregation plots, seismogram data files are available from the United States Geological Survey Earthquake Hazards Program website mentioned previously. These files contain acceleration time histories scaled to the peak ground acceleration or various values of spectral acceleration for the probability of exceedance, for a particular latitude/longitude location, as requested by the user. Site
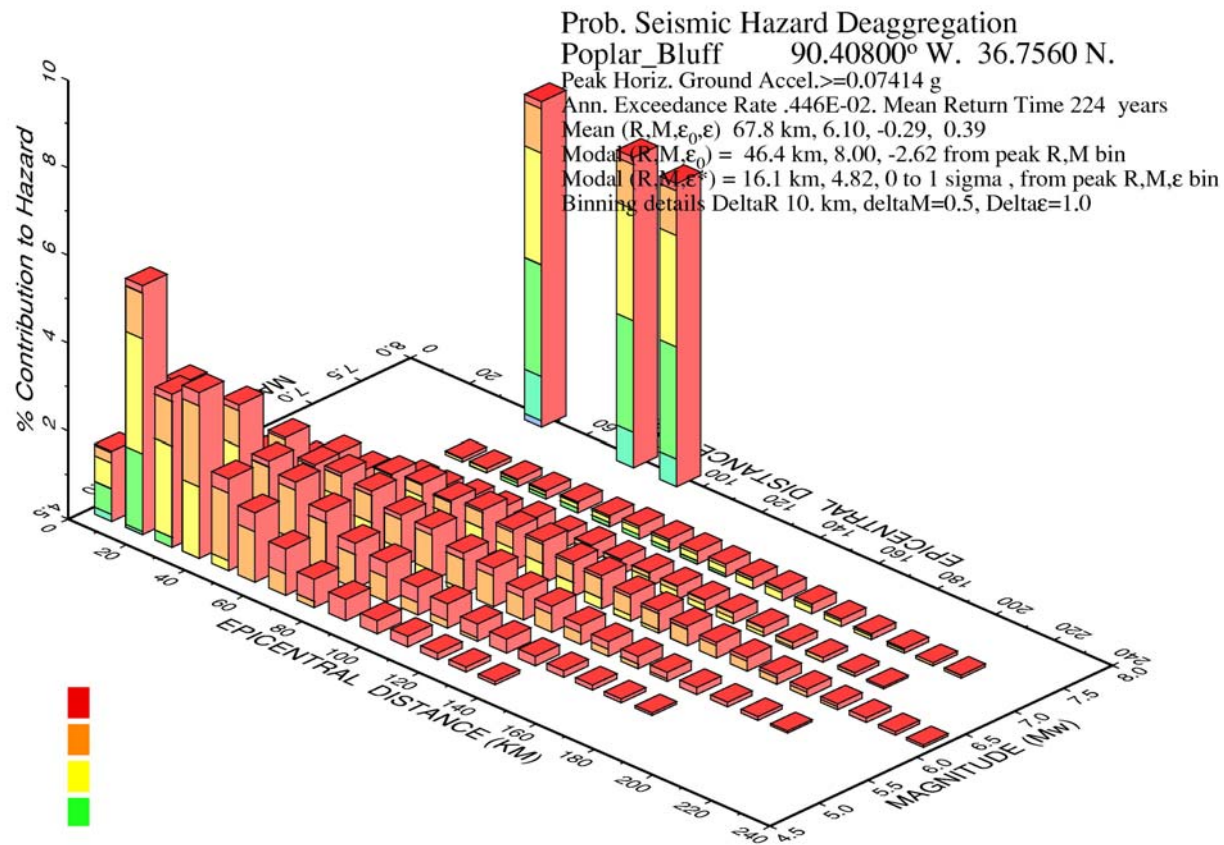
Figure 4.5. Seismic Hazard Deaggregation for 20% Probability of Exceedance in 50 yrs (USGS 2006a)
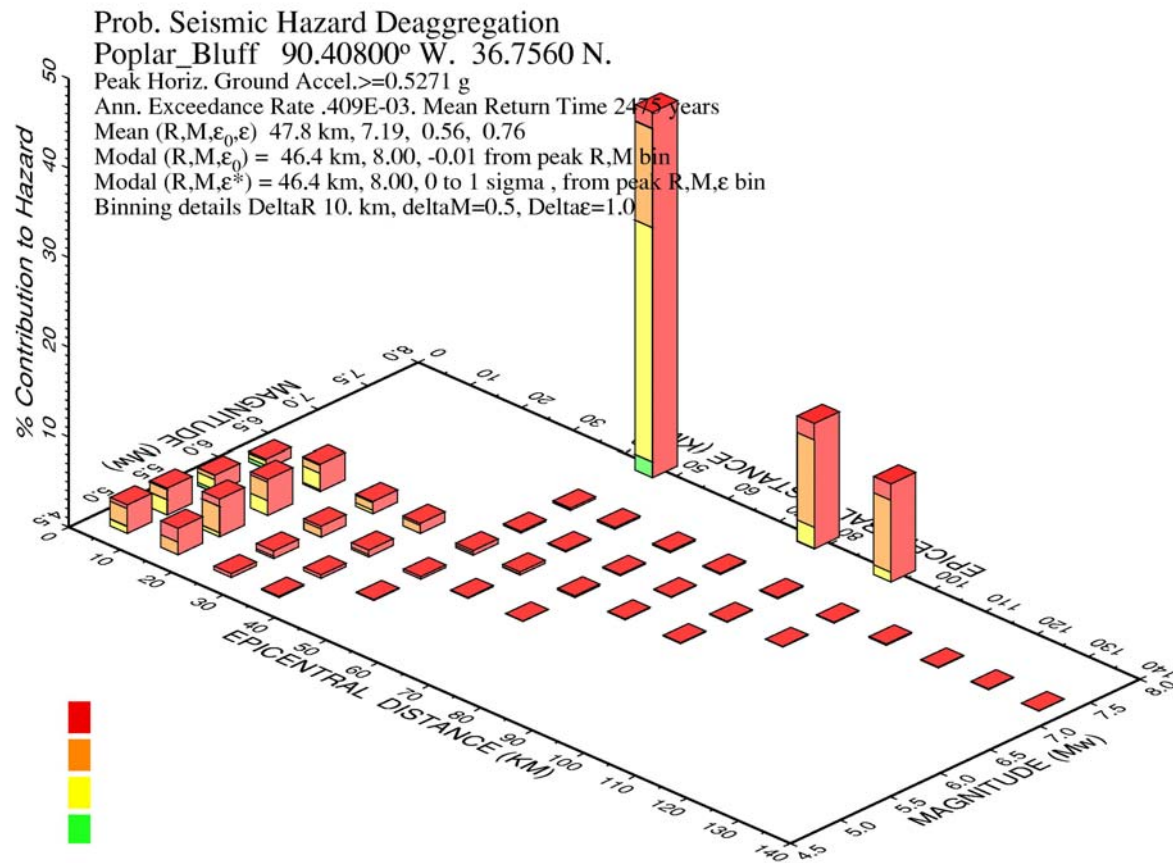
Figure 4.6. Seismic Hazard Deaggregation for 2% Probability of Exceedance in 50 yrs (USGS 2006a)

conditions for these time histories are assumed to be rock with average shear wave velocities of 760 m/s in the top 30m. (United States Geological Survey 2006b) Varying site conditions will alter the ground motion at a particular site, however for this application, a rock motion is desired. For this pilot study, acceleration time history files were produced and retrieved for both desired cases of study (224 year and 2475 year earthquakes) for the peak ground acceleration.

For the S4 input, two methods are available for entry of seismic ground motion time histories. The first method allows the user to simply enter numerical values for all desired seismic parameters (moment magnitude, peak ground acceleration, and predominant period of ground motion). This method is somewhat simpler at run time, as it only requires the input of a single number, but requires the user to have produced the required data from another source. The second form of entry involves inputting an acceleration time history text file for the desired ground motion at run time, and having the application determine the values of peak ground acceleration, and predominant period of ground motion. (It is still required to enter moment magnitude as a numerical value). As the second method is slightly more complicated to perform, but actually more automated for the user, this method was chosen for entry of ground motion parameters for the pilot study.

4.2.4. Non-Geotechnical Spatial (Map) Data. Spatial data layers for use within ArcGIS and the S4 application were taken from the Missouri Environmental Geology Atlas (MEGA) (Missouri Department of Natural Resources 2003). Developed by the Missouri Department of Natural Resources, MEGA is a collection of geographically referenced digital data for the state of Missouri, which includes GIS layers for county boundaries, roads, waterways, geological structures, surficial geology classifications, and many other data types. For the S4 application, three layers were imported from MEGA and included as background information for use within the application. These layers were a polygon theme containing county boundaries, a line theme containing major roadways, and a polygon theme containing classification of surficial geology. The scale for the first two layers is 1:100,000, which has an accuracy of approximately 240 feet. The scale for the surficial geology is listed as 1:1,000,000, which translates to an accuracy of approximately 2400 feet. While this accuracy may

seem poor, it is adequate for this application, as these layers are solely used for general bearings within the application. These data layers allow the user to obtain a rough approximation of where they are performing their analysis, but are not used numerically in the analyses. As with any GIS applications, any layer file could potentially be added to the layout to increase the functionality of the application (i.e. referenced air photos, urban boundaries, etc.). However, these three layers were chosen as the minimum functional data for demonstration of the S4 application.

4.3. RESULTS OF PILOT STUDY

To demonstrate the functionality of the S4 application, a pilot study was completed for a series of boreholes along the highway system near Poplar Bluff, Missouri. Two different ground motion scenarios were analyzed, and as can be expected, results from the pilot study were highly dependant on the input ground motion. The results of these scenarios are discussed in the following sections.

This pilot study exemplifies the use of the S4 screening tool; however, the data used in this pilot study was not fully prepared for an exact study (e.g. extension of soil layers to bedrock for period calculations was not confirmed, etc). Therefore, the data was only used to demonstrate the functionality of the S4 application, and the results may not be representative of actual projected conditions. Accordingly, the results obtained from this study should not be taken out of the context of this demonstration.

4.3.1. Seismic Input Parameters. A major advantage to performing a seismic screening analysis using the S4 application is the ability to analyze different input seismic events very rapidly on the same set of data. For this pilot study, two ground motion scenarios were analyzed, to show results for hazard scenarios of two different magnitudes. The two selected scenarios correspond to a 224 year (20% in 50 years) and 2475 year (2% in 50 years) mean return period earthquakes at the study location. The ground motion parameters for these scenarios are a magnitude 6.1 earthquake with a peak ground acceleration of 0.074g, and a magnitude 7.2 earthquake with a peak ground acceleration of 0.527g, corresponding to a 224 year and 2475 year mean return period earthquake, respectively (United States Geological Survey 2006a).

For the desired ground motion scenarios, acceleration- time history data files were downloaded from the USGS website corresponding to the PGA, for the desired return interval, at the desired location near Poplar Bluff, Missouri. Text formatting of the input files was required before importing into S4. (The required format for acceleration time histories for use within S4 is a single column of acceleration values in g with a time step of 0.02 seconds. This format is described in more detail in Appendix A: Guide for Future Development.) These acceleration-time histories were then imported directly into the S4 application at run time and the PGA and predominant period of ground motion "read" or computed directly from them.

The same geotechnical data was used for each analysis. This data is the combined research-based and MoDOT transportation data as discussed above.

4.3.2. Presentation of Results and Discussion. Results from the S4 application are presented in the form of color and size graduated circles overlaid on the base map at each analyzed borehole location. These colors and relative sizes are set based on the factors of safety for liquefaction potential or magnification factors for site resonance from a given input ground motion. As previously mentioned, for this pilot study, two ground motion scenarios were analyzed.

4.3.2.1 Magnitude 6.1 earthquake with PGA 0.074g. For the first analysis, a relatively small earthquake corresponding to a 224 year return interval was entered. This earthquake was entered by inputting an acceleration time history text file, as discussed in Section 4.3.1. A plot of this time history is shown in Figure 4.7. Upon analyzing this time history within S4, the PGA was calculated to be 0.074g, verified by the value given on the USGS deaggregation plot (Figure 4.5).

4.3.2.1.1 <u>Magnification factor.</u> The amplification of ground motion, shown as a magnification factor, varies with respect to the tuning ratio, or the ratio of the characteristic site period to the predominant period of ground motion, and can be used to assess the resonance effects. The first step in this procedure is the automated computation of the Fourier power spectra, which yielded a predominant period of the ground motion, T_P, of 0.571 seconds. A plot of this Fourier power spectrum is shown in Figure 4.8. The magnification factor was then calculated for each of the 22 locations with shear wave velocity data.
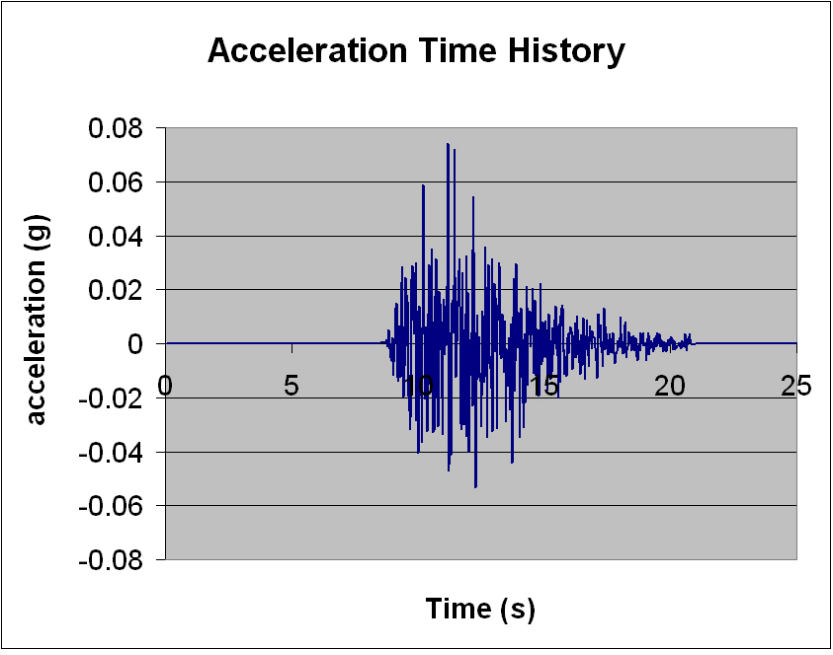
Figure 4.7. Acceleration Time History for 224 Year Mean Return Period Ground Motion
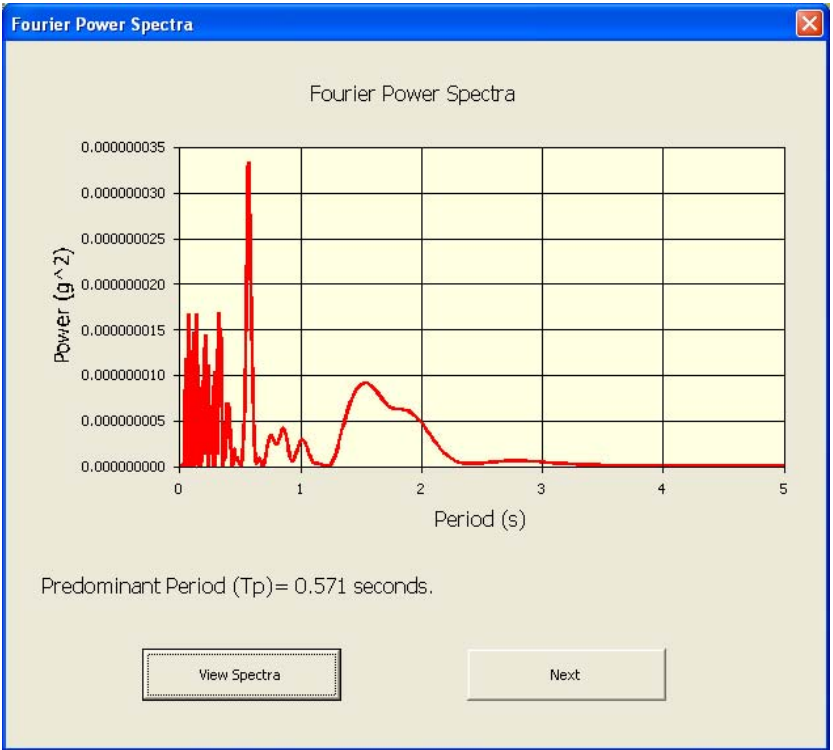
Figure 4.8. S4 Plot of Fourier Power Spectra for 224 Year Mean Return Time Ground Motion

Upon calculation of the magnification factor, several locations showed signs of significant hazard potential. S4 output results of this analysis are shown in Figure 4.9. 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 4.10 shows the S4 resonance output in relation to the surficial geology of the region. By viewing this figure, 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.

Some of the highest magnification factors were located near structure RTZ_A2201U, in the alluvial region. Analyses of the SCPT locations near structure RTZ_A2201U, namely TR040329_31_1, TR040329_31_2, TR040329_31_3, TR040329_31_4 and TR040329_31_5, resulted in magnification factors of 1.6, 1.6, 2.5, 1.3 and 2.1 respectively. For further screening, the characteristic site periods and magnification factors can be displayed for each of these boreholes by running the resonance viewing module. Within this module, an option is also available to enter a value for 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 and 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. An example image of this analysis screen for location TR040329_31_3 is shown in Figure 4.11. As can be seen in this image, a magnification factor of 3.7 may occur from resonance between the soil column and 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. These locations should be studied in more detail with additional analyses. Also, for a more in-depth analysis, each of the other locations should also be analyzed with the desired input structure period, as ground motion magnification from resonance between the structure period and the characteristic site period may occur even if the soil column has not amplified the ground motion.
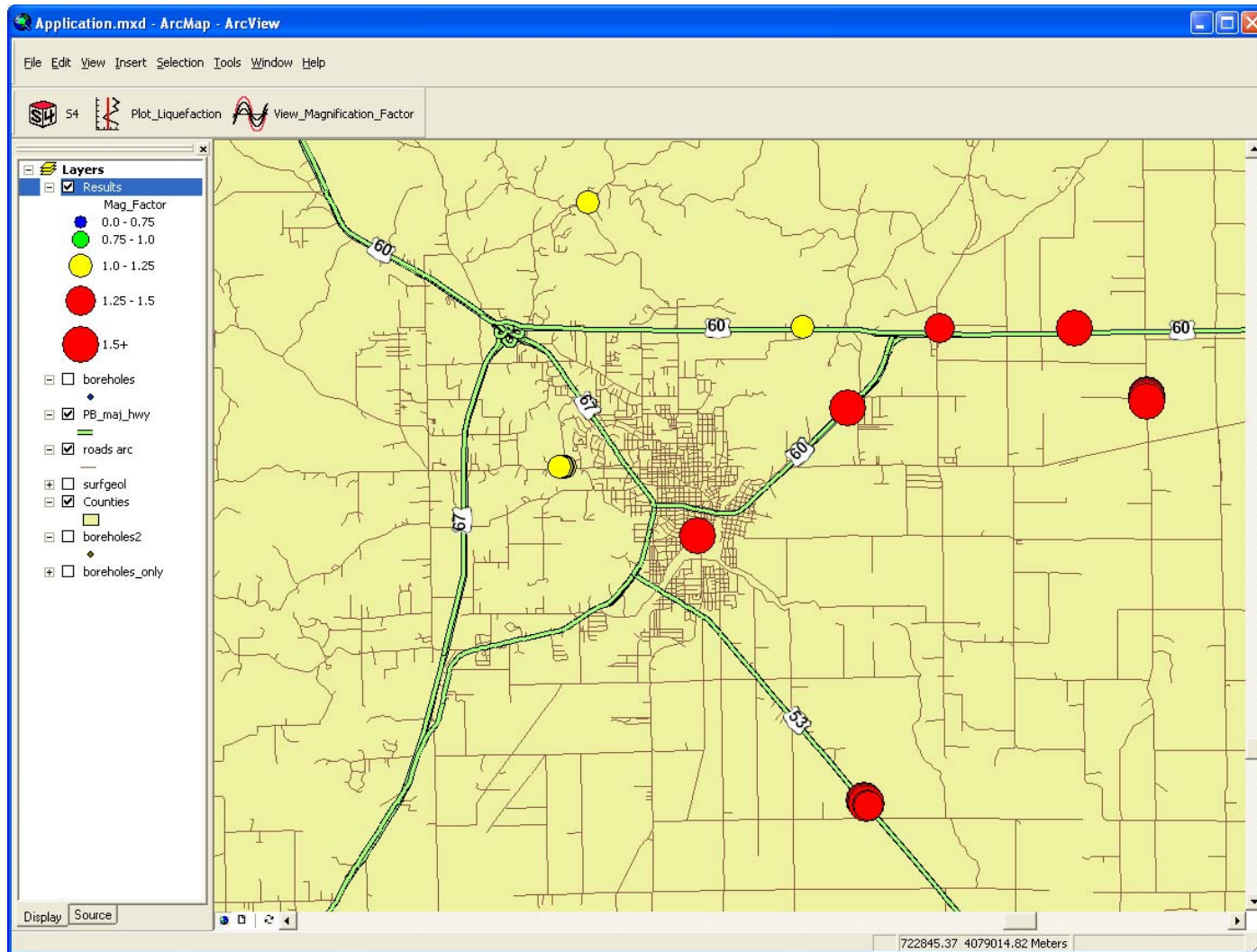
Figure 4.9. S4 Ground Motion Magnification Factor Results for 224 Year Mean Return Period Ground Motion
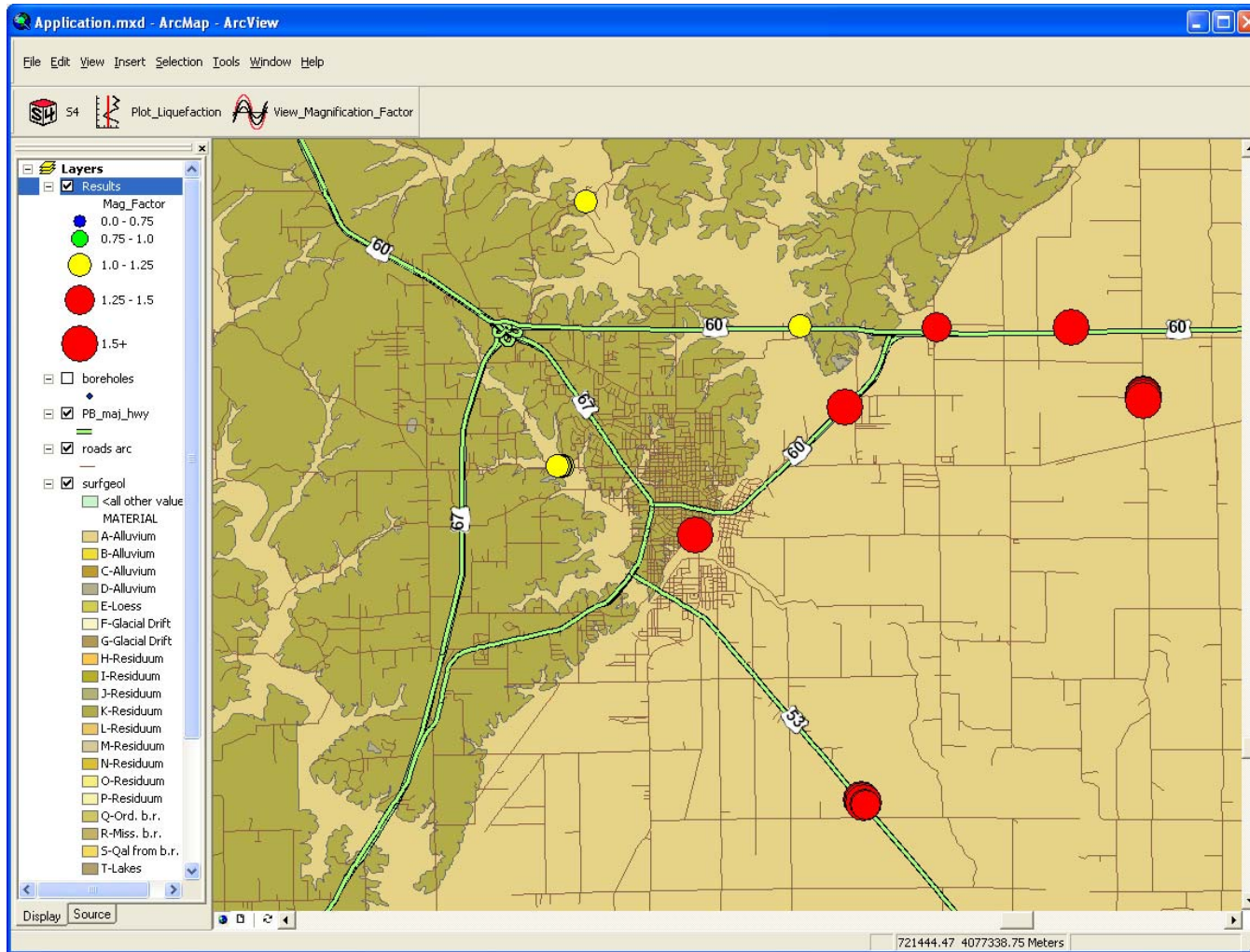
Figure 4.10. S4 Ground Motion Magnification Factor Results Overlaid on Surficial Geology Layer for 224 Year Mean Return Period Ground Motion
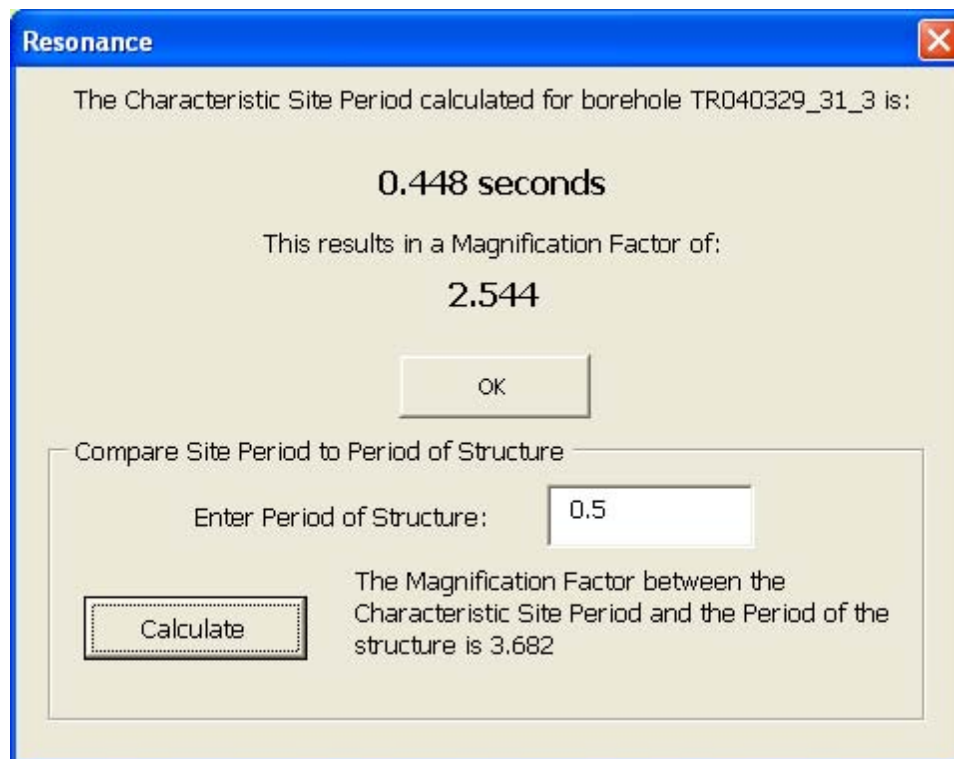
Figure 4.11. S4 Output Screen for Viewing of Resonance Parameters, TR040329_31_3.

4.3.2.1.2 Liquefaction potential. Liquefaction potential was calculated based on this PGA and the input moment magnitude for each of the 85 boreholes in the surrounding area. Figure 4.12 shows the liquefaction potential results as plotted within the S4 application. As shown in this figure, the majority of the factors of safety against liquefaction are above 1.5 for this input ground motion. Factors of safety for seven of the remaining borehole locations plot in the range of 1.25 to 1.5, while the remaining seven boreholes locations have factors of safety within the range of 1.0 to 1.25. By displaying the surficial geology map layer within the GIS Data View, it becomes apparent that most of the borehole locations with relatively low factors of safety (F.S. = 1.0 – 1.25) fall within the alluvial lowland region around Poplar Bluff. This is to be expected due to the sand composition of the soil in this lowland region. Figure 4.13 shows the S4 liquefaction potential output in relation to the surficial geology of the region.

The set of values with factors of safety in the range of 1.0 to 1.25 are fairly low and may warrant additional in-depth analyses. To further narrow the selection of
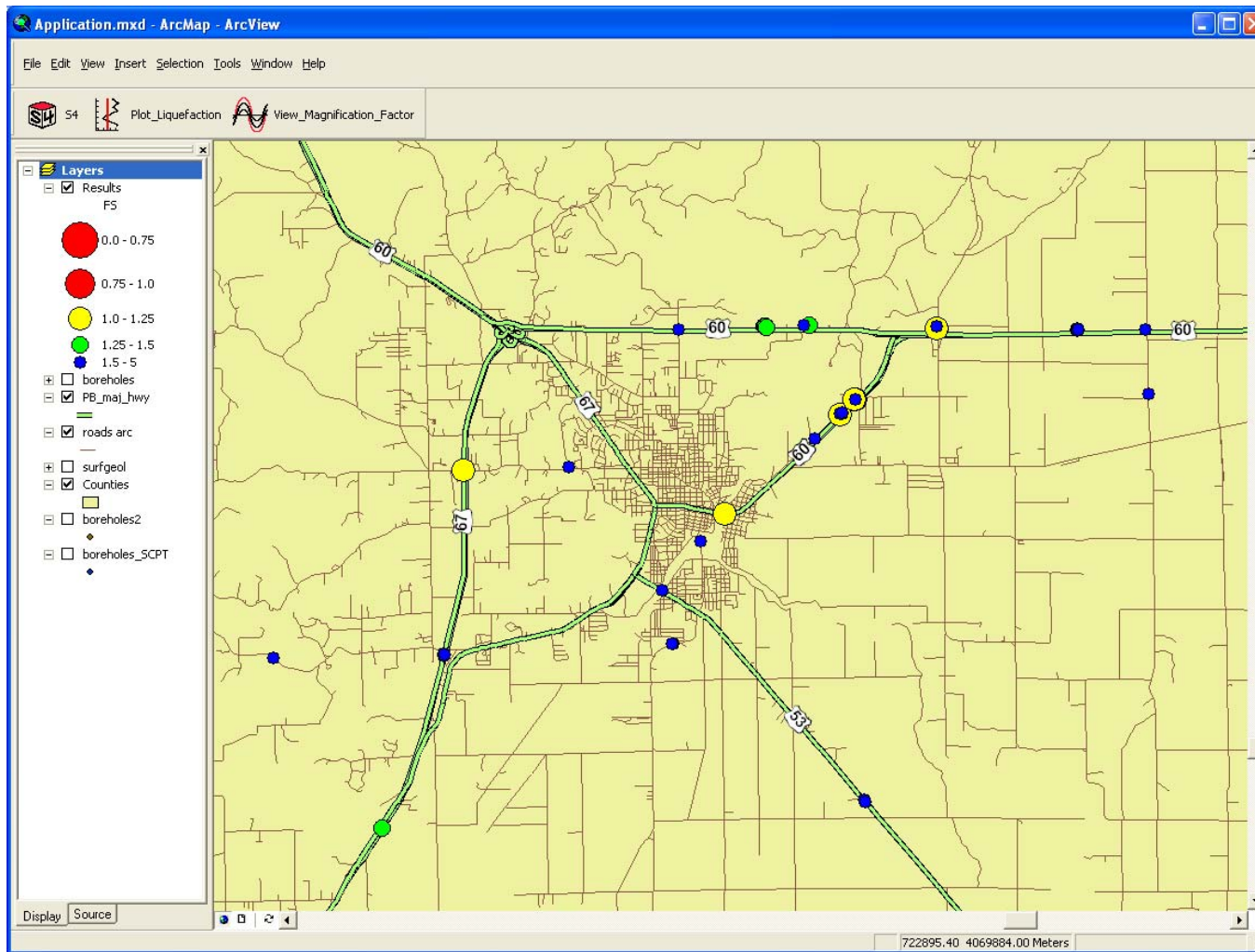
Figure 4.12. S4 Liquefaction Potential Results for 224 Year Mean Return Time Ground Motion
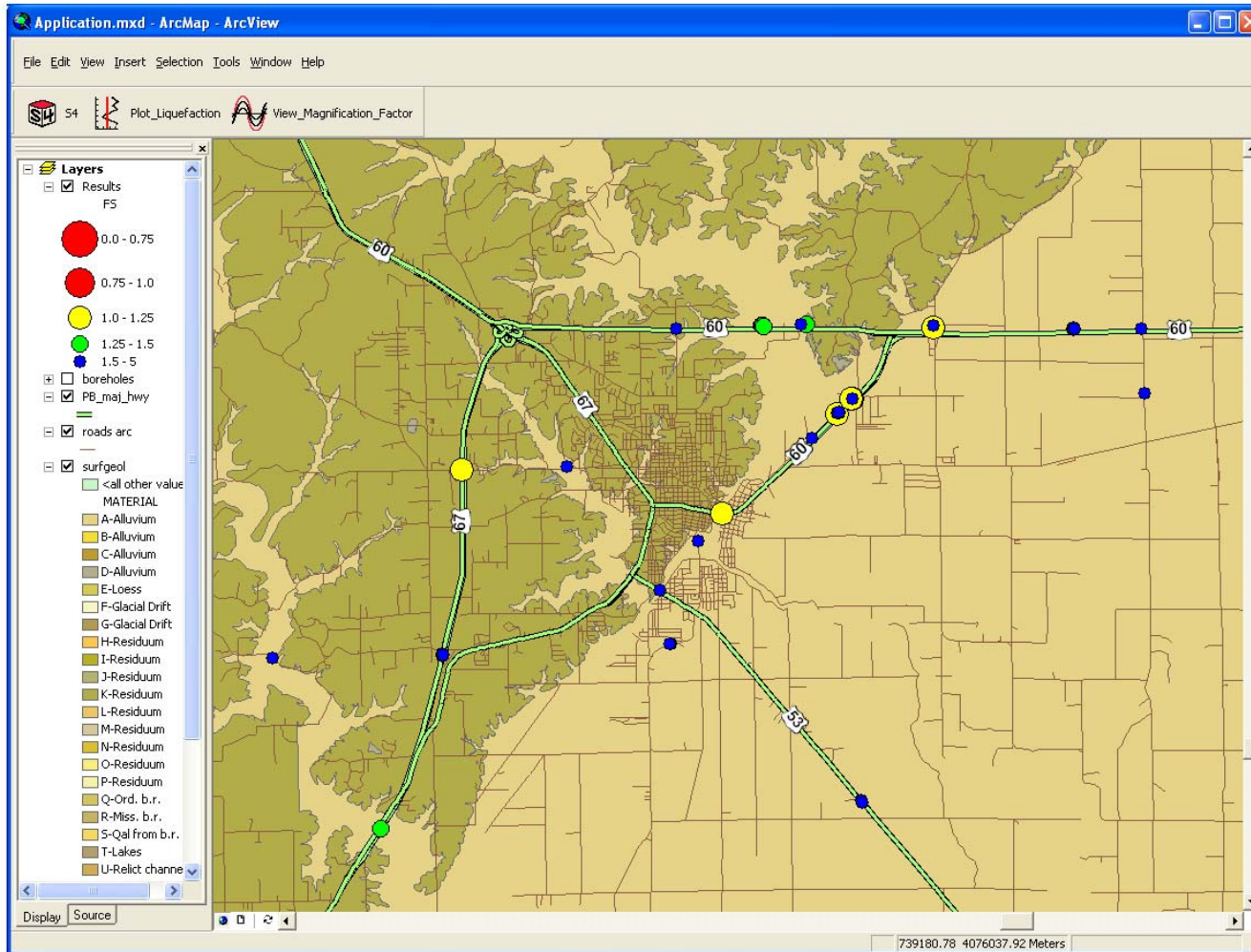
Figure 4.13. S4 Liquefaction Potential Results Overlaid on Surficial Geology Layer for 224 Year Mean Return Time Ground Motion

boreholes which may require additional analyses, the liquefaction plotting module may be initiated, and the factors of safety against liquefaction versus depth displayed for each borehole. From running this module, it can be seen that most of these boreholes show only one low factor of safety, bounded by higher factors of safety above and below this liquefiable zone. Based on these plots the user may determine whether or not to further analyze these locations. In contrast, three of the locations show multiple points with relatively low factors of safety, and in the case of two of the locations, show significantly thick liquefiable layers. These boreholes represent areas of potential concern and should be analyzed in more detail. One of the potentially worst boreholes (from a liquefaction potential standpoint), BU60_A3686E137+6522R, located at bridge A3686E137 shows a significantly thick, near surface, potentially liquefiable layer. After initiating the plotting module, and then clicking on the graduated circle for the site, the plot of factor of safety against liquefaction versus depth is displayed as a window for further inspection, as shown in Figure 4.14.
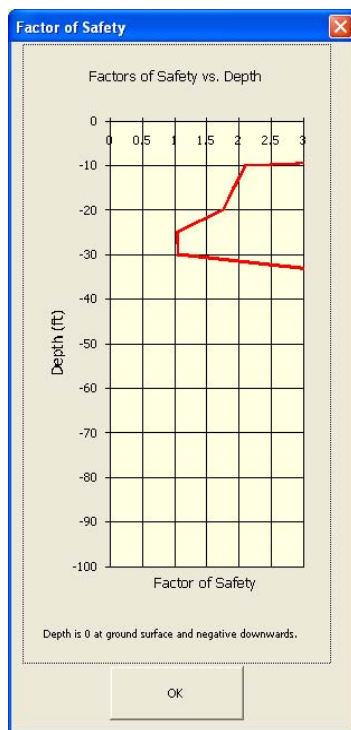
Figure 4.14. S4 Plot of Factor of Safety against Liquefaction versus Depth for Borehole BU60_A3686E137+6522R

Of additional interest are several boreholes that fall in the residual upland region, though still show relatively low factors of safety. Specifically, boreholes near structures MO67_A5524U, CRDMAR_A3723U, and MO67_A5523S, appear to be located in deposits of clay residuum, with fairly deep depths to the piezometric surface. However, upon viewing the plots of factors of safety versus depth, a relatively deep (roughly 45 feet) potentially liquefiable layer is evident, which is verified by a loose sand layer, below the piezometric surface, shown in the original boring logs. Generally, however, the factors of safety at these sites, and the rest of the locations analyzed with this particular ground motion, are not low enough to be a concern or warrant additional analyses.

4.3.2.2 Magnitude 7.2 earthquake with PGA 0.527g. In contrast to the above analysis, a second analysis was completed for a different, strong ground motion. The seismic data used for this second analysis corresponded to a 2475 mean return time earthquake, (2% PE in 50 years). As before, this earthquake was entered by inputting an acceleration time history into the S4 application. A plot of this time history is shown in Figure 4.15. Upon analyzing this time history within the S4 application, the PGA was calculated to be 0.527g.

4.3.2.2.1 <u>Magnification factor.</u> The amplification of ground motion shown as a magnification factor from resonance between the characteristic site period and the predominant period of ground motion was again analyzed for the input ground motion. From computation of the Fourier power spectra, the value for the predominant period of ground motion was determined to be 0.566 seconds. A plot of this Fourier power spectrum is shown in Figure 4.16. The magnification factor was then calculated for each of the 22 locations with shear wave velocity data.

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. As before, calculation of the magnification factor resulted in most locations showing signs of significant hazard potential. S4 output results of this analysis are shown in Figure 4.17. In this analysis, all of the processed locations with shear wave velocities contained magnification factor results higher than 1.0, with fourteen over a threshold of
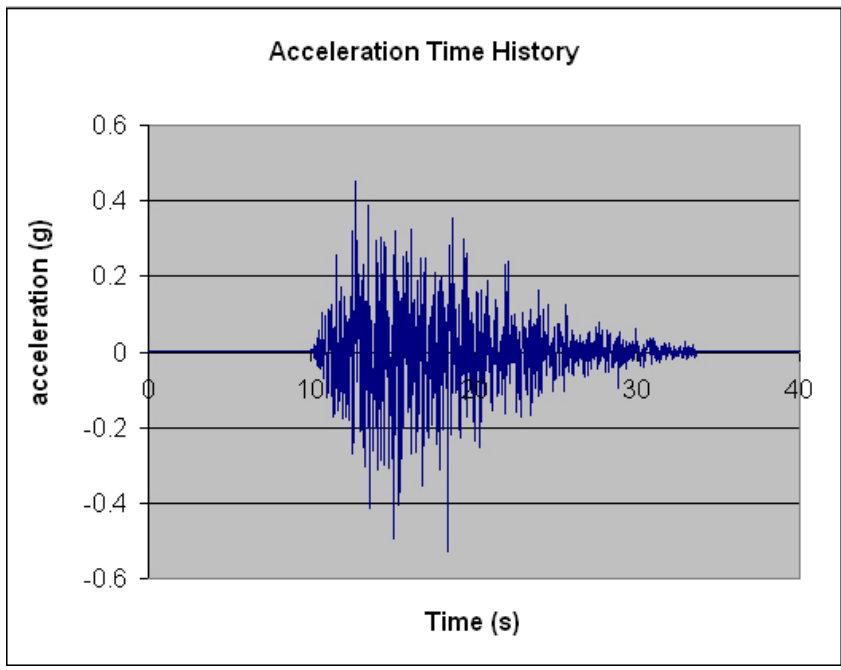
Figure 4.15. Acceleration Time History for 2475 Year Mean Return Period Ground Motion
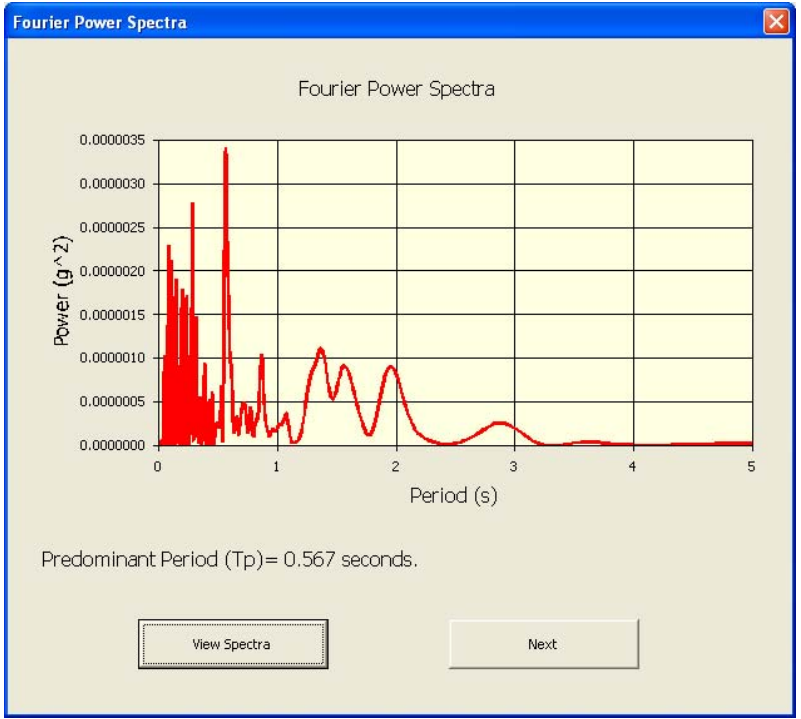
Figure 4.16. S4 Plot of Fourier Power Spectra for 2475 Year Mean Return Period Ground Motion
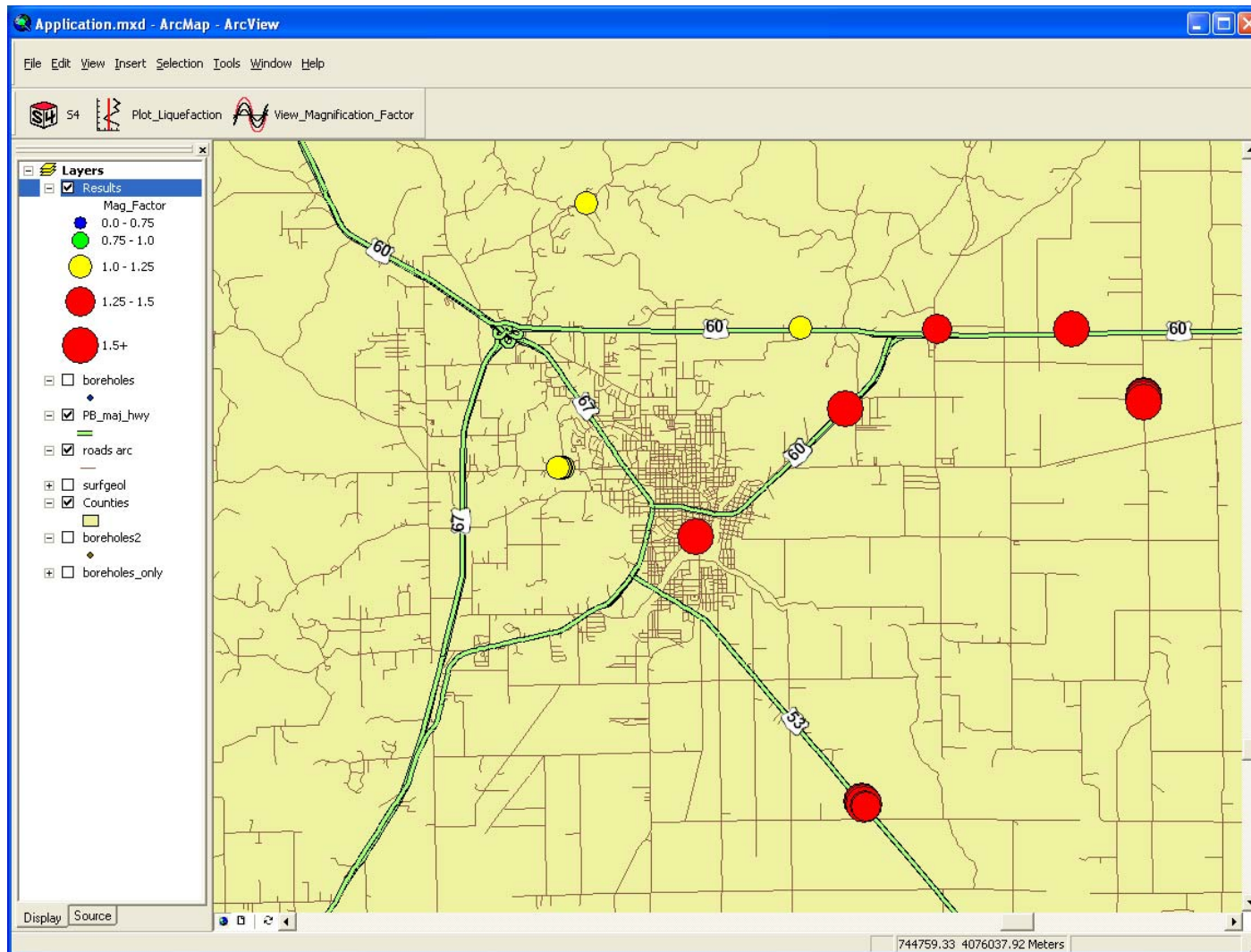
Figure 4.17. S4 Ground Motion Magnification Factor Results for 2475 Year Mean Return Period Ground Motion

1.25. Again, one of the worst locations was located near structure RTZ_A2201U, in the alluvial region. Figure 4.18 shows the S4 resonance output in relation to the surficial geology of the region. As before, by viewing this figure, 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.

Analyses of the five locations near structure RTZ_A2201U, specifically TR040329_31_1, TR040329_31_2, TR040329_31_3, TR040329_31_4, and TR040329_31_5 resulted in magnification factors of 1.62, 1.62, 2.60, 1.33 and 2.11 respectively. For further screening, the characteristic site periods and magnification factors can be displayed for each of these boreholes by running the resonance viewing module. As in the previous analysis, a hypothetical period for a multispan continuous concrete bridge, of 0.5 seconds (Nielson and DesRoches 2005) was used as a default value to demonstrate the calculation of the ground motion magnification by the structure. This computation is done by comparing the characteristic site period to the user-inputted period of the structure. Again, as can be expected from running a second analysis with a similar predominant period of ground motion, 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. An example image of this analysis screen for location TR040329_31_3 is shown in Figure 4.19.   As can be seen in this image, a magnification factor of 3.7 may occur from resonance between the soil column and the structure. As before, these locations could present a serious problem in the event of a ground motion with similar period to the one utilized in this study. These locations should be studied in more detail with additional analyses such as site-specific ground response analysis. And as previously mentioned, a more in-depth analysis is warranted for all locations due to the fact that magnification from resonance between the structure period and the characteristic site period may occur even if the soil column has not amplified the ground motion.

4.3.2.2.2 <u>Liquefaction potential.</u> The liquefaction potential was calculated similarly to the previous analysis, based on a PGA of 0.527g and the input moment magnitude for each of the 85 boreholes in the surrounding area. Figure 4.20 shows the liquefaction potential results as plotted within the S4 application. As shown in this
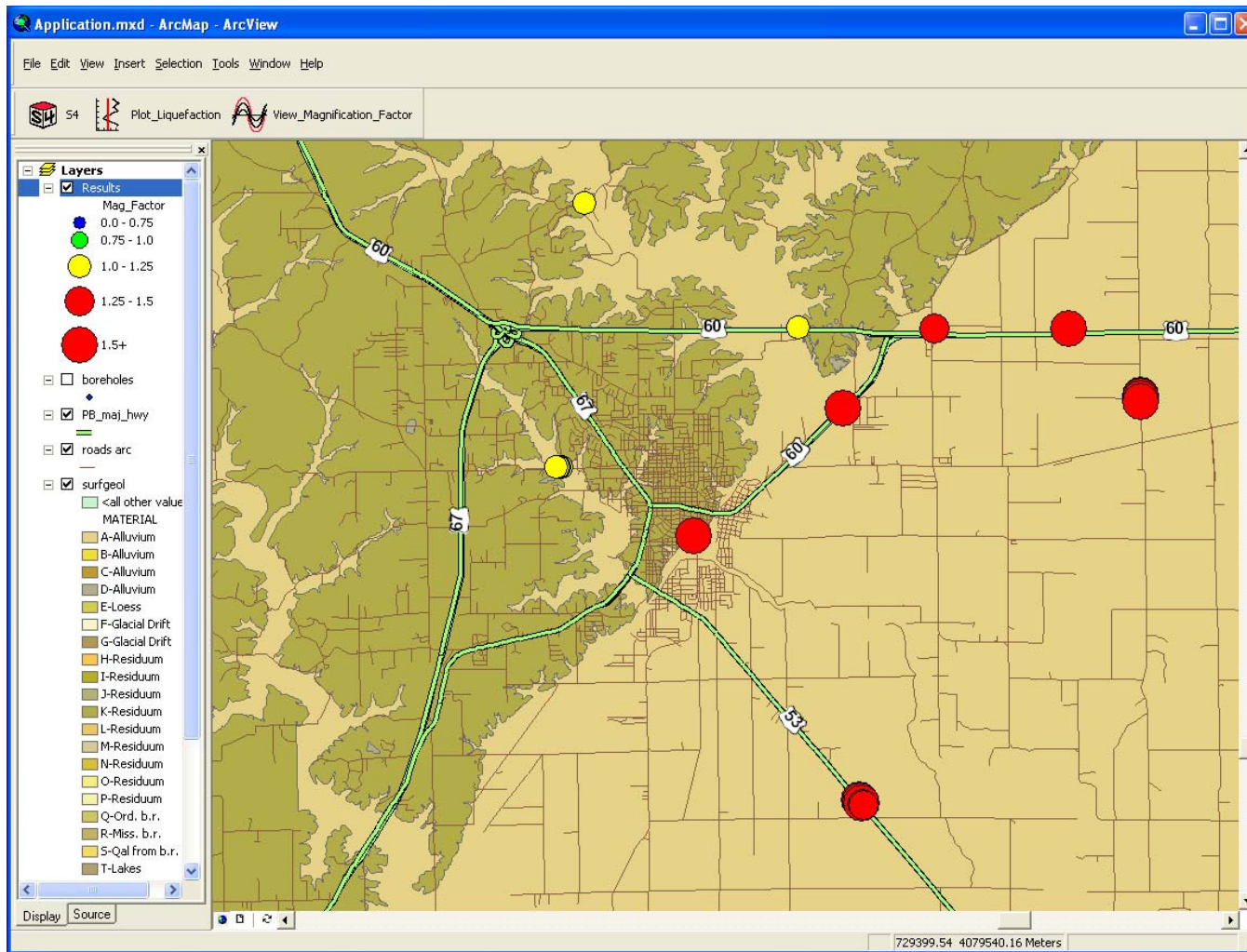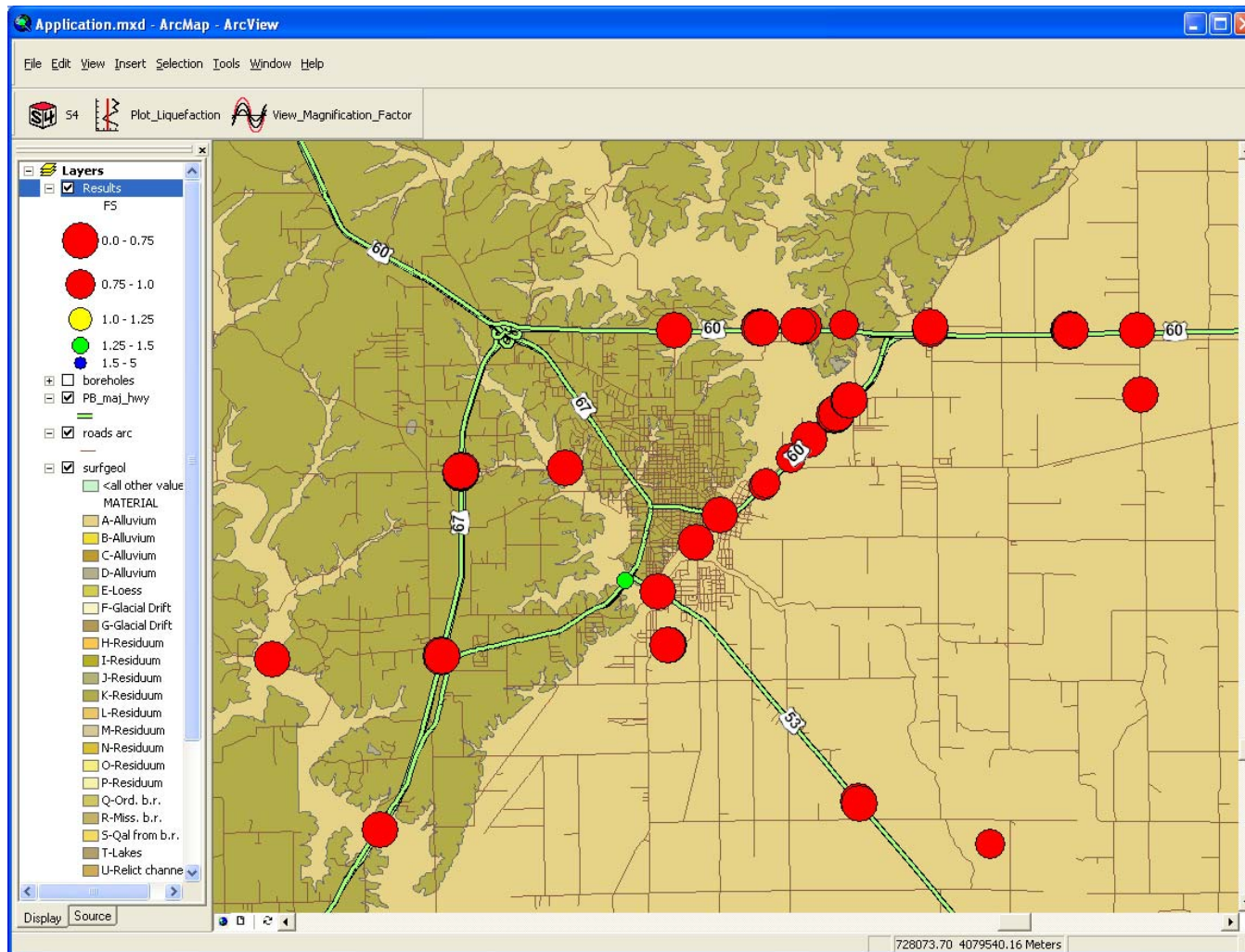
Figure 4.18. S4 Ground Motion Magnification Factor Results Overlaid on Surficial Geology Layer for 2475 Year Mean Return Period Ground Motion
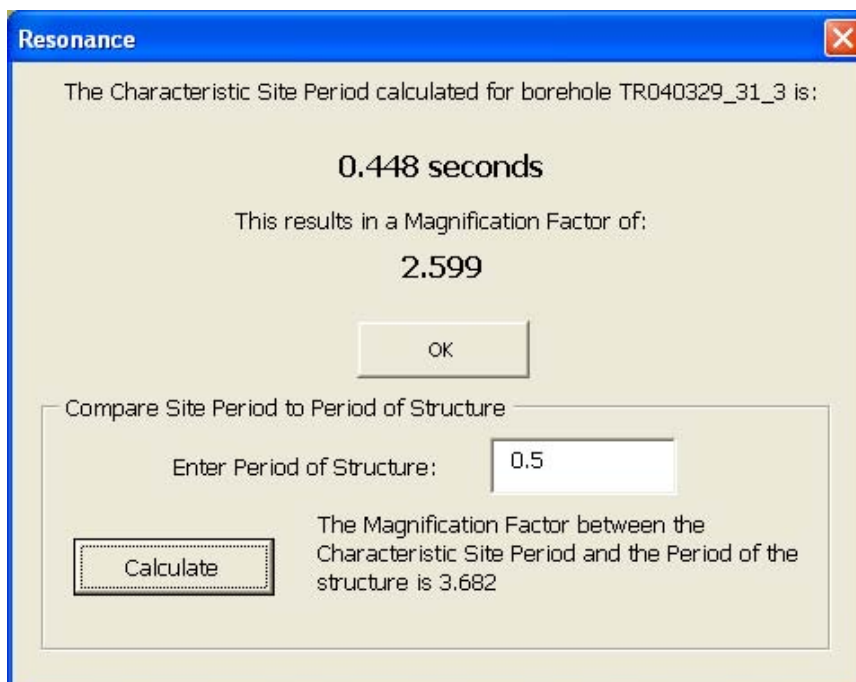
Figure 4.19. S4 Output Screen for Viewing of Resonance Parameters, TR040329_31_3

figure, nearly all boreholes drilled in sand present a hazard for liquefaction potential for an earthquake of this magnitude. By displaying the surficial geology map layer within the GIS Data View, it again becomes evident that borehole locations, and thus structures, that fall within the alluvial regions are at a distinct risk for liquefaction. Figure 4.21 shows the S4 liquefaction potential output for the 2475 year mean return period ground motion in relation to the surficial geology of the region.

Upon running the liquefaction plotting module and viewing the plots of factors of safety versus depth, it becomes apparent that unlike the previous analysis, where low factors of safety were mostly isolated, factors of safety of less than one are very prolific, many times occurring in thick layers, near the ground surface. An example of this is shown in Figure 4.22. This plot, for borehole BU60_A3686E137+6522R located at structure A3686E137, is fairly typical for this analysis. Based on the plots of factors of safety against liquefaction versus depth, the user may determine whether or not to further analyze these locations. However, in an analysis such as this, the majority of the boreholes should be studied further.
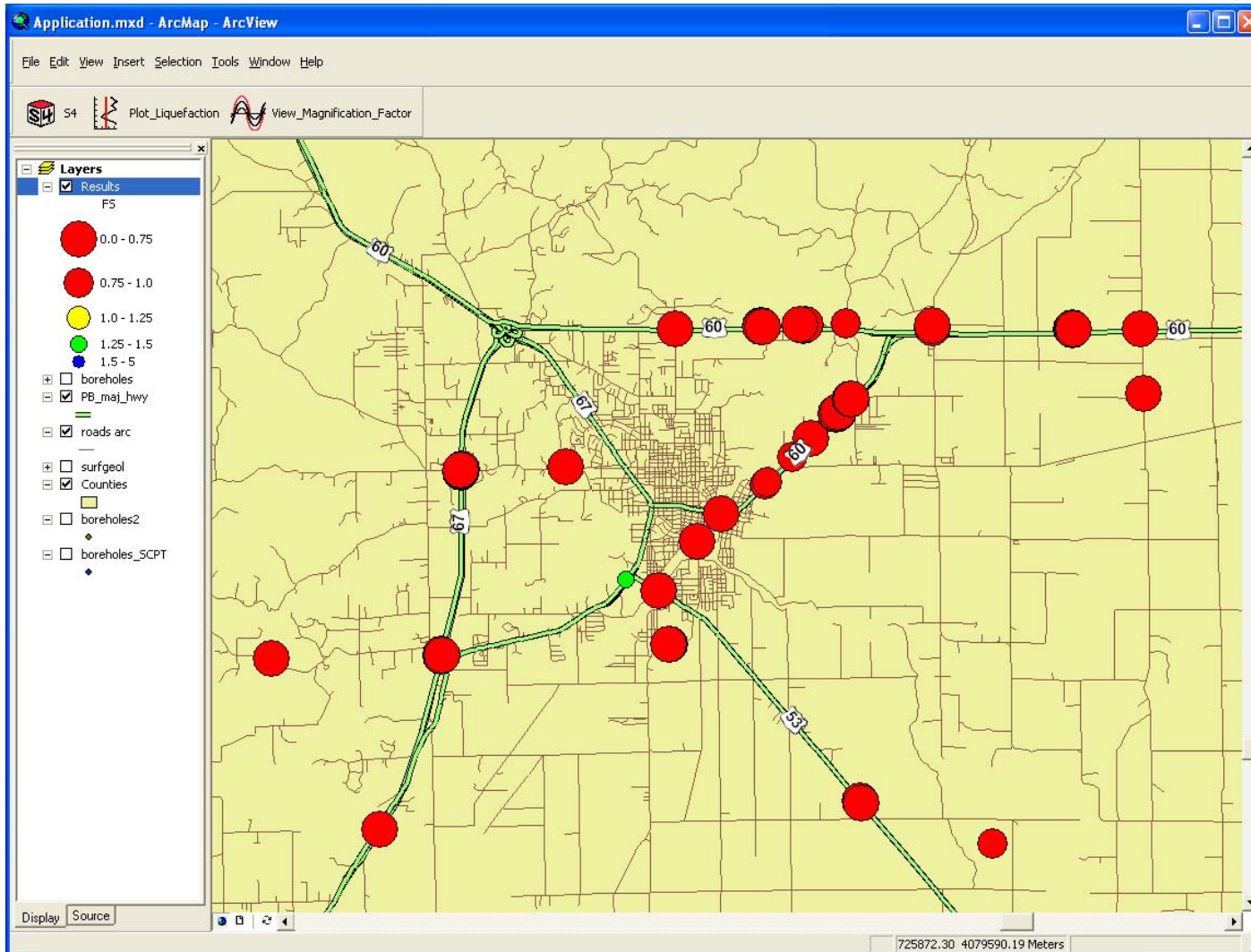
Figure 4.20. S4 Liquefaction Potential Results for 2475 Year Mean Return Period Ground Motion

Figure 4.21. S4 Liquefaction Potential Results Overlaid on Surficial Geology Layer for 2475 Year Mean Return Period Ground Motion
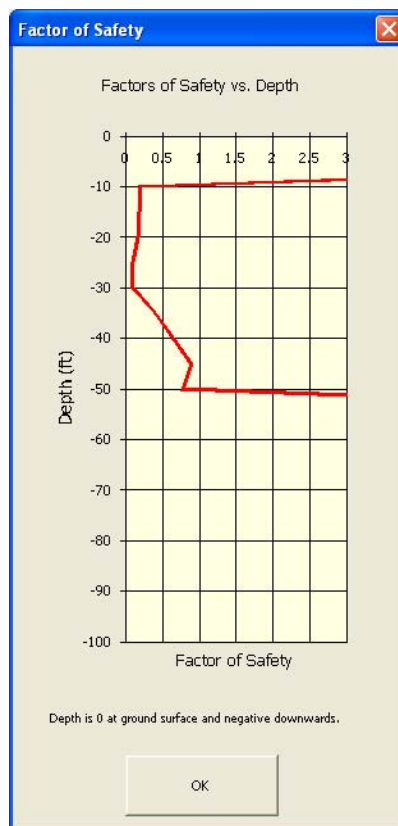
Figure 4.22. S4 Plot of Factor of Safety against Liquefaction versus Depth for Borehole
BU60_A3686E137+6522R

In the previous analysis, several boreholes showed relatively low factors of safety, despite the fact that they appeared to fall within the upland region of clayey residuum. Specifically, boreholes near structures MO67_A5524U, CRDMAR_A3723U, and MO67_A5523S, appeared to be located in deposits of residuum, with fairly deep depths to the piezometric surface. Similar results were obtained from this analysis with the same boreholes showing low factors of safety. As was determined in the previous analysis by viewing the plots of factors of safety versus depth, this is due to a loose sand layer, below the piezometric surface, shown in the original boring logs. Judgment in an analysis such as this is left to the analyst to determine if these values are reasonable or if less conservative values can be used to eliminate the reporting of potential liquefaction at these locations. However, it is noted here as at first glance it appears erroneous, though it is correctly computed based on actual recorded borehole data.

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, and specifically around structure RTZ_A2201U, as it showed the highest potential for hazards of all of the locations analyzed. Likewise, the rest of the structures could be prioritized for further in-depth analyses based on the combination of liquefaction and magnification factor results.

It should be noted that both analyses discussed above were fairly conservative in nature. The assumptions made when processing the geotechnical data (discussed in Section 4.2), as well as some of the procedures, programmed into the application (magnitude scaling factor, etc.) were purposefully chosen based on their conservatism. As the S4 application was developed as a screening procedure to identify locations where additional analyses should be performed, it is required to be, by nature, a conservative application. Once potentially problematic areas are located by the S4 application, it is then left in the control of the user to determine how conservative or unconservative of an analysis they would like to pursue for an in-depth study.

This pilot study demonstrates the effectiveness of utilizing the S4 application for the screening of two specific seismic hazards. As shown with the data used within the pilot study, this application performs well for 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.

5. CONCLUSIONS AND RECOMMENDATIONS

This research developed the Spatial Seismic Screening Software (S4) prototype software application, designed to screen for two specific seismic hazards (liquefaction and magnification factor) within a modern GIS environment (ArcGIS 8.3). To demonstrate the functionality of the software, a pilot study was completed and the results reported and discussed in the previous section.

5.1. CONCLUSIONS

The S4 application includes procedures using borehole specific engineering profiles for calculation of liquefaction potential in the form of factors of safety against liquefaction and also calculates the site resonance between the ground motion and the characteristic site period in the form of a magnification factor. By looping through each borehole profile, the application can quickly assess the seismic hazard potential at many sites and provide a rapid overview that is independent of site and scale. Additionally, ground motion parameters (a_{max}, M_w, T_P) within the application can be quickly modified to analyze different seismic scenarios. For these reasons, its value as a screening tool is apparent.

To demonstrate the functionality of the software, a pilot study was completed for a section of highways around Poplar Bluff, Missouri. A database of boreholes and shear wave velocity profiles from seismic cone soundings (mostly in the vicinity of highway structures) were analyzed for both liquefaction and site resonance, for two separate seismic ground motion scenarios. These synthetic ground motion scenarios were generated by the USGS as a 224 year mean return time earthquake with magnitude 6.1 and a peak ground acceleration of 0.074g (20% probability of exceedance in 50 years), and a 2475 year mean return time earthquake with magnitude 7.2 and a peak ground acceleration of 0.527g (2% probability of exceedance in 50 years). Results for the site resonance procedure produced very similar results for each case, as the predominant period of each input ground motion was very similar. Results for both cases showed potential ground motion magnification for nearly all analyzed locations, especially those

located in the alluvial lowland region. With respect to the liquefaction analysis, the results of these two analyses were vastly different with the 224 year event showing minimal liquefaction hazard potential at limited locations, while the 2475 year event showed liquefaction hazard potential to be very high at nearly all locations where alluvial deposits were present.

Specifically, magnification factor results from the 224 year mean return period input ground motion showed potential for magnification of ground motion for all locations, with fourteen of the twenty-two locations having magnification factors above 1.25. There is a clear division in the magnification factors coinciding with the geological environment of the area. Most if not all locations in the alluvial lowland region result with a magnification factor greater than 1.25 and all results for locations in the lowland region were below this value. In contrast, the liquefaction potential results of the analyzed locations showed only relatively low factors of safety in isolated areas. Only seven locations produced factors of safety less than 1.25, with no factors of safety resulting in values less than 1.0.

The results for the 2475 year ground motion produced very similar results for the ground motion magnification factor analysis, as the predominant period of the input ground motion was very similar. Again, all magnification factors were above 1.0, with fourteen of the twenty-two locations having magnification results higher than 1.25. Again, all magnification factors with values higher than 1.25 were located in the alluvial lowland region. Contrary to the analysis completed for the previous ground motion, the liquefaction analysis for the 2475 year earthquake produced results indicating very high potential for liquefaction hazards. The surficial geology maps again indicate a correlation between the geology of the region and the low factors of safety. It was observed that in an earthquake of this magnitude, nearly all structures founded in the regions of alluvial deposits would be at risk for liquefaction. Reviewing the plots of factors of safety against liquefaction versus depth indicates that the soil layers with potential for liquefaction were not isolated and infrequent, but were generally thick layers, frequently near the surface, and occurring very frequently among the boreholes.

This pilot study demonstrates the use of the S4 application for the screening of two specific seismic hazards. Additionally, this study showed that this application

performs well for data distributed spatially across a project site or small city, as evidenced by the specific types and distribution of the data used for this study. 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. For example, a transportation agency that intends to seismically retrofit a certain percentage of the highway structures in a district could use the S4 application to determine the most vulnerable structures for various ground motion scenarios. As an agency like this would likely already posses the required subsurface data, and in many cases have it compiled in a database similar to the one included in this study, implementation of the S4 application could be a first step for an agency that needs to prioritize the vulnerability of the structures within their transportation system and could reduce the time and effort of analysis.

5.2. RECOMMENDATIONS FOR FUTURE WORK

While significant effort was made to include the procedures for the anticipated user of the S4 application, countless items came to the attention of the author that would be useful to include in a future software package. Unfortunately, the line needed to be drawn somewhere as to what to include, or this project would have never reached a conclusion. The following items were identified as potential areas of continued development of the proposed screening tool, S4:

- The absence of a universal format for the storage and dissemination of geotechnical data was noted as an area of proposed development. Several data formats are currently in use within the geotechnical community (as discussed in Section 2.4), with a few of the formats having the potential for widespread use. Unfortunately, until the majority of the geotechnical engineering community adopts a universal standard, data will continue to be stored and transferred in many different formats, and the use and manipulation of it will continue to be cumbersome. Additionally, with several different formats available, the development of software applications, like S4, will be inhibited, as they will not be designed for a

single standard format and will require data conversions. For this reason, no specific data format was chosen and the S4 application was designed with a simple text based input file system, so any future data standard could be input with the creation of a converter to read the standard data file and translate it into the S4 format.

- Several additional methods are recommended for further development. Primarily, the addition of cone penetration test-based liquefaction resistance analyses (Stark and Olson 1995, Robertson and Wride 1997) would be a worthwhile endeavor. Cone penetration testing continues to increase not only as a means to determine strengths, stratigraphies, etc., but also as a means to estimate liquefaction resistance. The addition of this procedure to the S4 application would add a useful tool and create synergy within the program.

- Additionally, along the lines of the CPT-based liquefaction computational ability, the addition of other forms of liquefaction resistance calculations would prove useful within S4. Among these are analyses based on the Becker penetration test (Harder 1997), and shear wave velocities (Youd et al. 2001), especially as shear wave velocity profiles are already included within the application for the calculation of site resonance.

- The liquefaction resistance analysis of silts and clays as proposed by Boulanger and Idriss (2006) could be implemented as an additional criterion to evaluate for this hazard. While liquefaction of these materials has classically not been considered, they have become more of a concern as more research is completed. For completeness, this procedure should be integrated into S4.

- Other useful additions could include determination of the NEHRP site class at each location, correlations to estimate data that is not present (i.e. estimate of Vs from SPT blowcounts), the ability to output a summary report of the analyses, and the ability to use either English or metric units for data input.

- Finally, there are potential additions that could be made that, while they would not directly affect the results or increase the breadth of the operations, would increase the functionality of the S4 application. Probably the foremost example of this group is the recommended addition of the liquefaction potential index (LPI) as proposed and applied by Iwasaki et al. (1978) and implemented into GIS liquefaction applications by Luna and Frost (1995) and Carroll (1998). The LPI, as discussed in Section 2, provides a means of representing another dimension in the analyses (factors of safety versus depth) as a two dimensional representation of the severity of a given incidence of liquefaction at the ground surface. The S4 application currently displays the results of the liquefaction analysis as the resultant lowest factor of safety for a given location, and provides factors of safety with depth, but does not integrate the effects into a single value. The user can then quickly scan the results visually and determine for which locations they would like to view a plot of factors of safety versus depth. By replacing this value for the lowest factor of safety with the computed LPI, one more level of automated screening could be added to the S4 application, by ruling out minor instances of liquefaction (i.e. thin, very deep, liquefiable layers).

The S4 application has been shown to be useful as a preliminary screening tool for seismic hazards as a prototype application. In addition, the "Guide for Future Development" has been produced and is included in Appendix A. With future development, an indispensable application can be created for screening of seismic hazards for a focused engineering market.

The methodology presented herein was intended to put 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 ground motion amplification and liquefaction analyses are performed. However,

seldom is the site-specific level of analyses performed for a complex infrastructure system with spatially distributed data. Hence, the application of this methodology should be limited as a preliminary screening tool.

APPENDIX A.

GUIDE FOR FUTURE DEVELOPMENT

S4: SPATIAL SEISMIC SCREENING SOFTWARE
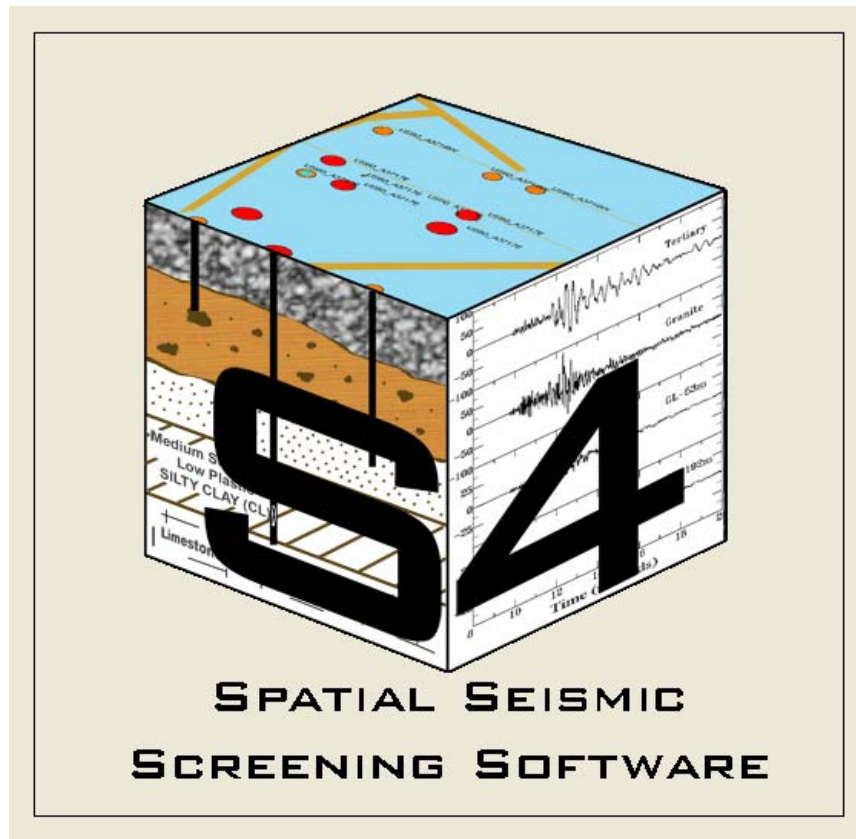
GUIDE FOR FUTURE DEVELOPMENT

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1.0   Introduction

This document describes the processes and procedures for completing a geotechnical earthquake engineering screening analysis within S4. However, as the S4 application is only available in prototype form, it is not yet suited for the average user. For this reason, this document was written as a guide for future development for those wishing to build on the S4 application and develop it into a working, distributable product. Specific details about the programming aspects of the application are included. While these aspects may be potentially helpful to the developer, they are likely irrelevant to the average user. Recommendations for future development are also discussed.

What is S4?

S4 or Spatial Seismic Screening Software is a geotechnical earthquake engineering tool designed to run within the ArcGIS 8.3^{TM} environment by ESRI. The S4 application was designed to be used for analysis of two separate geotechnical earthquake engineering hazards: 1) the liquefaction potential and 2) the amplification of ground motion calculated as a magnification factor between the predominant period of ground motion and the characteristic site period. After calculation, the results are displayed spatially on a map of the study area. The S4 application is based on the liquefaction procedure presented by Youd et al. (2001) and the magnification factor procedure as described by Kramer (1996). S4 provides functionality not included within the "off-the-shelf" installation of ArcGIS, but has the potential to operate seamlessly within the GIS environment.

About S4

S4 was developed in prototype form by Andrew J. Wilding at the Missouri University of Science and Technology as partial fulfillment of a Master of Science degree in Civil Engineering, under the direction of Dr. Ronaldo Luna. Special thanks go to Dr. Richard Stephenson and Dr. J. David Rogers for their review of the M.S. thesis associated with this project. Finally, Gustavo Ordonez and Joshua Joy were invaluable in providing code and assisting with program development.

2.0   Installation of S4

Currently, an automated installation routine does not exist for S4, so before operating the application on a computer, the completion of several steps is required.

System Requirements

S4 was designed to operate on a PC running the Windows XP operating system. It has not been tested on systems running other versions of the Windows operating system. Approximately 10 megabytes (Mb) of hard disk space is required for the installation of the program, in addition to the amount of space required for associated data files. It is recommended to have approximately 250 Mb of free hard disk space for optimal program operation, as a small collection of spatial layer data can easily exceed 200 Mb in size. At this stage of development, processor speed and memory requirements are dictated by the minimum ArcGIS requirements.

ArcGIS 8.3

The first step in installation of the S4 application is the installation of ArcGIS^{TM} by ESRI. Additionally, Visual Basic 6 must be installed for the graphing procedures to operate properly. Refer to the product instructions that came with these software applications for information on installing these products.

S4 was developed to operate within the ArcGIS 8.3 environment. From limited testing, S4 has been shown to operate within other versions of ArcGIS, up to and including Version 9.2. However, more intensive testing should be completed before implementation within versions other than Version 8.3. S4 will not operate within earlier versions of ESRI products, (before Version 8). Additionally, S4 will not operate under any other GIS program.

S4 Installation

The S4 application is contained in one folder, aptly named "S4", which must be copied to the root of the "C" drive on the desired computer. This requirement should be modified

by future developers at a later date, as this location is "hard-coded" within the application and the source code would currently need to be modified if a computer's drive designations did not include a local hard drive with the "C:\" designation. Additionally, several Visual Basic (VB) references will need to be activated within ArcGIS to allow the use of graphing within the application. The S4 application will not run without activating these references.

Perform the following steps to install S4 on a PC:

1. Copy the "S4" folder to the root of the "C:\" drive.
2. Open ArcGIS.*
3. From the menu, select 'Tools', 'Macros', 'Visual Basic Editor' This will open VBA.
4. Within VBA, from the menu, select 'Tools, 'References.' This will open the 'References' window.
5. Scroll through the available references and click to select the checkbox beside the following references:
   - Microsoft Common dialog Control 6.0 (SP3)
   - Microsoft Chart Control 6.0 (OLEDB)
   - Microsoft PictureClip Control 6.0

   (Checkboxes may already be selected due to other installed programs. If a checkbox is already selected, do not unselect).
6. Click 'OK.'
7. Close the Visual Basic Editor window.
8. The installation is now complete.

* Steps 2 through 7 are not required if the S4 application is installed for use with ArcGIS Version 9.0 or later.

Double clicking the application.mxd file will open the application within ArcGIS, and the S4 application toolbar can be seen in the data view, signifying that the application is installed.

3.0   Important Considerations Concerning Data

Before performing a geotechnical earthquake engineering screening analysis with S4, input data needs to be imported or created. As the output of the application is dependent on this data, several important considerations concerning input data should be made.

Geospatial Data

The geospatial data for use within S4 is limited only by the "boreholes" layer. The project must contain a point-based layer named "boreholes" with at least one feature. Data files can be developed for this layer, and attributes will be written to the layer's attribute table. Additionally, the position of this layer must reside at the top of the project Table of Contents, (or directly below the "Results" layer, if an analysis has been completed) for the application to execute properly.

Any other layers may be added to the project, provided they fall below the "boreholes" layer in the table of contents, and are not also named "boreholes". These additional layers will not affect the computational analyses, but may help the user during the screening process.

Finally, this application operates independently of site and scale. Project scale is only limited by the input data (borehole locations and sample depths), but care must be taken to not interpolate results to a finer scale than for which the initial data was collected. Likewise, the project site is only limited by the data available for the analyses. An analysis may be completed anywhere for which data has been collected.   With these two items in mind, projects may be developed for analyses which incorporate data with a reasonable map extent. If only one ground motion scenario is being used, the user should limit the area to the seismic zone of influence (e.g. a project site, town, or small city).

Geotechnical Database

In this application, the quality of the output is highly, if not completely, dependant on the quality of the input. Within both the liquefaction potential and the magnification factor computations of the S4 application, the accuracy of the results is only as good as the estimation of the input parameters. Additionally, data formatting for the S4 input files is very particular and all data must be in the required format if the application is to execute. If one digit is out of place, it could result in a program termination error. For this reason if data is entered manually without the use of the input dialogs, detailed checking of this input data is a necessity before executing the application. The formats for the input text files are discussed in Section 4.0.

Seismic Ground Motion Data (Acceleration Time Histories)

As with the geotechnical database, it is imperative to have quality seismic ground motion data in order to produce reasonable results within S4. Whether it is chosen to enter ground motion parameters manually as numerical values, or to input an acceleration time history text file, the quality of the values is directly translated through the program to the results.

Additionally, it is important to have all associated data developed from the same source. Values for moment magnitude are directly related to their corresponding acceleration time histories and/or a_{max} values, and should not be used independently. For example, a given acceleration time history should not be used with multiple, different moment magnitude values as (for a synthetic motion) it was developed for a specific magnitude. Using magnitudes other than the one for which it was developed would not produce reasonable results. The same restrictions apply for recorded ground motions as well.

For the ground motion data used within S4, specific data format requirements must be followed. The input file for acceleration time history is input as a text file with acceleration values (one per line) with a time step of 0.02 seconds. Three sample acceleration time history input text files are included in the installation files for S4.

4.0   Initiating S4

The processes for completing an analysis, as well as general descriptions of application functionality and issues are described in this section.

After installation, to initiate S4, the user should open application.mxd within ArcGIS 8.3. This file is essentially a project file, with background maps included. The screen should look similar to the image below, with the S4 toolbar visible. (Screen layout may differ based on loaded layers and other visible toolbars).
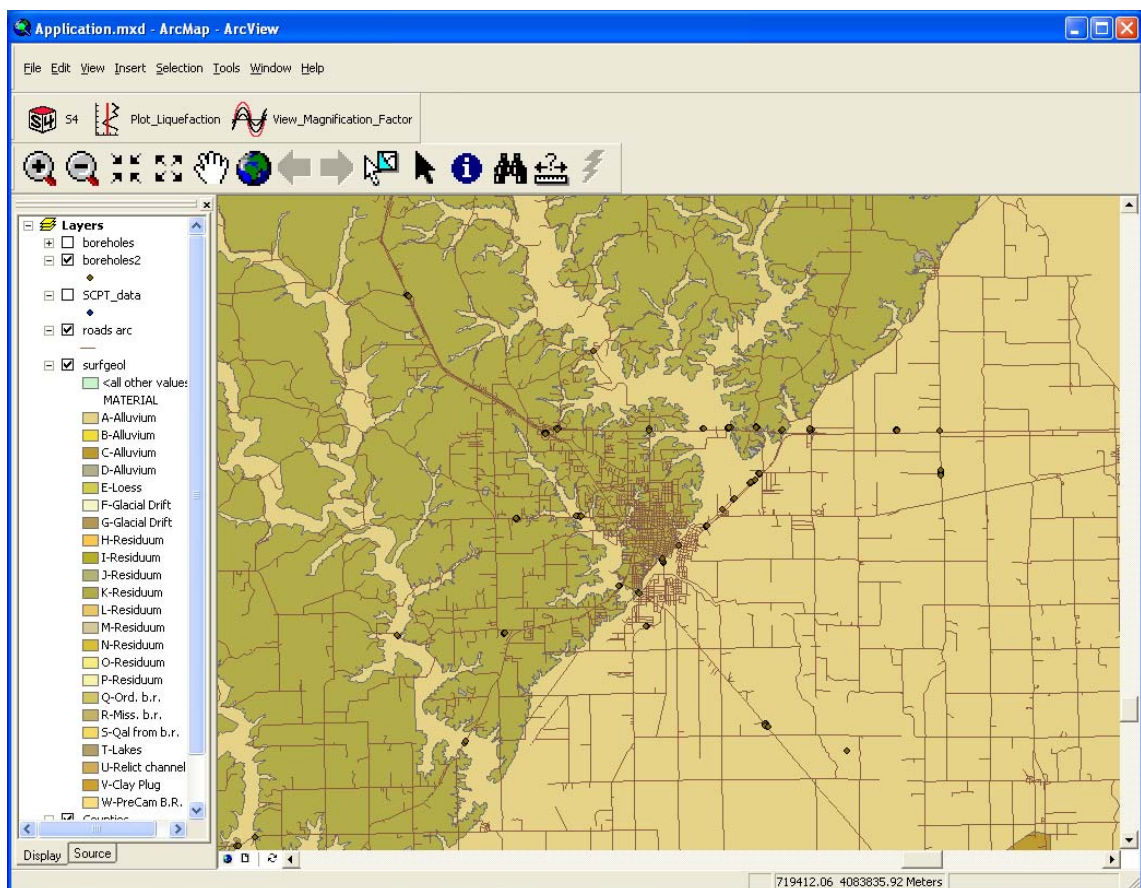
Before proceeding with any of the S4 operations, it is required for the user to have added points to the "boreholes" layer in the data view and selected the data points for which they would like to perform an operation. This is done with any of the ArcGIS "Add Feature" or "Select Feature" options. As these are standard ArcGIS procedures, please refer to the ArcGIS documentation for instructions on how to perform these tasks. (A

data layer containing the data used in the pilot study for this application is included in the installation files).

Next, the user should click the S4 button, as shown below, located on the S4 toolbar.
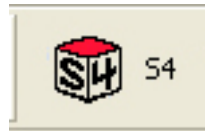
This will open the S4 welcome screen, with an option to view the acknowledgments window.
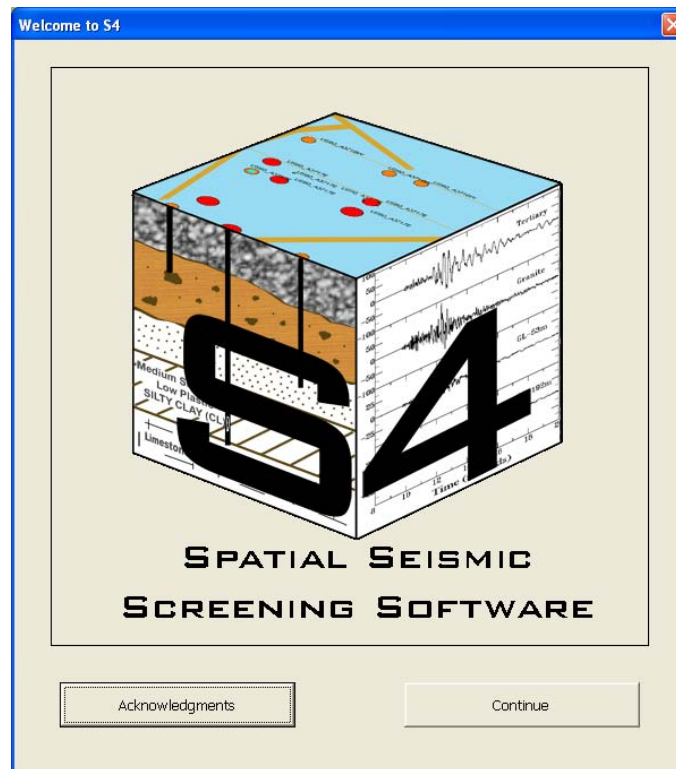
The acknowledgments window simply provides additional information about the development of the S4 application. The acknowledgments window is displayed below:
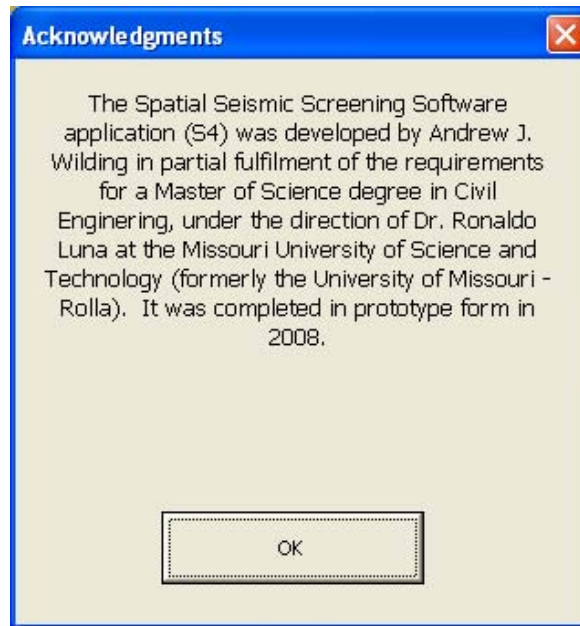
After closing the acknowledgments screen, an option window can be displayed by clicking the "Continue" button on the main welcome screen. This window allows the user to decide what they would like to do next. By selecting one of the three radio buttons, this screen allows the user to decide whether to enter data, calculate the magnification factor, or calculate liquefaction potential.
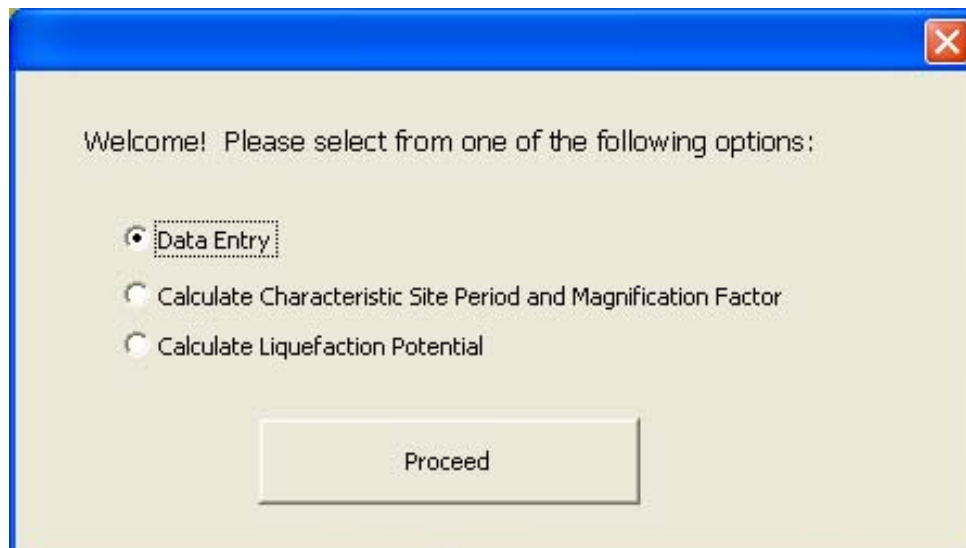
5.0   Data Manipulation Operation

The first available option from the above screen is the option to enter data. Currently this procedure only allows the creation of new input files via the user interface. This procedure was originally intended to allow the user to import or manage data, instead of only creating data files manually, as this procedure is very time consuming and somewhat tedious. However at this time, manual creation of data files is the only option. It is, however, somewhat automated, which adds a level of convenience.

After selecting the "Data Entry" option and clicking "Proceed", the following screen is displayed to the user with the options to input an engineering soil profile, input SPT data for a liquefaction analysis, input SPT data using existing engineering profiles, or view or manage previously entered data.
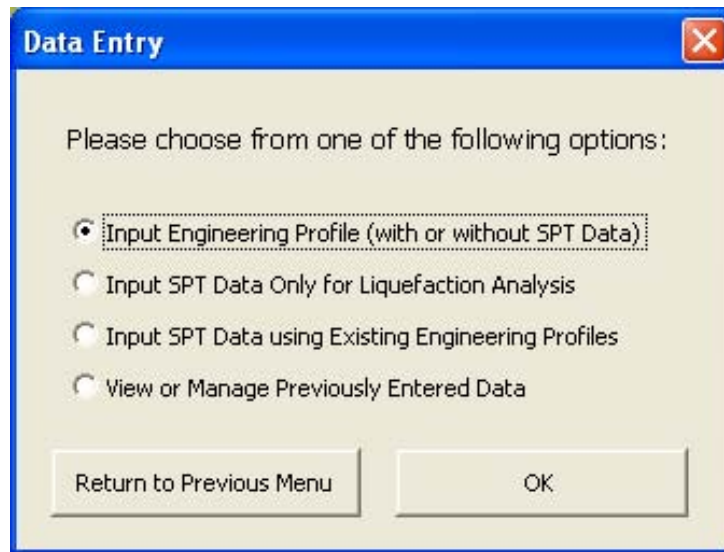
Currently, the option to input SPT data using existing engineering profiles and the option to view or manage previously entered data are unavailable. At this time, clicking on these options will display the following error message:

Adding these features should be a priority for future developers.

By selecting one of the first two options, the user is presented with a procedure to input the desired form of data.

The first available option allows the user to create an engineering soil profile input file for use with the magnification factor procedure. If this option is selected, the application loops through the selected boreholes and displays a message box informing the user of the number of boreholes selected. An example of this message box is shown below:
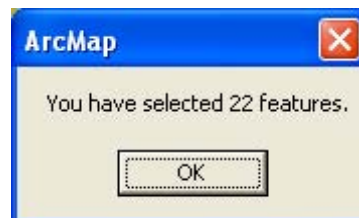
Once the "OK" button on this message box is clicked, a dialog is initiated to loop through each of the selected features and request two values from the user for the given location. These values are the number of layers to input and the depth to the groundwater table. The input screen for these values is shown in the following image:

After this input is entered by the user, the application loops through the number of entered layers and displays an input form so the user can enter the data for each layer. This input form is shown below:

This input form is displayed once for each layer requested by the user in the previous form. Once this input is complete, the user is also given the option to input SPT data for the creation of an input file for the liquefaction procedure. This decision is made by the user on the following form:
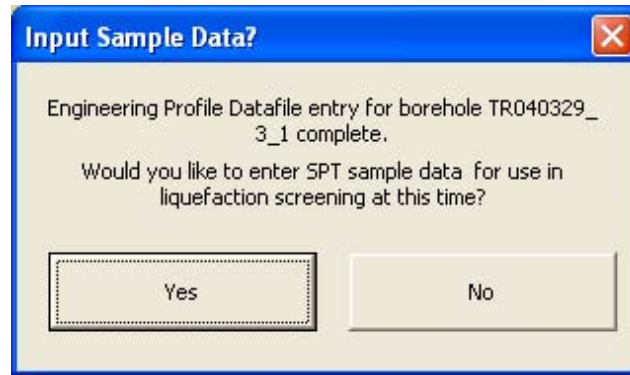
If the "No" button is clicked, the application closes the newly created input file and proceeds to the next selected borehole and begins the procedure again. However, if "Yes" is selected, another procedure is invoked which semi-automatically produces the input file for the liquefaction potential procedure, by manipulating the data entered for the engineering soil profile input file. Input of additional data, specifically the SPT blowcounts and associated depths, is required for the creation of this file. The first step in the creation of this file is to enter the desired number of SPT sample depths in the screen below:
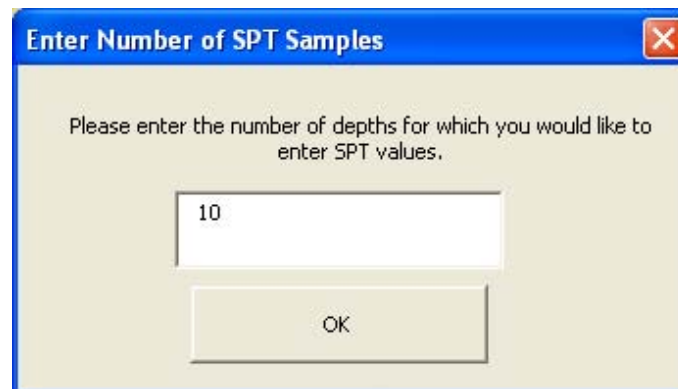
Entry of a value in this form allows the application to loop through the entry screen for each sample depth, and request an SPT value and depth.

SPT sample information is then entered for each requested depth using the following screen:

This screen is displayed via a loop, once for each requested layer. Additionally, from this screen the "Advanced SPT Corrections" screen can be displayed. This screen allows the user to input parameters used for calculating $N_{1(60)}$ for that sample. If no values are entered by the user at run time, the default values are used as shown in the following image:

If a σ'_{vo} value is not entered in this form, a value of 1.0 is used for the C_N correction value. Additionally, a "Help" button is included, for the future addition of a window to show a description of each of the available correction factors. (No information is currently included in this help file).

Once the required information is entered for each sample, the input file is written by the application and saved as a text file with the name of the boring. All required headers and labels are automatically written in the input file by the data entry module. The newly created textfile is then closed and the screen below is then shown to inform the user of input completion:
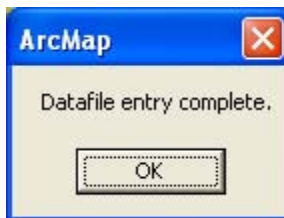
This concludes the data entry procedure for the engineering soil profile input file. An example engineering soil profile input file is shown in the following image. A text file in this format is produced for each of the boreholes selected.

```
Boring Name
US60_A3799E41+5535L

Water Table Depth

5

Line, Top Depth, Bottom Depth, Gamma, USCS, FC, Vs, Su, Phi
1,0,5,125,SW,10,800,0,33
2,5,10,128,SM,25,800,0,33
3,10,15,125,SP,0,900,0,34
4,15,20,125,SP,0,950,0,34
5,20,25,127,SM,15,1000,0,33
6,25,30,120,CL,95,1000,1200,0
7,30,35,120,CL,95,1250,1250,0
8,35,40,125,SP,2,1000,0,34
9,40,45,125,SP,1,1000,0,34
10,45,50,125,SP,4,1000,0,34
```

Likewise, a procedure exists for creating an SPT based input file for the liquefaction potential procedure without creating an engineering soil profile input file. This option is invoked by selecting the "Input SPT Data Only for Liquefaction Analysis" from the "Data Entry" menu.

After selection of this option, the application loops through the selected features and the following screen (denoting the number of selected boreholes) is displayed as before:

Once the user clicks through this screen, the data input procedure again loops through the selected features to perform the data input. However, a check is also performed at this time to determine whether previous data exists for the selected locations. If a location is found where data already exists, the following screen is displayed to question the user whether they would like to overwrite existing data:
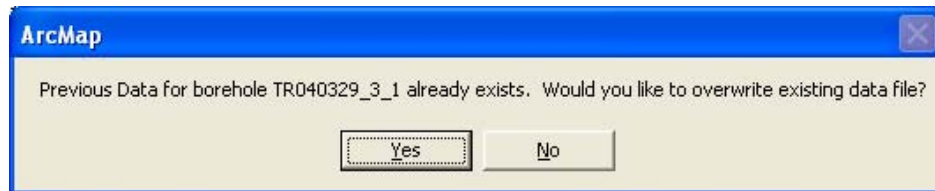
If "No" is selected from this screen, the application simply skips this location and moves on to the next location. If "Yes" is chosen, the data for that location is erased and the user can proceed with data entry. The following screen is then displayed.

As before, in this screen the user enters the depth to piezometric surface, and the number of sample depths.   After this screen is closed, a window is displayed to enter specific data for each depth. This screen is shown in the following image:

The application displays this screen once for each depth, as requested by the user in the previous window, until the data entry for the input file is complete. This data is written to a text file that is saved with the name of the borehole/sounding and given an *.lpf extension. Advanced SPT corrections can be accessed from this screen as described previously. Once input in the "Soil Layer Data Entry" form is complete, the newly created text file is closed, and the following screen is then displayed:

After completion of each input file, the application loops to the next location and begins input file creation again. Once the application reaches the end of the list of selected features, the following screen is displayed:
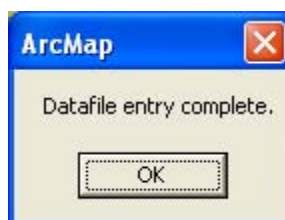
At this point, the data entry procedure is complete. An example input file for the liquefaction potential procedure is shown below:

```
Boring Name
US60_A3717E41+1418L

Water Table Depth
6

Line, Depth, Gamma', Sigma', N, USCS, FC, Vs
1,5,110,550,10,SM,5,500
2,10,110,1100,6,SP,0,300
3,15,110,1650,12,SP,2,600
4,20,110,2200,11,SP,0,500
5,25,110,2500,6,SP,0,760
6,30,110,3300,7,SP,0,800
7,35,110,3500,9,SM,2,900
8,40,110,4400,14,SM,12,900
9,45,110,4500,8,SM,1,950
10,50,110,5500,15,SM,4,700
```

At any time, additional data may be added to the existing "boreholes" layer by simply running the data entry procedure with different locations selected. Additionally, data for a given borehole may be overwritten by selecting the icon for that borehole and re-running the data entry procedure.

It should be noted that these data entry procedures are rather rudimentary and devised simply for the initial input of data. As previously mentioned, it should be the goal of future developers to create additional routines for the importation and manipulation of data. Of particular importance is the future addition of a procedure to import and translate data from a known data standard, as this would greatly add to the functionality of this software.

6.0   Magnification Factor Screening Analysis Operation

The magnification factor procedure is initiated from the main menu by selecting the third radio button labeled "Calculate Characteristic Site Period and Magnification Factor". When this procedure is initiated, it is required for the user to have previously selected locations for analysis. If no locations are selected, an error message will display and the application will terminate. If acceptable features are selected, the following screen will appear alerting the user of pending computations:
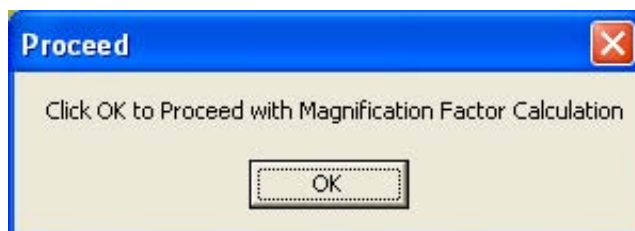
Once "OK" is clicked on this screen, a progress screen is very briefly displayed to show the progress of creating a new layer for the output. For analyses with few boreholes, this screen may appear too briefly for the user to see. For a layer with many selected borehole locations (i.e. several hundred), this screen notifies the user that the program is still running. This screen is displayed below:
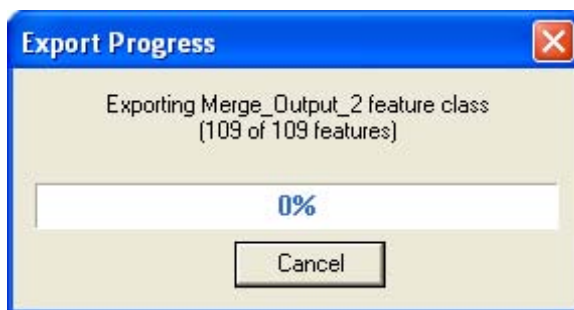
If an analysis has already been completed using S4, previous results will exist in the form of a "Results" layer and output text files. The user is given the option to overwrite these files, or exit the application in the following screen.
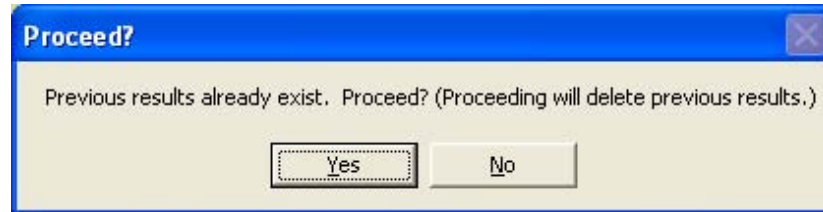
Currently, no method exists for saving the results of an analysis. This would be a worthwhile addition for future developers.

Next, the user is given a choice as to whether to enter an acceleration time history text-based input file, or to enter the ground motion parameters manually, as shown in the image below:
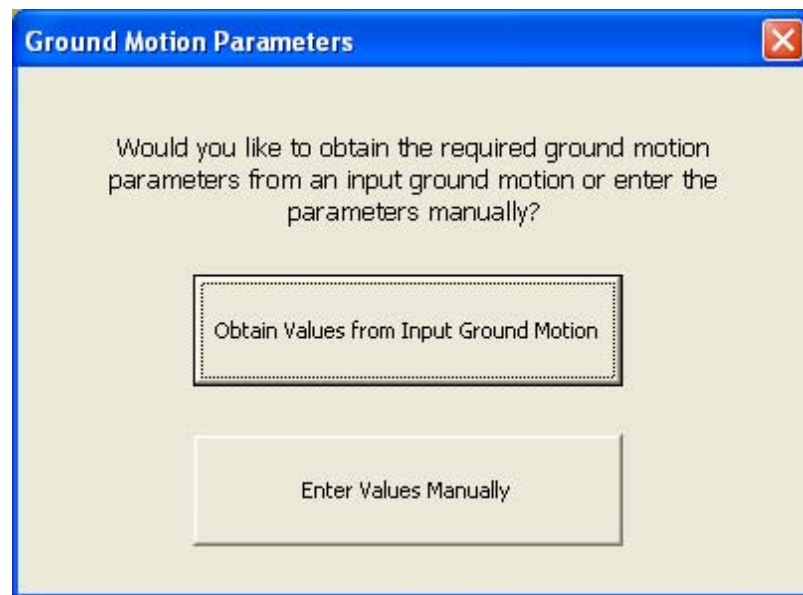

In most cases for the site resonance procedure, it will be simpler for the user to enter an acceleration time history instead of numerical values for the ground motion parameters. While entry of the numerical values is perhaps easier at run time, development of these parameters is greatly simplified by the S4 application.

If the option is chosen to enter the values manually, the following screen is displayed for value input. (Note that input in the maximum acceleration input box is not activated as that value is not used in the site resonance calculations.)
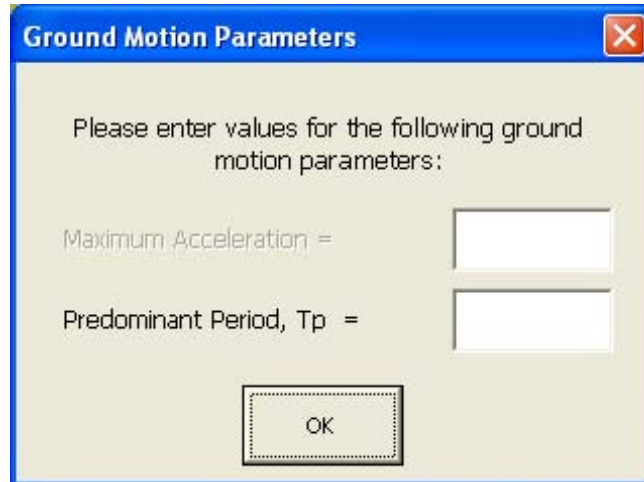
If it is desired, the ground motion parameter values may be calculated from the acceleration time history. Choosing this option displays the following dialog box:
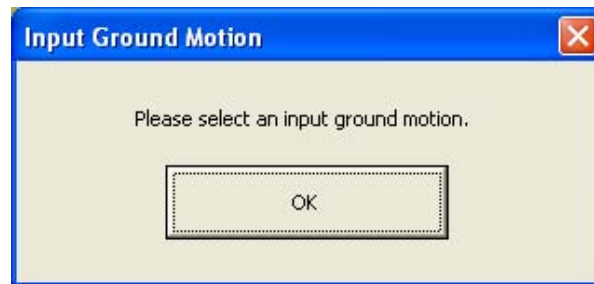

Acknowledging this screen opens the Open File dialog, which allows the user to search their computer for input acceleration time histories. (Currently it is required for the time history input file to reside in the "App77" folder within the "S4" folder on the C:\ drive. Though this was not intended by the original developers of the S4 application, this is an idiosyncrasy of the "shell" command used within the S4 application that should be adapted in future development.) The File Open dialog is similar to most Windows based programs as shown below:
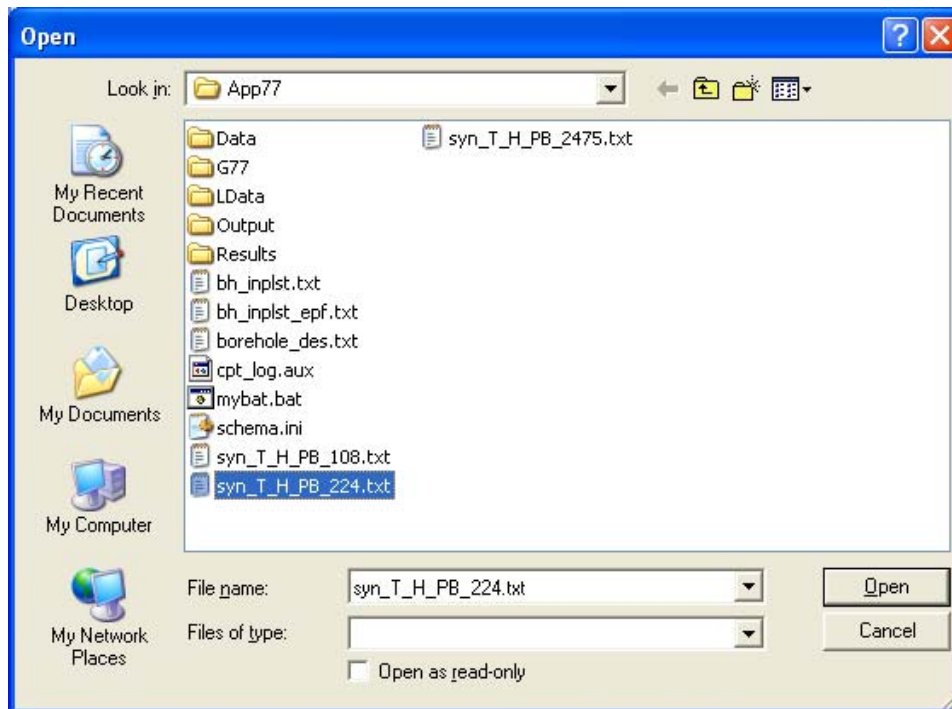
After an input file is selected form this dialog, the following screen is displayed, allowing the user to view a plot of their file:
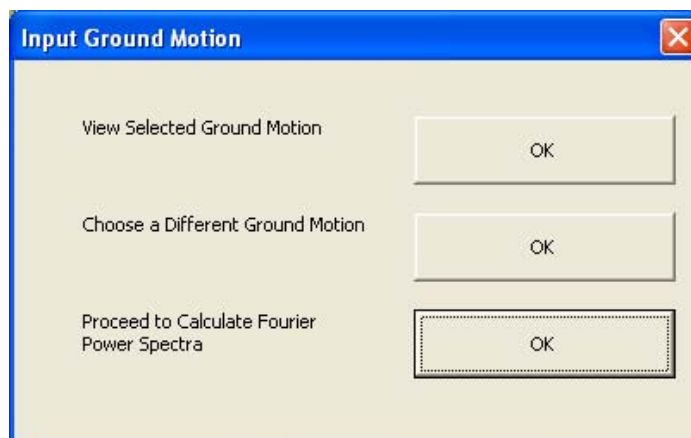
By clicking the "OK" button next to "View Selected Ground Motion", the following screen is displayed:
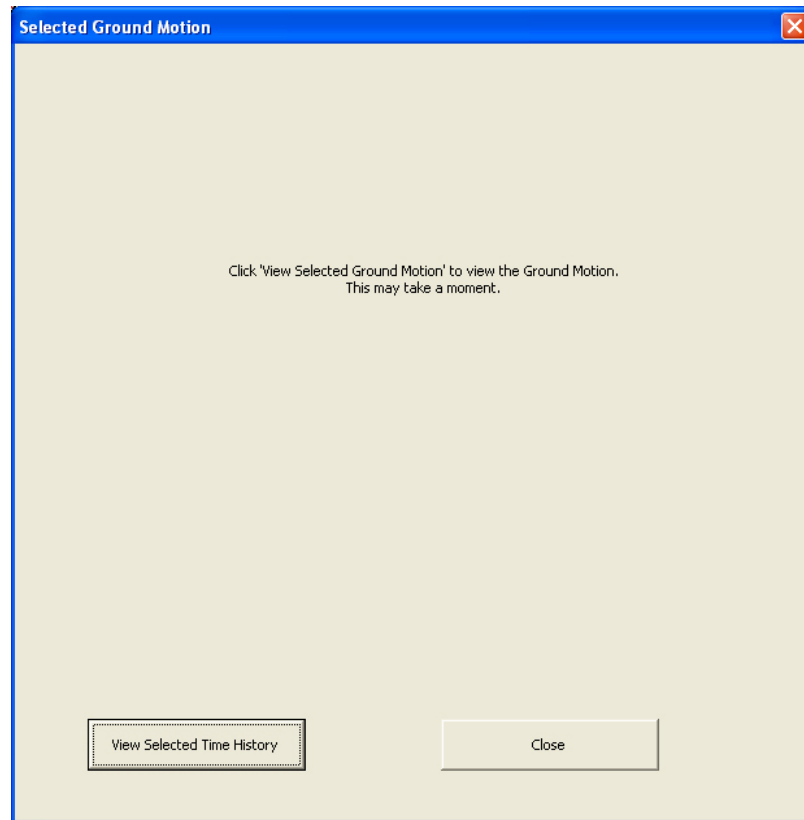
This screen view is an intermediate step that could be removed in the future, though currently is necessary for the program to execute. On this screen, the user is required to click the "View Selected Time History" button, which displays a plot of the time history and calculates a_{max}. (Note that a_{max} is not used in the magnification factor calculations). It is recommended to eliminate this step in future development. After clicking of this button, this screen is updated to look like the following image. (Note that the actual plot will differ based on the selected time history).
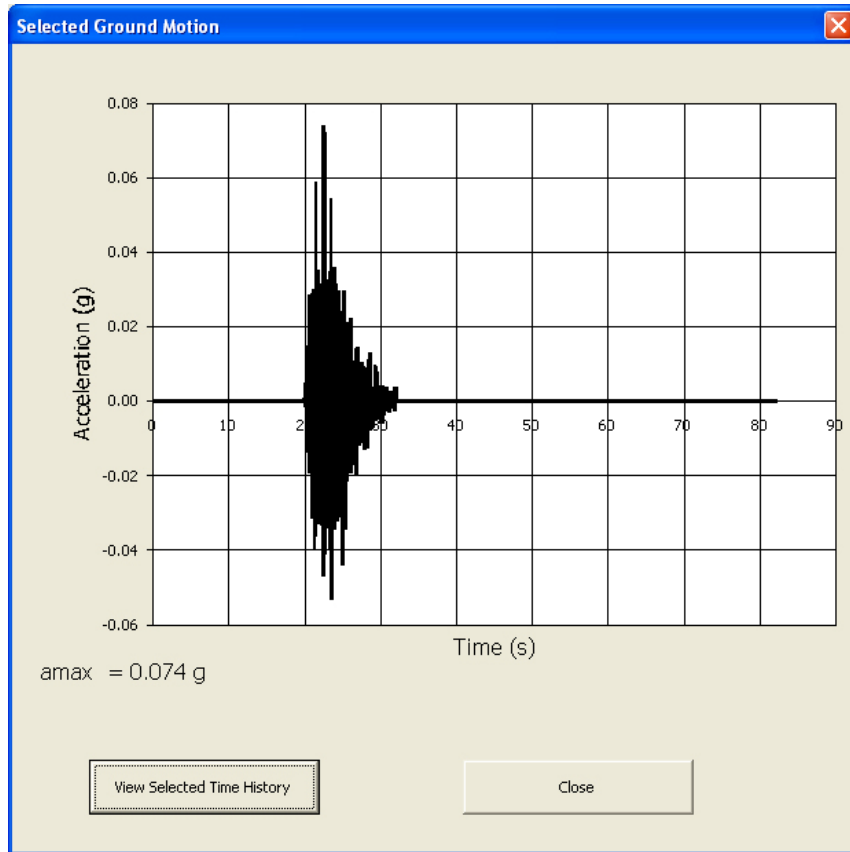
For more information on the acceleration time history input file, please view the section titled "Important Considerations".

The user then clicks the "Close" button to proceed. This returns the user to the "Input Ground Motion" screen, where they have the option to view a different acceleration time history, or proceed to calculate the Fourier power spectra. The user may cycle through as many time histories as desired viewing each one before selecting one and proceeding to spectra calculation.

Once a desired time history is chosen, the user should click the button labeled "Proceed to Calculate Fourier Power Spectra". This will display the following window, similar to the window for viewing the ground motion:

Again in this intermediary step, the user is required to click the button labeled "View Spectra" to view the Fourier power spectra and calculate the predominant period of ground motion. By clicking this button, the display is updated, the predominant period calculated, and the spectra plot is displayed:
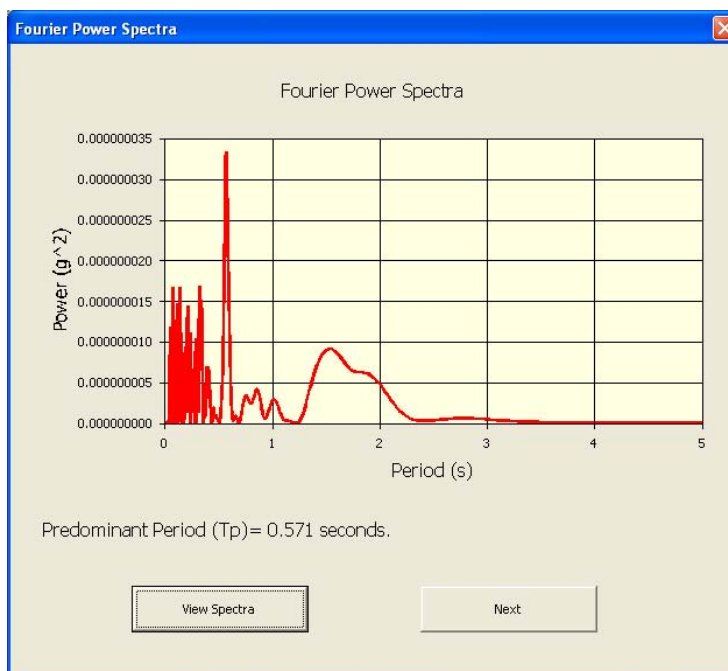
At this point the user can click the button labeled "Next" and the following message box is displayed to inform the user of the number of data points for which computations will be completed.
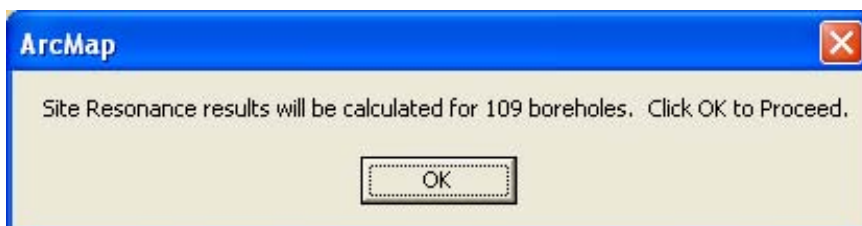
Next, the user is prompted to enter a damping value for the magnification factor calculation. This value is important, because if no damping is specified and the tuning ratio equals 1.0, the magnification factor will approach infinity and the program will "crash". The value of this entry is left up to the user as it can significantly affect the results of the computations, though 5% is used as a default if no other information is available. The damping factor input screen is shown below:
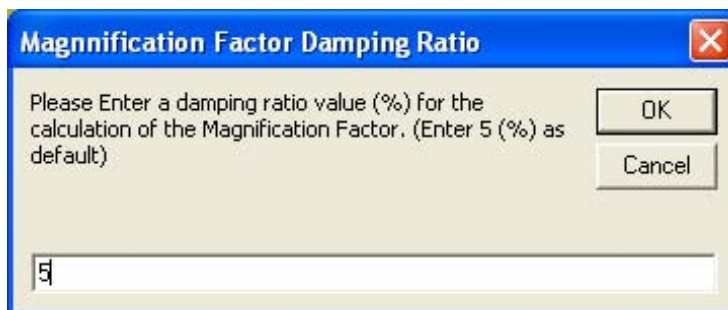

Once this value is entered, and the button labeled "OK" is clicked, computation will commence. At this point the application loops through each of the selected boreholes to compute the characteristic site period based on the shear wave velocities, and ultimately the magnification factor for each location. If no data file exists for a given location, the following screen is displayed and the application loops to the next feature:

While this screen is generally dismissed rapidly, it should be noted by the user as it is
the only alert they will receive on this subject. If important data is missing, analysis of
that location will be omitted, potentially skipping important data for the analysis.

Once computations are complete, the magnification factor for each location is written to
an output file for each location and to the "Results" layer attribute file. The data view is
then updated to display this layer with graduated symbols and colors relating to the
severity of the hazard potential. The location name attribute is also displayed at this
time for ease of further analysis. An example output view is displayed below:
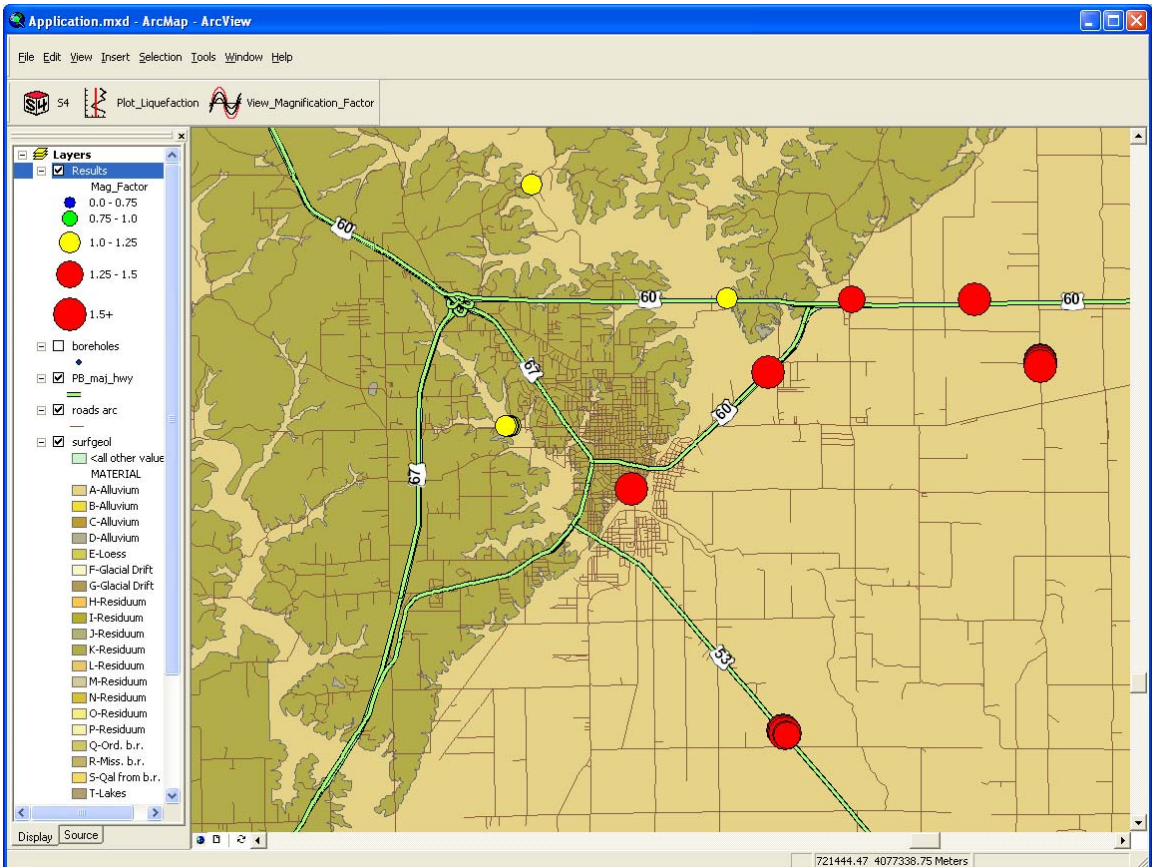
Once this basic site resonance analysis is completed, the user has the option to further manually analyze each location by opening a window to view the characteristic site period and the magnification factor for each location. Additionally, the user is given the option to enter a period value for a structure to compare the structure period to the characteristic site period for additional resonance analysis. To initiate this procedure, the user may simply click the button to initiate the "View Magnification Factor" procedure. This button is located in the S4 toolbar and is shown below:
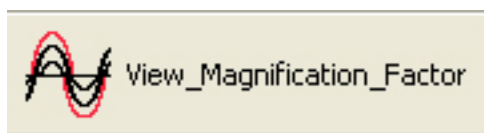
After this procedure is activated the user can click on any analyzed location to view the resonance values for that location, and calculate the resonance between a given structure and the characteristic site period. A sample of this dialog is shown below:
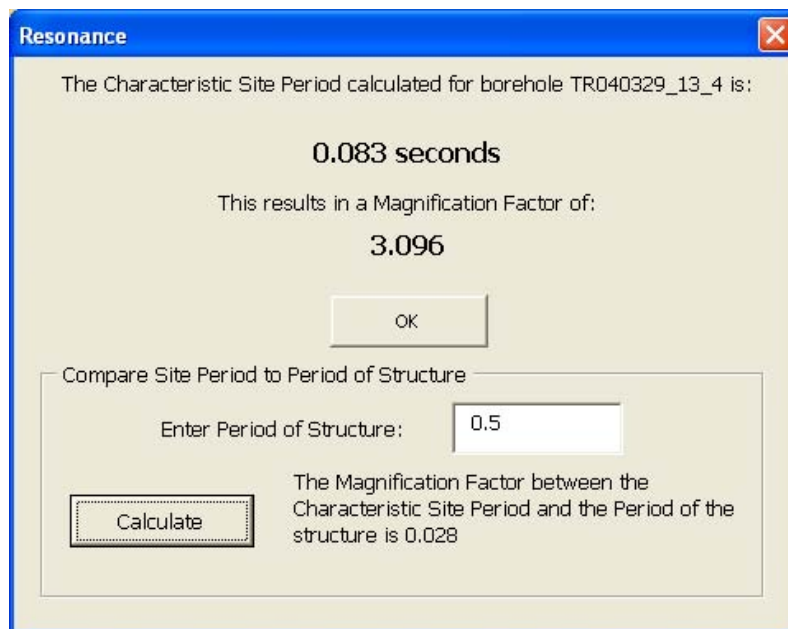
This plot can be dismissed by clicking "OK", and additional plots viewed as desired. It should be noted that the feature icons are generally small and care must be taken to be on the desired location, as it is possible to inadvertently select adjacent features unintentionally. Additionally, it is somewhat easy to "miss" clicking on a feature. If a

feature is "missed" when clicking, or the mouse is clicked off of a feature, the following error is displayed:


This message may then be dismissed and additional plots viewed.

This concludes the magnification factor calculation procedure.

7.0   Liquefaction Potential Screening Analysis Operation

The procedure for computing the liquefaction potential is very similar to the magnification factor procedure with a few key differences.

Similar to the site resonance procedure, the liquefaction potential procedure is initiated from the main menu by selecting the second radio button labeled "Calculate Liquefaction Potential". As with the previous procedure, when this procedure is initiated, it is required for the user to have previously selected locations for analysis. If no locations are selected, an error message will be displayed and the application will terminate. If acceptable features are selected, the following screen will appear alerting the user of pending computations:
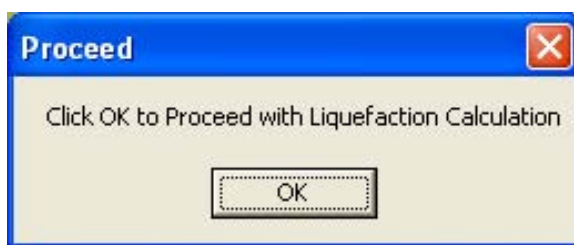
Once "OK" is clicked on this screen, a progress screen is very briefly displayed to show the progress of creating a new layer for the output. For analyses with few boreholes, this screen may appear too briefly for the user to see. This screen is displayed below:
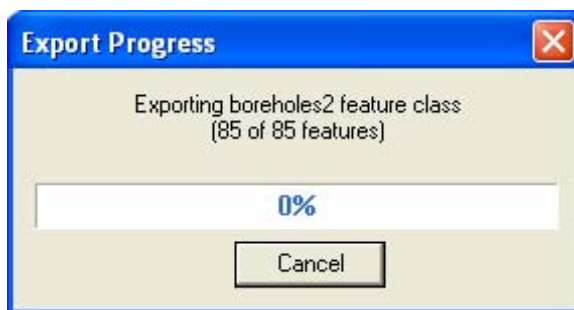

If an analysis has already been completed using S4, previous results will exist in the form of a "Results" layer and output text files. The user is given the option to overwrite these files, or exit the application in the following screen.
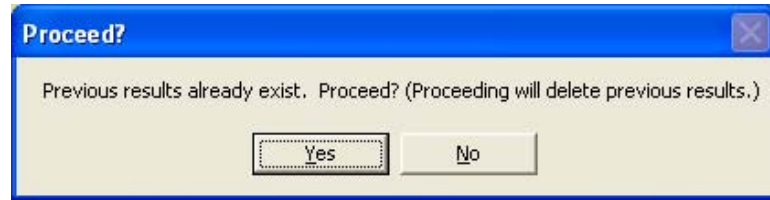
Currently, no method exists to save the results of an analysis. This would be a worthwhile addition for future developers.
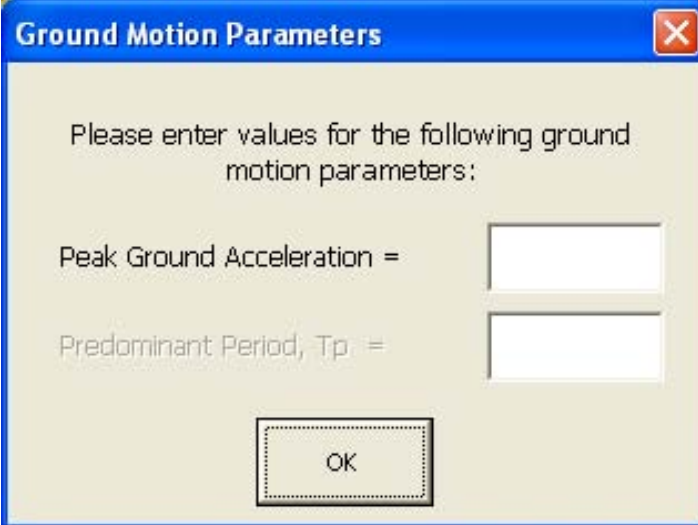
Next, the user is prompted to enter a moment magnitude value for the ground motion. This value is intrinsically linked to the input time history (or a_{max} value) used, so care should be taken to ensure that these values correspond to each other. The magnitude input screen is shown below:
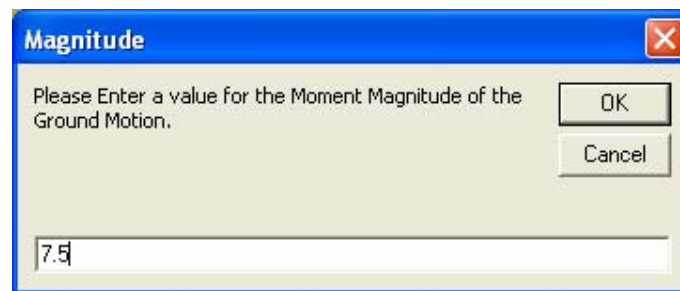
Once the magnitude is entered, the user is given a choice to enter an acceleration time history text-based input file, or to enter the a_{max} value manually, as shown in the following image:
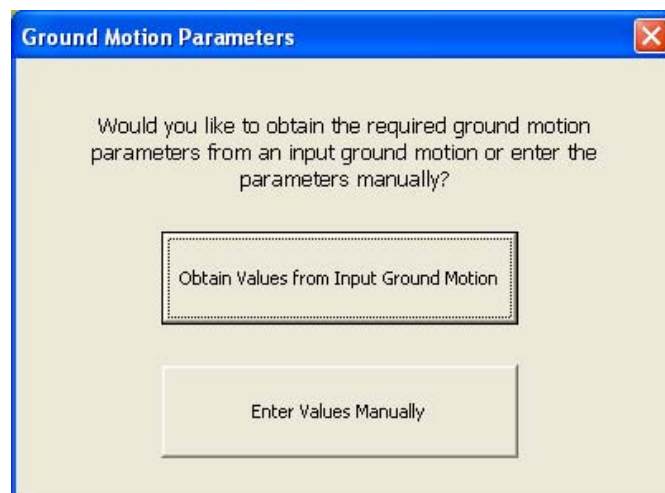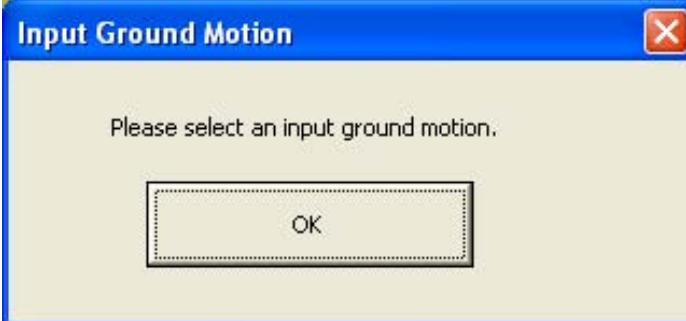
Contrary to the magnification factor procedure, in most cases for the liquefaction potential, it will be simpler for the user to enter a numerical value for a_{max}. If this option is chosen, the following screen is displayed for value input. (Note that the predominant period input box is disabled as that value is not used in the liquefaction potential calculation.)

If it is desired, the a_{max} value may instead be calculated from the acceleration time history. Choosing this option displays the following dialog box:

Acknowledging this screen opens the "File Open" dialog, which allows the user to search their computer for input acceleration time histories. The "File Open" dialog is similar to most Windows based programs as shown below:
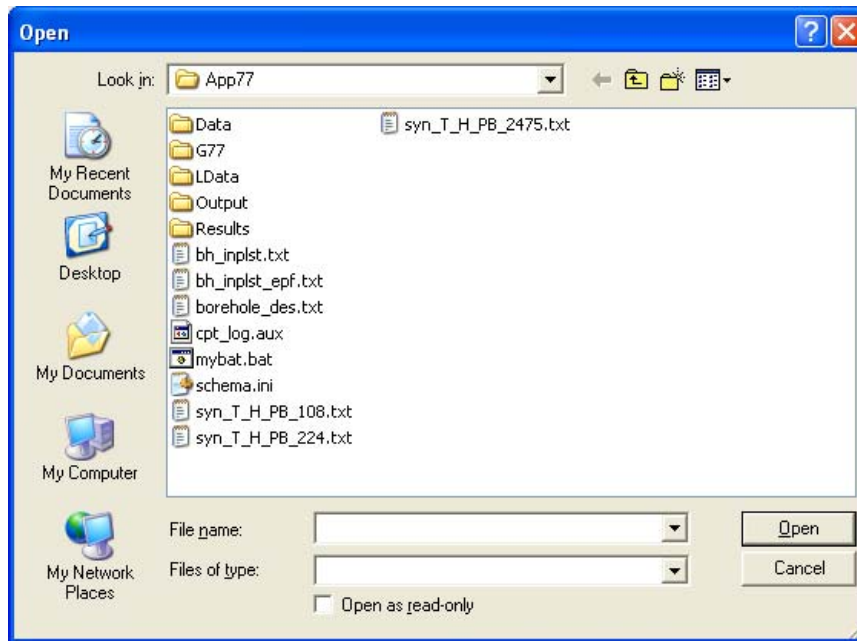
After an input file is selected form this dialog, the following screen is displayed, allowing the user to view a plot of their file:
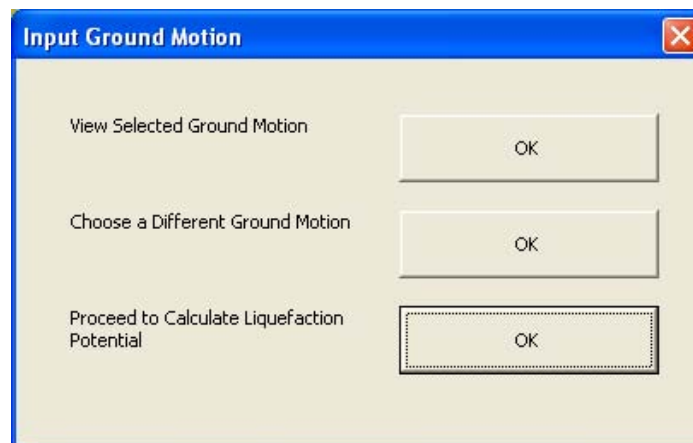
While it is possible to bypass this step, viewing this screen is a necessity for the user, as the a_{max} value is calculated during the display of this plot. By clicking the "OK" button beside "View Selected Ground Motion", the following screen is displayed:
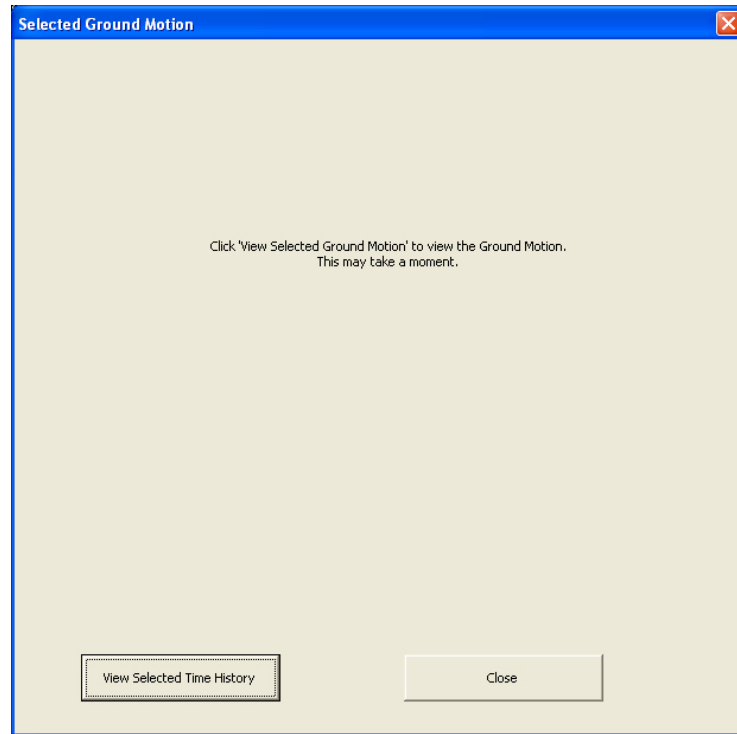
As in the magnification factor procedure, this screen view is an intermediate step that could be removed in the future, though currently it is necessary for the program to execute. On this screen, the user is required to click the "View Selected Time History" button, which displays a plot of the time history and calculates a_{max}. It is recommended to make this step automated in future development. After clicking of this button, this screen is updated to look like the image below. (The actual plot will vary based on the input ground motion time history).
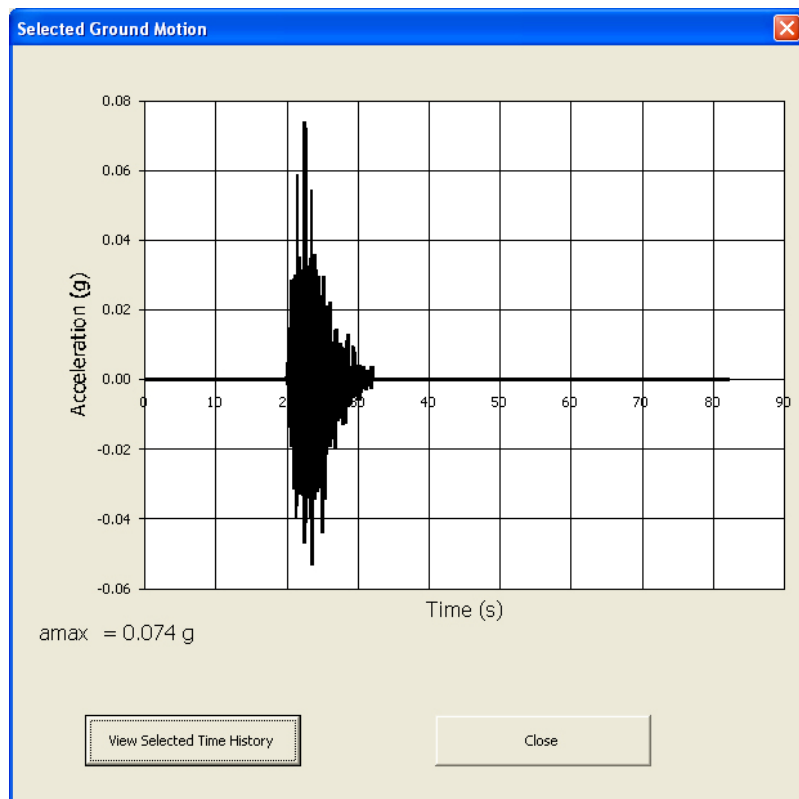
For more information on the acceleration time history input file, please view the section titled "Important Considerations".

The user then clicks the "Close" button to proceed. At this point the application loops through each of the selected boreholes to determine if a data file exists for that location. If no data file exists, the following screen is displayed and the application loops to the next feature:
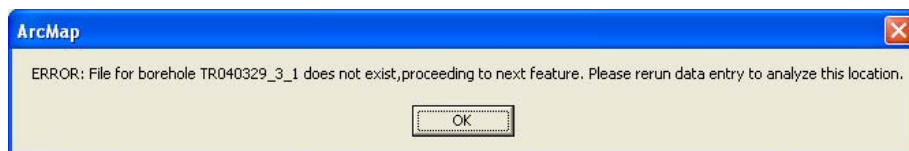
While this screen is generally dismissed rapidly, it should be noted by the user as it is the only alert they will receive on this subject. If a borehole location is included in the layer file and is selected, but does not contain the required text file, this message will be displayed and analysis of that location will be omitted, potentially skipping important data for the analysis.

For the locations with data, the following message box is displayed to inform the user of the number of data points for which computations will be completed.
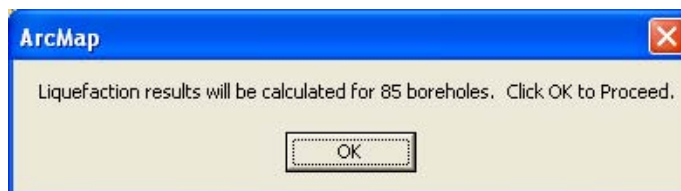
This final messagebox is displayed immediately before calculations are completed for liquefaction potential. Dismissing this window with the "OK" button initiates these computations. Once computations are complete, the lowest factor of safety for each location is determined via a loop and written to the "Results" layer attribute file. The data view is then updated to display this layer with graduated symbols and colors relating to the severity of the hazard potential. The location name attribute is also displayed at this time for ease of further analysis. An example output view is displayed below:
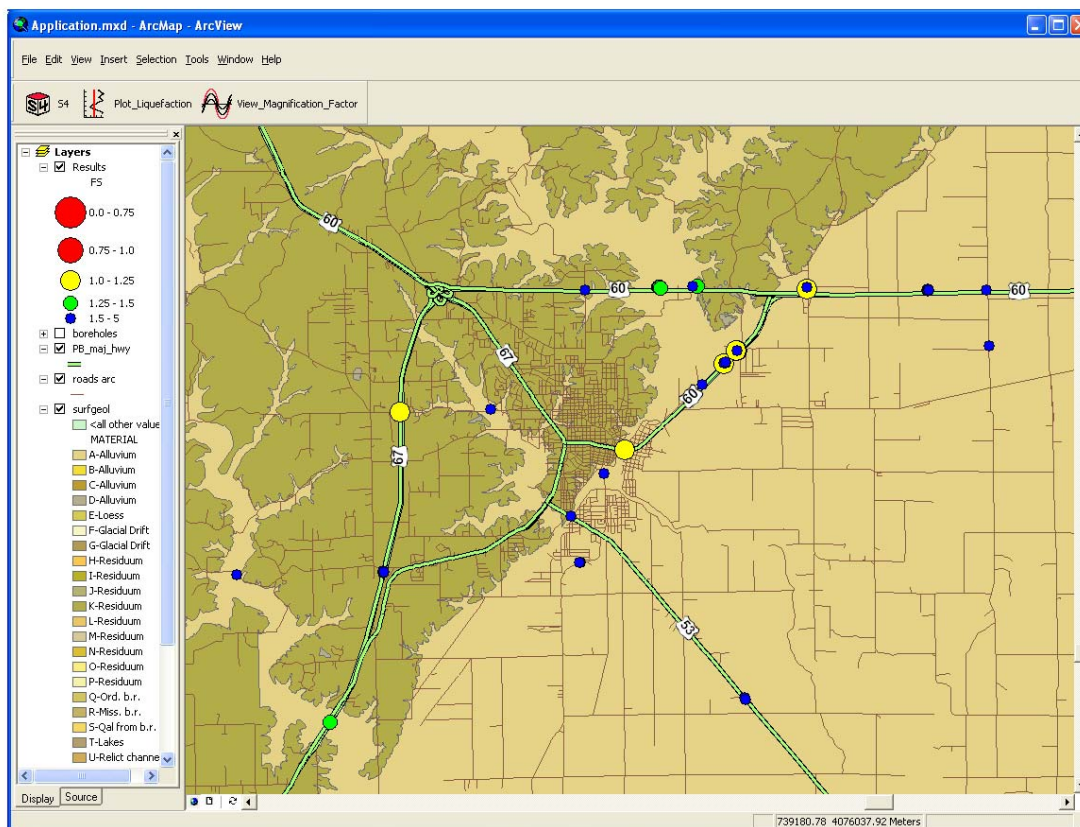
Once this basic liquefaction potential analysis is completed, the user has the option to further manually analyze each location by viewing a plot of factor of safety versus depth for each location. To initiate this procedure, the user may simply click the button to initiate the "Plot Liquefaction" procedure. This button is located in the S4 toolbar and is shown below:

After this procedure is activated the user can click on any analyzed location to view the plot of factor of safety against liquefaction versus depth for that location. A sample of this plot is shown by the following image:
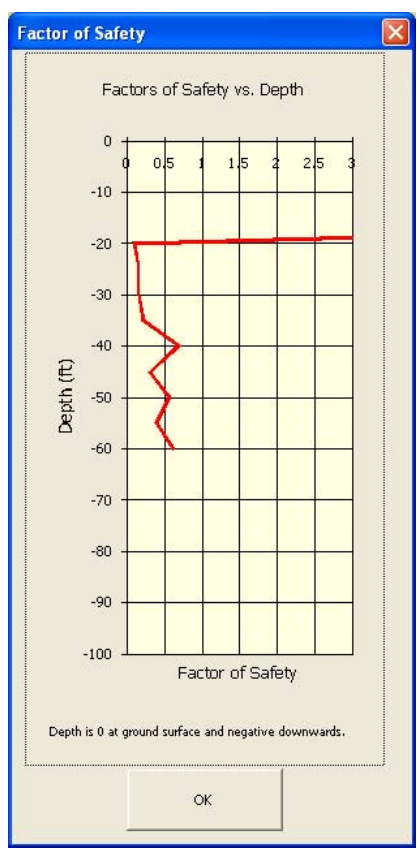
This plot can be dismissed by clicking "OK", and additional plots viewed as desired. It should be noted that the feature icons are generally small and care must be taken to be on the desired location, as it is possible to inadvertently select adjacent features

unintentionally. Additionally, it is somewhat easy to "miss" clicking on a feature. If a feature is "missed" when clicking, or the mouse is clicked while not on a feature, the following error is displayed:
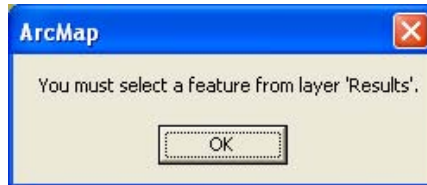
This message may then be dismissed and additional plots viewed.

This concludes the liquefaction potential calculation procedure.

8.0   Design and Geotechnical Calculations

The methodology used within the S4 application for the design and geotechnical calculations is described in detail in the M.S. thesis associated with this application. Specifically, the System Architecture is described in Section 3.2. The algorithms for the geotechnical calculations are described in Section 3.3. Magnification factor algorithms are detailed in Section 3.3.1 and liquefaction algorithms are described in Section 3.3.2. Section 3.4 details the input and output requirements of the S4 application.

9.0   Limitations

Several known limitations exist within the S4 application. As this is a prototype application, countless small omissions, dead ends, and programming errors will undoubtedly surface as the prototype program is analyzed. However, due to the nature of a prototype, these can be expected and will not be discussed here. The major limitations associated with the S4 application are:

- Within the liquefaction potential calculations, the revised simplified procedure for liquefaction potential estimation was chosen as it is the most straightforward and widely accepted method used today, though drawbacks and limitations to it do exist. Perhaps the most important limitation is that it only applies to relatively clean sands, though liquefaction has been documented in both silts and gravels (Andrews and Martin 2000); (Andrus 1994). Due to a lack of generally accepted methods for calculation of liquefaction in these materials, these procedures were omitted from this application.

- Within the magnification factor computations, specifically within the characteristic site period calculations, a limitation exists which can significantly affect the analysis results. The characteristic site period is only calculated based on the user-entered layers, so if a borehole was not extended to bedrock, and estimations were not made for the remaining depth, the calculated period will be computed incorrectly. To account for this in S4 (for boreholes that were not extended to bedrock), it is required to enter an additional estimated layer that extends from the bottom of the measured layers to bedrock.

- Though scale independent, the S4 application is also limited by the scale of the analysis. A given seismic scenario is only relevant for the area for which it was developed. In most cases, this is a point located a certain distance and direction from the contributing sources. It is recommended that S4 analyses be limited to areas encompassing project sites, towns or at most, small cities, as generally, these areas are small enough to permit the use of a single ground motion scenario. Areas larger than this will introduce significant enough errors so as to be unusable if a single

ground motion scenario is used. Larger areas may be analyzed by discretizing them into smaller projects and analyzing them with different ground motion scenarios.

- Data formatting for the S4 application is very particular and all data must be in the required format if the application is to execute. If one digit is out of place, it could result in a catastrophic crash of the application. For this reason if data is entered manually without the use of the input dialogs, detailed checking of this input data is a necessity before executing the application.

- Additionally, the FFTPowerSpec program, and the S4 application in general, will currently only support the input of acceleration time histories having a time step of 0.02 seconds. A single value was required to be hard-coded into the FFTPowerSpec tool, so the value of 0.02 seconds was chosen, as: a) it is a generally recognized standard time step for acceleration time histories, and b) it is a larger time step than most other accepted intervals, so data with a smaller time increment can easily be converted to this standard by removing data points in a spreadsheet.

- In any "black box" application, the quality of the output is highly, if not completely, dependant on the quality of the input. Within both the liquefaction potential and the magnification factor computations of the S4 application, the accuracy of the results is only as good as the estimation of the input parameters.

- Finally, the methodology presented for the S4 application was chosen to demonstrate simple and fundamental concepts of geotechnical earthquake engineering in a framework that allows for the analysis of spatially distributed data within a GIS. These methods are somewhat simplified and have little merit when compared to what can be accomplished in a site-specific geotechnical analysis when ground motion amplification and liquefaction analyses are performed.

10.0   Recommendations for Future Development

While significant effort was made to include the procedures for the anticipated user of the S4 application, countless items came to the attention of the author that would be useful to include in a future software package, but were omitted due to time and resource constraints. The following items were identified as potential areas of continued development of the proposed screening tool, S4:

- The addition of a conversion tool to convert data from a standard data format to the text file format used by the S4 application.
- The addition of cone penetration test-based liquefaction resistance analyses (Stark and Olson 1995, Robertson and Wride 1997).
- The addition of other forms of liquefaction resistance including those based on the Becker penetration test (Harder 1997), and shear wave velocities (Youd et al. 2001).
- The addition of the liquefaction resistance analysis of silts and clays as proposed by Boulanger and Idriss (2006).
- Other useful additions could include determination of the NEHRP site class at each location, correlations to estimate data that is not present (i.e. estimate of Vs from SPT blowcounts), the ability to output a summary report of the analyses, and the ability to use either English or metric units for data input.
- The addition of the liquefaction potential index (LPI) as proposed and applied by Iwasaki et al. (1978) and implemented into GIS liquefaction applications by Luna and Frost (1995) and Carroll (1998).

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APPENDIX B.

VISUAL BASIC CODE ON CD-ROM

1. INTRODUCTION

Included with this Thesis is a CD-ROM, which contains the VISUAL BASIC CODE for the S4 application. This code represents the raw internal workings of the S4 application. Each module of the VISUAL BASIC CODE has been developed using either VISUAL BASIC for APPLICATIONS for ArcGIS 8.3 or VISUAL BASIC PROFESSIONAL 6.0. All documents have been exported as Microsoft Word 2000 document files (Windows XP). An outline of the contents of the CD-ROM is as follows.

The included code is divided into three files: a) VISUAL BASIC Module Code, b) VISUAL BASIC Form Code, and c) VISUAL BASIC FFT Code. The first file, contains the main components of the code, termed "module", as it was developed in modules, roughly grouped to achieve a common task, and flows independent of any graphical user interface (though it does initiate the components of the user interface). This file (and the code in general) is divided into subroutines or "subs" and functions, which each perform a specific task. The second file is also divided into subs and functions; however the difference with these routines is that they are all initiated from a user interface (i.e. form, button, drop-down menu, etc.). Images of these forms are not included in this file, though most of them are included in the previous appendix. Intrinsically, these subroutines are identical; however they have been divided this way for ease of reference. The third file contains the code for the Fast Fourier Transform (FFT) executable. Again, this code is divided into subs and functions, though these routines were developed within VISUAL BASIC PROFESSIONAL 6.0 and were compiled into an executable for use within the S4 application. As such, this code is included in its own file.

2. CONTENTS

Info.TXT

<u>VISUAL BASIC Code</u>:

Module_Code.DOC

Form_Code.DOC

FFT_Code.DOC

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