SEISMIC MICROZONATION OF GROUND MOTION
IN SOUTHWESTERN COLORADO USING
GIS AND S-FACTOR AMPLIFICATION ANALYSIS

by

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Seismic Microzonation of Ground Motion in Southwestern Colorado using GIS and S-Factor Analysis

Thesis directed by Professor Nien-Yin Chang

Abstract

Earthquakes worldwide accounted for more than $300 billion in damage and over 21,000 lives in 2011 (USGS, 2011). That year saw one of the worst earthquakes ever in Sendai Japan of an earthquake of Mw 9 and produced a tsunami wave that caused unprecedented damage along the eastern coastline of Japan (USGS, 2011). Advances in satellite imagery, GIS software, and computer capabilities have forwarded our ability to monitor, predict, and plan for the devastating toll that earthquakes frequently ravage on many parts of the world.

Over the past 100 years, our understanding of the propagation of earthquakes through the earth’s crust has vastly improved. Monitoring stations worldwide have recorded earthquake events in ways that have not been accomplished before. Today we have more data about seismic waves and how they propagate through various geological structures, which has reframed our concept about the complexity of these seismic waves.

The ICBO, or International Conference of Building Officials, introduced the Uniform Building Code in the 1990’s that gave us a reliable prediction classification system that would not tell us where or how strong an earthquake would be, but would tell us where
the worst damage would be likely to occur during an earthquake event. With the introduction of S-Factor or Site Coefficients, this classification system allows for the designation of certain wave amplification factors based on soil and geological conditions of various earthquake prone areas.

The past 20 years also have seen significant improvements in GIS software that enables the modeling of various natural phenomena in ways possible that were heretofore unseen. Utilizing raster computing methods described in this study, this work develops a seismic hazard risk model, also known as a seismic microzonation model, capable of providing information on areas of significant ground motion danger during an earthquake in various regions of Southwestern Colorado. The maps and data produced in this work are for regional and hazard planning purposes, and are not intended to be utilized for engineering or structural design.

The form and content of this abstract are approved. I recommend its publication

Approved: Nien-Yin Chang
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I am indebted as well to numerous professors and staff at Metropolitan State University through which my B.S. based in GIS and physical geography, generated in me the foundation for knowledge of the earth sciences and a mastery of GIS without which this work would have been impossible. I would like to give particular thanks for the ongoing support and staff at the FAST lab at the University of Colorado Denver.

Special thanks to Martin Huber director of MIS, and Mary Coussons Read for their support in the MIS program. Special thanks to ESRI, the developer of GIS software and their graciousness to the academic community, and striving to make GIS not only a leading edge software but the field of science it actually represents. Finally, thanks to my wife, family, mother, father-Jerry Quinn, Ed Morrow, and friends without whose unwavering support this would have not been possible.
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CHAPTER I

INTRODUCTION

Various natural phenomena can be modeled in GIS using raster analysis techniques that divide the phenomena in nature being studied into a grid system that classifies values of the occurrence in nature according to their strength. In geology, GIS can utilize this modeling approach to formulate various structures in the earth from petroleum explorations, to hydrology findings, or seismic activities. Each level of strata can be modeled accordingly and assigned various attributes and values. For instance, aquifers can be modeled according to various depths and data provided from well logs. The data can be used to provide approximations of the aqueous body below the surface, its size extent and depth. Rock structures as well can be modeled in GIS and assigned qualitative as well as quantitative data. Qualitative aspects could be the age of the rock, Paleozoic, Precambrian, Cenozoic or geologic formation type, such as alluvium, talus, or shale. Quantitative aspects could be rock hardness, density, or in this case, the use of the amplification of seismic waves through geologic layers of the earth’s crust.

Earthquakes are frequently modeled using a fairly uniform fashion. The occurrence of earthquakes along a given fault line, their intensity, and recurrence through the years are often sufficient to give the general public awareness of this kind of activity in their area. The level of information and the reality of how energy is dissipated through the earth, however, is not that simple as the uniformity of geologic structures in the earth are rarely so consistent, and are particularly more complex along fault lines. The approach in this study combines GIS modeling approaches, knowledge of geosciences, and geotechnical engineering to develop a more complete picture of where these earthquakes occur, their
intensity and variations passing through geological rock structures, as well as their potential threat to human involvement on the earth’s surface.

Geological hazard mapping is an important function of many state and federal agencies that undertake such mapping processes to present maps for enhancing the public awareness and minimizing the potential destruction that the hazards place upon the community. The role of the mapping of these hazards in such agencies is often understated due to the intermittent nature of geological hazards, yet when geological hazards occur from landslides to earthquakes or rock fall, they tend to be destructive in nature and costly. Without the summarizing information presented to the public after the availability of the information provided by initial geological investigation and general hazard mapping processes, the public would remain largely unaware and uniformed as to their hazardous potential and severity. As well, engineers wouldn’t have sufficient guidelines for the design of hazard mitigation measures and resistance structures. This study aims to establish the procedures of using the latest available resources for modeling earthquake hazard potential, mapping such potential earthquake hazards in the Southwestern region of Colorado. It also serves as a guide for the context of such mapping processes, and the appropriate community level and planning level response for preparing for and mitigating such hazardous events.
CHAPTER II
COLORADO GEOLOGY

The origins of the Rocky Mountains involve complex plate tectonics and are somewhat different compared to most mountain ranges. Typically mountain formations occur along plate boundaries, such as the Sierra Nevada Mountains or the Cascade Mountains, where the Cascadia fault along the Pacific coastline of Washington State uplifts these mountains. The Pacific Plate and the North American Plate at this time are moving transversely past each other with the North American Plate moving southward and the Pacific plate sliding northward. This was not always the case, and millions of years ago the Pacific Plate was subducting under the North American Plate, and when the Pacific Plate subducted, it would melt and form plutons, which rose from convective forces into the North American Plate. The resulting convective uplift also created the coastal mountains at that time. A separate plate off the coast of Washington, the Juan de Fuca plate, still has a part of the Pacific Plate subducting underneath it, which accounts for the active volcanism along this coastline, as was exhibited by the eruption of Mount Saint Helens in 1980.

The Rocky Mountains still exhibit somewhat of an anomaly being a mid-continental significant mountain range that is neither currently nor ever was along an active plate boundary or continental to continental boundary as is exhibited with the Indian Plate crashing into the Eurasian plate developing the Himalayan Mountains. Instead, the best theory that explains the development of the Rockies is that at the time that the Sierra Nevada Mountains were being uplifted, part of the asthenospheric Pacific Plate that was subducting under the North American Plate, subducted at an abnormally low trajectory
instead of at a deep angle under the North American Crust (Figure II.1). When this occurred, a significant portion of the Pacific Plate was melted deep below the North American crust creating vast plutons of magma that resultantly became the Laramide Orogeny, approximately 70 million years ago, pushing up the majority of the Rocky Mountains (USGS, 2004). This was followed by a series of continued uplifts that continued to generate the extent of the Rocky Mountains as we know it today.

Following these dramatic uplifts, the nature of the Pacific Plate and North American Plate interaction changed into one of a transverse motion of plates compared to an oceanic plate subducting beneath a continental plate. The years following this change resulted in a quieter interior of the North American plate geology that was then affected more by glacial and erosional forces than anything else through the years. However, active volcanism, geothermal, and seismic activity has as well been characteristic of the area in the past 70 million years.

**Figure II.1. Laramide Orogeny, uplifting of the Rocky Mountains. (USGS).**
The reason for the continued activity in the Rocky Mountain region can likely be attributed to hot spots or magmatic plutons underlying certain portions of the Rocky Mountain Area. One such area in particular is the geological formation known as the Colorado Plateau. This was an area that was uplifted past the original orogeny that created the Rocky Mountains. The most likely theory put forth for the existence of the Colorado Plateau was through a process of delamination of the lithospheric crust into the asthenosphere (Summerfield, 1991). The occurrence of the process likely began with deep faults that extend well into the crust in this region into the asthenosphere. Some magma may have extended upward into these faults and broke down portions of the lithospheric crust above. A significant portion of the lithosphere then detached and sloped downward into the asthenosphere and melted.

The melting of portions of the lithospheric crust produced plutons and the hot magma of the asthenosphere rose and filled areas where the existing lithosphere was, generating at that time volcanic activity on the surface for significant lengths of time. This as well can be seen by the extensive volcanic fields that exist in the area of Southern Colorado and along the Colorado Plateau. The area that was filled by the plutonic magma that took place of the delaminated lithosphere, then replaced that portion of the crust underneath adding to the crustal material but remaining as a separate material than the lithospheric rock and more in direct contact with the asthenosphere below. This process resulted in hot spots in areas below the lithosphere in portions of the Rockies and is characterized by geothermal and occasional seismic activity as well as the potential for active volcanism (Summerfield, 1991). As well, because there are active hot spots below these regions and plutonic forces gradually uplifting these areas, tensional stresses fracture the rigid
portions of the overlying lithosphere and occasionally this can result in earthquakes as well.
CHAPTER III

STUDY AND ANALYSIS

General Earthquake Hazard Mapping

Earthquakes are typically analyzed from a consistent approach using various seismic models that account for the peak ground acceleration through the earth based on normalized curves that assume consistent rock structures throughout the extent of the earthquake. These formulations do give us a general idea of the extent of an earthquake’s damage, but in no way specify variation or location according to geological rock structure. The map below was generated using GIS and assumes an earthquake of an Mw 5.5 in the Montrose region of Colorado (Figure III.1). The earthquake propagates through the terrain in a predicted, yet generalized manner that would assume a consistent geology throughout and normalized PGA averages from the hypocenter. This data, however, serves as a baseline from which further attenuation can be calculated based on specific geologic structure.
The geologic structure of the earth is far from a consistent harmonious rock layer, however, and varies substantially. These various structures can attenuate or transmit seismic energy according to their structures depending on the direction of transmission and variation of geological material stiffness. Harder more dense materials, such as quartzite, granite, and solid igneous structures can transmit the energy more quickly and efficiently. In upward and vertical propagation, soils tend to absorb earthquake energy, while amplifying the earthquake motion as it propagates upward under gradual upward reduction of soil stiffness (Chang and Torres, 2013). This study focuses on the variations in the soil layers above bedrock that so often characterize the extent of destruction seen in most earthquakes.
Development of Classification Systems Based on Ground Motion Amplification Through Geological Structure

Over 100 years of study of various earthquakes around the world has yielded a better understanding of the propagation of seismic waves through the earth’s surface. Spatial variations of earthquake destruction remained largely unexplained, when say for instance, one part of a city would be completely devastated and other parts of the same city would not have similar damage in a given earthquake. In the 1950’s and 1960’s an understanding of these variations began to gradually emerge as geophysicists, geologists, and geotechnical engineers began to study the mechanics of materials involved in earthquakes to understand their properties when subject to various waves and pressure. These studies remain a complex work that was more useful for engineering purposes and the understanding of how such waves would impact a particular structure, and the soil or rock properties of a building foundation that would be more or less favorable for a given earthquake, as well as how to mitigate such foundations in light of that knowledge.

The complex formulas developed an understanding of the physical properties of materials, and laid some foundation for the fundamentals of general earthquake destruction pattern, but did not give a clear understanding as to where and how that selected destruction would occur. Over many years of study, geophysicists have recorded earthquakes using seismometers at seismic monitoring stations spread out in a web like fashion in earthquake prone regions. These seismic studies combined with visual and recorded observations eventually led to a trend of understanding in how seismic waves would propagate through various geological mediums, rock or soil.
A consensus slowly developed that the greatest destruction from earthquakes would occur in regions with deep soil deposits, and areas with more exposed bedrock exhibited less destruction depending on the closeness of the natural frequency of a building/structure to the predominant frequency of an earthquake. The presence of soil alone did not necessarily dictate the severity of damage. It was found that varying soil depths and soil compositions could foretell the severity and variance of destruction from a particular earthquake. In general, a soil deposit with increasing stiffness with depth tends to amplify the peak ground acceleration (PGA). This means structures sitting on a softer and weaker soil layer would suffer more severe earthquake damage due to higher surface PGA, particularly when its natural frequency approximates the predominate frequency of an earthquake. A group of Japanese Scientists in the 1960’s based a classification scheme on this soil system that could be roughly useful in identifying destructive foundation soil types (Finn, 1991).

The chart below is a summary of this system that indicates the degree of amplification that would be experienced in an earthquake based on various substrate of the earth’s surface. The system proposed by this team of scientists was useful, but did not fit other observations recorded by seismologists in time, so modifications of the system and new classification systems were introduced. What is important in their findings is the degree of amplification of seismic waves that were experienced through various zones depending on the geological structure near the earth’s surface. It was found that waves could be amplified by as much a four times depending on the looseness and composition of the near surface geology, in particular deep soil regions of unconsolidated materials (Figures III.2 and III.3), like the Mexico City clay deposit. This behavior of wave
amplification laid the foundation for much of the seismic wave amplification classification systems that were to follow.

Figure III.2. Seismic wave amplification based on geologic zones. (Kenai and Tenaka, 1961)

<table>
<thead>
<tr>
<th>Zones</th>
<th>Soil Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Ground consisting of rock, hard sandy gravel or the like classified as tertiary or older strata</td>
</tr>
<tr>
<td>II</td>
<td>Ground consisting of sandy gravel, hard sandy clay, loam or the like classified as diluvial, or alluvial gravel about 5 meters or more in thickness</td>
</tr>
<tr>
<td>III</td>
<td>Standard ground other than Zone I, Zone II or Zone IV</td>
</tr>
<tr>
<td>IV</td>
<td>Ground consisting of soft alluvial delta deposits, topsoils, mud or the like about 30 meters or more in total thickness</td>
</tr>
<tr>
<td></td>
<td>Ground made by the reclamation of a marsh, muddy sea-bottom or the like about 3 meters or more in thickness, where less than 30 years have elapsed since the time of reclamation</td>
</tr>
</tbody>
</table>

Figure III.3. Seismic amplification zones based on soil conditions (Kenai and Tenaka 1961).
In the 1970’s numerous underground nuclear tests were conducted in Nevada, and geoscientists utilized the seismic waves produced by these tremendous blasts to explore their propagation through the earth’s crust. One particular study conducted by Robert Borcherdt of USGS, analyzed the S-waves produced by the nuclear tests, to develop wave profiles and characteristics as the seismic waves passed through the San Francisco bay region. The goal of the study was to shed further light on the destruction pattern produced by the seismic waves in the 1906 catastrophic earthquake in San Francisco (Borcherdt, 1975).

Thirteen recording stations were set up in the San Francisco bay area on a variety of soil types and geological structures, ranging from bedrock to alluvium and bay mud. Seismic waves produced by nuclear blasts strongly parallel seismic wave profiles produced by earthquakes, as can be seen in figure III.4 that charts wave propagation for the nuclear blasts, as well as for an actual earthquake that occurred in the region in 1952. The accelograph recordings of the seismic waves passing through various geological strata are shown in figures III.5 and III.6. Figure III.6 labels each recording station and depicts the horizontal spectral amplification for each recording station. Alluvial soils and bay mud exhibit high levels of S-wave amplification that would correlate with strong ground motion during an earthquake.
Figure III.4. Comparison of spectral wave amplification for the 1970 underground nuclear blast in Nevada and the 1952 San Francisco earthquake at two sites, Southern Pacific Building (A) and Golden Gate Park (B). (Borcherdt, 1975).
Figure III.5. Horizontal spectral amplification recorded by accelographs at various sites in San Francisco for the 1970 underground nuclear blast in Nevada. (Borcherdt, 1975).
Figure III.6 Horizontal spectral amplification at recording stations in San Francisco. Sites are grouped according to geological conditions, and show recorded seismic waves from the underground nuclear blast in Nevada. (Borcherdt, 1975).
In the 1980’s another group of scientists laid a framework for earthquake attenuation and wave propagation based on soil type and composition, however this system was lacking a comprehensive classification system that could be used for general earthquake mapping or destruction prediction (Finn, 1991). The attenuation curves that follow are helpful in applying our understanding of wave propagation through various geologic structures, but also do not leave us with a clear system that can classify seismic wave amplification based on geological structures (Figure III.7).

![Spectral acceleration curves for various geological substrate.](Seed and Idriss, 1983)
In the 1990’s, the International Conference of Building Officials (ICBO), an international team of geotechnical engineers and scientists, who had worked with these gradually evolving classification systems of earthquake and seismic wave propagation were able to offer a more complete system. Their findings were based on various other data through the years, but in particular, they had more accurate recordings and observations of an earthquake in the Mexico City area where several recording stations were also positioned to record the wave energy as it passed through various regions (Finn, 1991). The stations during these earthquake observations in the 1985 earthquake in Mexico were also positioned such that soil depth and type could be shown to exhibit unique amplification patterns that could be attributed to the soil depth and composition from which was developed a 4 stage amplification factor system (Figure III.8) based on soil types and depth of soil, and would yield a predictable wave amplification value that could help foretell the wave amplification based on certain geological conditions.

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
<th>S Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>S₁</td>
<td>A soil profile with either: a) A rock-like material characterized by a shear wave velocity greater than 2,500 ft per second or by other suitable means of classification; or b) Stiff or dense soil condition where the soil depth is less than 200 ft.</td>
<td>1.0</td>
</tr>
<tr>
<td>S₂</td>
<td>A soil profile with dense or stiff soil conditions, where the soil depth exceeds 200 ft.</td>
<td>1.2</td>
</tr>
<tr>
<td>S₃</td>
<td>A soil profile 40 ft or more in depth and containing more than 20 ft of soft to medium stiff clay but not more than 40 ft of soft clay.</td>
<td>1.5</td>
</tr>
<tr>
<td>S₄</td>
<td>A soil profile containing more than 40 ft of soft clay.</td>
<td>2.0</td>
</tr>
</tbody>
</table>

**Figure III.8. UBC amplification classification system using site or S-Factors. (ICBO 1991).**
With this data, and a comprehensive understanding of the geology of this area, the ICBO was able to see patterns in earthquake destruction that largely coincided with soil profiles and depths in relation to the bedrock. Also from their observations, they were able to record how waves propagated through the areas of greater destruction, and found that wave amplitude was significantly higher in areas of typically deeper and looser soil. Conversely, wave energy in areas exposed to bedrock was of a much lower amplification, but higher frequency. Essentially, seismic wave energy tends to transmit through more solid bedrock and foundations, and the wave energy tends to amplify and absorb into areas of looser and more unconsolidated materials. The areas of looser and more unconsolidated materials tend to experience higher degrees of amplification, and subsequently higher ground motion and destruction.

An analogy of this wave amplification could be envisioned much like a wedding cake sitting on a stable table, the table is kicked hard and the table suffers no damage, but transmits the energy to the cake which shakes and bounces and topples depending on the size of the kick. The earth’s crust responds in much the same way during an earthquake with the table being the bedrock below transmitting the energy from the hypocenter and ruptured fault, and the cake being the loose soil profile above at a specific site, or lack of soil profile if the surface has exposed bedrock.

With this model also known as the Uniform Building Code system, it became much more practical to develop a map of hazard potential for earthquakes based on certain measureable geologic conditions. The strength of ground motion is really only relative to
a combination of the intensity of the energy released from the hypocenter and the relative
geology it passes through. We do not know what strength any quake will be or when it
will occur for that matter, but with this system we can determine where those waves will
most violently be amplified and where other areas may be least affected and by what
degree.

An earthquake of an Mw 3 would see little damage on areas of deep soil or bedrock, but
the waves in the deep soil would still be amplified more compared to bedrock, however
overall damage would be minor in either location because of the low magnitude of the
seismic force. An earthquake of an Mw 5.5 would likewise have the same amplification
factors and some areas with high amplification will see significant damage, and other
areas will have lessor damage that have low amplification such as bedrock outcrop areas.
Earthquakes above an Mw 6 begin to exhibit nonlinearity in amplification, and while
certainly destructive, it becomes more complex to predict the exact behaviors of the
seismic waves involved (Cioflan, 2009). An earthquake of an Mw 9 would show wide
overall destruction regardless of the location, however areas of high amplification would
be much worse and those of low amplification would not suffer as much but certainly
would still take on damage in an earthquake of this size.

So the intensity of ground motion amplification is relative to surface geology and the
ground motion characteristics, but the overall magnitude of the quake is still the force
that sets events into motion. Using the UBC system, however, we can focus on the soil
and bedrock conditions that would be least favorable, or conversely, more favorable in an
earthquake, and give it a mathematical factor, or S-Factor as it is known in the UBC, as to
how those waves will be amplified. As mentioned, we cannot predict when a quake will
occur, how long it will last, or even the magnitude, but we can use this system to identify where the worst damage would be likely to occur and to help designate areas that may be prone to high amplification and may either have critical infrastructure or plans for such infrastructure. Employing this hazard mapping approach, we can plan accordingly as well as mitigate infrastructure that can be strengthened through geotechnical engineering methods that may lessen damage.
CHAPTER IV
GIS IN EARTHQUAKE MODELING

Our efforts now will focus on how to implement the recent developments in earthquake ground motion amplification modeling based on subsurface geomaterial (soils and rocks) characteristics into a computer model that is possible with the use of the latest GIS software available. We will begin with a brief on the use of GIS modeling as it pertains to geology and why this approach using raster modeling is a favorable approach for modeling this phenomena. While some readers may not find it necessary to review this section on GIS modeling, as they may be practiced in GIS, it is still recommended that it is reviewed as this is a raster intensive process and may be somewhat different than the vector based approaches that are inadequate for this process and are currently being pushed many of today’s GIS programs, however often lack the scientific modeling that GIS is capable of.

GIS can be used to model various natural phenomena using a raster modeling approach. GIS data typically is used in two major forms of data, that of vector data and that of raster data. Vector data consists largely of geometric lines, polygons and geometric figures to represent objects such as roads, boundaries, dams, buildings, airports and other typically man made features, although vector data is also used to map natural phenomena as well such as lakes, and even geologic formations can be mapped using a simple shape as well.

GIS data is by its nature linked to tables so that the data is not merely an image or visual representation on a screen, but interactive data such that the line or raster pixel has an associated value in a table that can garner knowledge and educate us about the visual
representation whether it be a vector geometrical shape or a raster pixel that has some
data value. For instance, in vector data, a line may represent a road, the road could be
selected and the road would be highlighted on the screen, and would likewise show a
record highlighted in a table that would identify that road for instance as I-25 and may
moreover indicate other information about that section of the road such as when it was
built or traffic data about that particular section of the road. Raster data, similarly, has the
same function and same connection, but in this case we may be looking at a single pixel
on a screen to find out about that data.

One instance of raster data could be looking at temperatures of say Colorado, and
selecting a single pixel to find that pixel represents 50 degrees in the associated table.
Raster data is data that can be most easily thought of as continuous data that is not easily
represented by geometric lines or polygons and requires a somewhat more complex grid
system to represent this data. Raster data can also be combined in such a way known as
raster math, where vector data does not have this ability. Raster math is a way that grids,
or sets of pixels, are overlaid on top of each other and calculated between grids so that
similar data in the same location can be combined to have the value of the two grids. Say
for instance, one grid represents snow fall amounts for one year and another grid uses
snowfall amounts for another year. The two grids can be laid over each other and the
cells combined mathematically to result in a combined value of snowfall. Likewise, the
resulting grid could be combined with other grids to achieve the results as desired;
combining other grids or years as necessary for the project.
The simple snowfall illustration below helps to envision how these grids work within the computer, and they can be combined mathematically in any way to achieve the results you want (Figure IV.1). The first grid represents one snowfall year and the next another snowfall year, they are combined by addition to give a snowfall total of the two years. The next set of grids is produced in a way to give a projection of next year’s snowfall. Say, for instance, that they are expecting a heavier year and forecast that about 10% more snow will fall that year than the previous year, so the 2010 grid is multiplied by 110% or 1.1 to give the resulting snowfall forecast grid for the following year. Similar, but more complex methods to use raster math will be utilized within this analysis to develop our understanding of earthquake propagation through the earth’s crust. Events in nature such as temperature, snowfall, rainfall, vegetation types are kinds of data that are best represented using a raster form of data that create a myriad of differences across an area geographically.

![Snowfall raster calculation diagram](image)

**Figure IV.1. Snowfall raster calculation.**
One important aspect about GIS is also that data in GIS is referenced using a graticule or grid system that is a reference locator of the data geographically, the latitude longitude system is one such system, but not the only system that can be used within GIS. Other systems such as UTM and state plane systems have their own way of representing location in GIS and as well can be incorporated into GIS software.

There are two sides to representing this data in GIS with a referenced coordinate system. The first is that it allows the points on the screen to have a location at least referenced in the computer system; it is not merely a point floating in space with no reference. This also allows for other data that have as well been developed with such a reference system to be combined or overlaid with each other much like a set of pancakes on top of each other, each with their own character. Additionally, each point that is in the same location can be easily seen, queried or called up so that we can observe mutually occurring phenomena or events in the same location. For instance, we could look at one point on a highway section of a map in GIS, and combine this with a live snowfall raster data and a third layer that indicates traffic accidents. The first layer would indicate the road section, the snowfall may indicate the depth of snow, and the third layer may indicate the occurrence of recent traffic accidents all occurring in that same location. The ability of GIS to combine these geographically referenced data is what sets GIS well apart from standard databases that are only utilizing table data with little or no geographical reference, and no visual mapping reference.

Data in tables is just that data in tables, and does not reveal the geographical association or pattern represented in it until such data is referenced and mapped visually. With this concept in mind, it can also be understood the potential for GIS, because literally billions
of records exist in such tables around the world that may have some geographical reference or address but have not been incorporated into a GIS, and so typically the pattern and meaning behind such data is not fully utilized and often not usable within such table except to a trained eye that uses the data so often they can recognize such patterns.

Consider, for instance, a data table that records crimes throughout a major city area and has the location of the crimes, but it is just a written record of such locations. Typically patterns within this kind of data are hard to find as streets may all be different as to where the crimes are occurring. GIS can take this data and the references to location and map it, however. The map will then reveal the patterns and may show these crimes occurring within a certain set of blocks that would not have been nearly so discernible in table form; this kind of transition from table data to mapped data could then help investigators find the perpetrator of the crime.

The complexity of this system, however, is also the requirements of making such data actually work together. It must be created in such as way that it is actually able to function within the GIS system. GIS is able to literally handle thousands of various projections, graticules, and grids and make them work together, however, often cumbersome transformations and georeferencing of the data is required before the data is actually prepared in such a way that it can work together seamlessly in an analysis. In this work for instance, maps were brought in that were not georeferenced in GIS or available as GIS data, but were only available as paper maps, accurate paper maps, but only available on paper. Such maps can be readily brought into GIS through scanning, and a process called georeferencing, or as some call it rubber sheeting, where the map is
adjusted within the GIS to already referenced data such as a road system or graticule, and matching points within the map are then adjusted within the system to develop a map that is known as rectified image having a defined coordinate system and projection and then can be used within GIS.

*Formal GIS Models*

To further illustrate the methodology of modeling in raster, the following examples and sources of information are available to understand this modeling process. While much GIS work is done in vector based systems, raster analysis still maintains a strong foundation for a significant amount of scientific work being done in GIS. Examples are given here as well in Appendix A to help clarify this modeling approach.

GIS models can vary widely in their modeling types, some models can be purely mathematical such as deterministic or probabilistic models, many models in GIS, however, are not mathematical models. GIS emphasizes the occurrence of two or more events occurring in the same spatial existence, whether those phenomena are mathematical or purely categorical. Most modeling in vector, for instance is of a categorical form.

Typical vector analysis functions, such as intersection are based on the occurrence of the events occurring in the same place. Raster models do tend to be more mathematical, especially in grid calculations, but raster models do not have to have a mathematical basis at all. Consider the following analysis; it would be using the common spatial analysis function known as intersection (Figure IV.2). The goal of intersection is to combine two different thematic layers into one that meets the criterion of both. The resulting grid or
layer, C, would meet the criterion of both layers. Say for instance, layer A is mountainous area, layer B could be forested areas, and layer C would represent a new layer in which it is both mountainous and forested. In this example, math is not required to derive a new layer of information, simply the occurrence of both conditions in the same place. The model in this study as well, relies more on the thematic occurrence of soil conditions and depth as thematic layers rather than a purely mathematical model, although math is used to combine the raster layers.

![Diagram of Raster and Vector intersection of thematic layers](image)

**Figure IV.2. Raster and Vector intersection of thematic layers. (Allen, 1998).**

The modeling process used in this approach could be best described as a raster data predictive model. Another name for it also could be an additive model, in that it
emphasizes the occurrence of two geological conditions in the same area, soil depth, and geological composition, which when combined can give us a general index as to seismic wave amplification at surface levels (Price, 2009). It is not a purely mathematical model, but a tessellation (Figure IV.3) based on a set of categorical criterion being met.

![Figure IV.3. Tessellation, where each grid cell represents an occurrence of the object on the ground. (Billah, 2001).](image)

Regardless of the model names, tessellation has longstanding been the basis for grid or raster modeling approaches where a grid cell or simply cell in a grid represents a given spatial theme possibly with a mathematical association as well in reality (DeMers, 2002). The approach in this study was taken because the UBC 91 site classification is based on a set of criterion being met rather than a raw mathematical approach. In fact, W.D. Liam Finn in his presentation of the UBC 91 system described the UBC 91 system in the following:
Microzonation based on broad and distinctly different soil categories has the advantage that rather distinct patterns of ground response are associated with each type. An important example is the different average spectral shapes associated with the four different soil categories shown in Figure 1 (Seed and Idriss, 1983). Idealized forms of these spectra (Figure 2) are used as spectral shapes in many building categories.

Microzonation based on soil categories which reflect different degrees of potential damage may be termed phenomenological microzonation as it is ultimately based on phenomena observed after earthquakes (Finn, 1991).

The modeling approach in this method parallels the LESA (Landuse Evaluation and Site Assessment) modeling approach, at least in the use of rasters not subject matter, used by the USGS to group a variety of categorical data to assess criterion for landuse and planning from that model. LESA is exhaustively discussed in the excellent text on the subject, *Modeling in Raster*, by Michael DeMers, which is one of the best primers on the subject in raster modeling currently written (DeMers, 2002). These categorical models, however, can simply be regarded as a formulated index based on sets of criterion being met. Appendix A shows a simpler development of a categorical model developed using raster for a certain set of habitat criterion. Two major examples of this kind of modeling are presented there to provide an expanded and formalized process to this kind of modeling. One is through a formal ESRI training course that goes in depth into the spatial analysis and raster math process that can be used in GIS. The other model is a simple additive model, adapted from this more complex model that combines a quantitative
value, land elevation, and an ordinal value slope aspect into a simple calculation that would create indexed habitat type for a particular species.

This utilization of these modeling processes and extensive data preparation is required for GIS professionals and a part of their daily routine, knowledge, and understanding of such work that enables the process to flow smoothly from data preparation to data implementation, and finally, to analysis and a complete and final product. Outside observers to the work being done in GIS are often puzzled and frustrated by the work that goes into creating a complete GIS work and analysis, largely because they are unprepared and unaware of the cartographic and geodetic requirements in order to make such data function within a computer system. Many people without knowledge of GIS somehow envision this large mainframe type of computer system that can literally be fed this data and spit out the results in little or no time. Nothing could be further from the truth; and the data has to be carefully managed and transformed in a way that is accurate and functional within a GIS system.

Smaller projects can be done by individuals doing GIS, but larger projects such as statewide analysis being done by agencies within the government often require significant GIS staff hirings to work full time with this data to enable it to work within this system and ready it for the final analysis stage which will reveal new information that was not realized without such analysis. Likewise, frustration and dropout rate among novice GIS users is also high because of the burdensome nature of the data or lack of quality instruction that enables the users to grapple with the complexity of working with data in a GIS.
GIS is, however, increasingly becoming the backbone of many large organizations that rely on any form of data that can be used within a georeferenced coordinate system. Most state and federal transportation agencies are now largely reliant on GIS as well as almost all geological mapping agencies. The move to this system has a few major pull factors that have enabled this transition. First, GIS can readily handle a wide variety of maps that makes them interactive, query able, and presentable within a computer system that is no longer reliant on decaying paper maps that could not be used in this way. This is not to say the paper maps are not significant, nothing could further from the truth, but the maps are now used within a digital georeferenced copy within the computer system that as well can be used with newer data that has been recently developed within the GIS system.

One other major pull factor to GIS has been because of the robustness of the GIS system, in particular the systems that ESRI has presented in the past 10 years, GIS is able to support and interact with virtually all forms of digital data, digital maps, and almost any form of database. It can combine, convert, and manipulate these databases with ease so that a multitude of seemingly disparate data can be combined readily in a GIS analysis. GIS is also capable of working as a server or with servers, and has the ability to work with live data that is either being retrieved from the field or interactively as maps online, and as well pulling in or sharing data with other servers that are using mapping data that can be shared by users through the world to complete their work in their research. Armed with this discussion of GIS, raster data, seismic modeling, and a vastly improved knowledge and classification system of surface geology to predict hazardous ground motion during an earthquake, let’s move onto the implementation of such knowledge to two cities of Colorado, Ouray and Grand Junction.
CHAPTER V
METHODOLOGY

Raster Development and Calculations

This GIS modeling process mainly utilizes the raster math approach mentioned earlier to develop models as to how earthquakes or seismic waves can propagate through the earth’s crust. The model also uses vector data to represent infrastructure that is represented geometrically and plays a role in this model.

The work in this GIS modeling approach began with a serious analysis of earthquake prone regions within the state of Colorado and finding data that would be necessary to support the S-Factor amplification model presented by W.D. Liam Finn in the 1991 Proceedings of the Fourth International Conference on Seismic Zonation (Finn, 1991). Namely, we would require the knowledge of soil depth and soil composition within these earthquake prone regions. Often such soil information is limited to only the first few feet as the intent is for agricultural purposes or recreational purposes, but not for geological purposes, so data that would give a fairly comprehensive and accurate knowledge was required to know the full soil depth to bedrock, soil composition, and most importantly exact geographic location would be required. USGS quadrangles were utilized for this purpose with their full extent of geologic information.

The areas of study chosen were Ouray and Grand Junction Colorado and their associated USGS quadrangles which also had cross section data that would indicate a reasonable amount of information for the soil profile and depths that would be sufficient for this mapping purpose (Figures V.3-V.6). More comprehensive methodologies do exist for the
modeling of soil profiles and are discussed later, but would require long term studies of
years and possible further geological exploration through borehole drillings to obtain an
exact level of accuracy. The geologic quads are suitable for most mapping purposes and
the USGS has gone through extensive efforts and usually years of research to develop the
geological quadrangles that have served as the keystone of most geological exploration in
America.

The area of Ouray Colorado was chosen for the frequency of earthquakes and magnitude
of them that has occurred in the past 100 years. Numerous quakes of over Magnitude 5
have occurred throughout this region, and modeling of this city was chosen because of its
proximity to these quakes as well as the reliability and quality of the particular geologic
quadrangle of that area, and the quality of the cross section in that quad that indicated
soil depth (USGS, 1962). Grand Junction as well was chosen for similar reasons, and
while not as many earthquakes have occurred in that location, they are still within the
region, and the impact of that larger city makes it a target for analysis. Likewise, the
quality and depth of the Grand Junction quad was excellent and provided the necessary
data for this analysis (USGS, 2002).

Once the locations and suitable supporting map data was found, the long process of
incorporating this information into the computer and analyzing it could begin. The
process began with obtaining scanned copies of the USGS quadrangles for the Ouray and
Grand Junction areas of Colorado (refer to flow chart Figure V.1 to reference steps in
methodology). The scanned images were not georeferenced so georeferencing the two
quadrangles to a known grid and coordinate system was the first step of the process. The
particular coordinate system used in this project was the UTM Zone 13 geographic
projection that would allow for work with other layers in this project including roads and infrastructure shape files some of which were obtained from CDOT.

Two major raster layers would have to be generated from these geologic maps however, and involved a process loosely known as raster painting to glean the data from the maps. GIS is unable to use such maps in themselves for raster calculation as the words and symbology on the maps confuses the computer and gives no certainty as to the values that it is looking at. For the raster to exist, the data must appear as simple uniform blotches of

Figure V.1. S-Factor Amplification Modeling flowchart using raster math.
color on the screen that can be assigned a particular value, a before and after
representation of such data is shown as to what is required for GIS to process the data as
a raster (Figure V.2). The process of raster painting enables the development of such data
to exist. To achieve this, a new layer is developed over the existing map layer. Using a
tool similar to an onscreen paintbrush, the cursor is then moved over and applied to the
areas to be developed in raster and likewise the process creates an existing table that
would be associated with a color value on the screen. As well, as the process is being
done in GIS, the data is automatically assigned a reference location value so that it can be
used in GIS and is not merely just an image without reference or associated data.

Figure V.2. Original geologic map and rasterized version of geological components.
The simplified raster version will then be connected to a table that will hold the values or other information about the colorized pixels that represents various geological components.

The first major raster to be created would be that of the geological layers themselves. Similar processes were done for both of the study areas Ouray and Grand Junction. In the Ouray area, the rasters were developed for the loose soil, alluvium and glacial till areas that are underlying the areas of Grand Junction using this raster painting method. Using the UBC, the emphasis of the system in terms of qualitative aspects were soft and loose soils, and hard or bedrock like materials, therefore rather than mapping for geological formations such as landslides, alluvium, or shale, the composition layer is mainly geared toward grouping these formations based on consistency, loose or hard, rocklike or soil like materials.

While these are very general ways of grouping, and subject to some interpretation, as will be discussed later, these consistencies are an important aspect in this classification system, and provide an important level of analysis when combined with soil depth. The resulting raster was developed for soil composition and consistency for the Ouray study area (Figure V.7). Likewise, using an interpolation method and the cross section that was provided in that map, a similar raster was developed for the depth of the soil that stretches underneath the Ouray area (Figure V.8). The soil depth areas vary and could be reasonably interpolated by the cross section provided in the geologic quad. The quads chosen both have specialized cross section studies that made this analysis possible, in the Ouray quad this cross section is denoted B and B’ and in the Grand Junction quad the cross section is denote A and A’ (Figures V.3-V.6). (Please refer to Appendix A for more
detailed views of original quads and the geological key.) In both areas it could be seen that extensive alluvium had filled the valleys from the upper highlands in the region forming areas that created deeper soil depths further down in the valley that had transported soil from erosion to these areas through millions of years of alluvial and erosional processes.

Figure V.3. Geological Map of Ouray Colorado. (USGS).

Figure V.4. Ouray cross section, B to B’, indicating depths and soil profile. (USGS).
Figure V.5. Grand Junction geological map and study area. (USGS).

Figure V.6. Geological cross section A to A’ of Grand Junction. (USGS).
Figure V.7. Soil composition raster of Ouray Colorado

Table V.1. Soil composition code of Ouray.

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<th>Count</th>
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<td>4</td>
<td>1400030</td>
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</tbody>
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Figure V.8. Soil depth raster of Ouray Colorado.

Table V.2. Soil depth of Ouray.

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<th>COUNT</th>
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<tr>
<td>9</td>
<td>93</td>
<td>1206340</td>
</tr>
</tbody>
</table>
The same process was done for the Grand Junction study area. First, a composition layer was developed that would develop a raster grid based on soil compositions (Figure V.9). A soil depth grid was also then produced for the Grand Junction area that would be necessary for the seismic wave amplification analysis (Figure V.10).

Figure V.9. Soil composition raster of Grand Junction Colorado.

Value is composition code type.
Once the process of the raster development was complete, the computer then had data it required to compute using GIS. At the early stage of the raster development however, the data was simply a set of pixels with a color value and a location, but no other data value
assigned to it yet such as depth or soil type. Depth values were assigned in a straightforward fashion by editing the raster table and a given pixel color or value was assigned a value in the table such as 30 ft. The soil composition raster could be assigned values in a similar way, and indeed a qualitative value can be put into the tables such as alluvium and this could indicate this in the tables. The problem with this however, is that a quantitative value and string or text value will not reasonably combine within a raster math process to yield a final result, and that is what was required. From the classification provided by the UBC, the determination of amplification combined a quantitative value of depth with a qualitative value of composition to have a final result that could be assigned an amplification factor.

To overcome this, and to allow both rasters to be combined in a way that would have a value that would indicate both rasters in one layer, the qualitative values were turned into numerical values that represented codes. The depth from one raster could be added to the other followed by a set of 00000 that would space the qualitative value and the quantitative values and its associated numerical code could easily be read in the new raster table. In this coding system developed for this model, 1200000 represents rocklike or bedrock materials, 1300000 represents a middle consistency that is neither soft nor consistently bedrock, and 1400000 represents the loosest soil material or claylike consistencies of material. These codes would then be added to depth layers such as 20 feet, and you would then have values such as 1200020 where the first value represents a bedrock material or rocklike consistency with a depth of 20 or less feet of soil. Such an area would be classified as minimal or no amplification based on the UBC system. Conversely, a completed code of 1400070 would indicate a loose or clay-like material
with a depth of at least 70 and would rank high on the wave amplification classification system. While this may seem a bit complex, it was not because there were only 3 major soil compositions that were needed for the S factor analysis, a soft or claylike soil (1400000), hard or bedrock (1200000), or a combined soil type (1300000) from the UBC classification.

Additionally, one more step was necessary as seen in the flowchart before the rasters could be calculated together. The rasters were required to go through what is known as a Lookup raster process in GIS which allows the field chosen to be the main value that the raster is calculated from and also generates a new raster based on that field. Unfortunately, GIS does not allow you to simply choose which field the calculation is done from and by default chooses the value field which were given alias names in the tables, but are always the first field next to object ID. This step adds to the complexity to achieve the calculation, but is none the less accomplishable. Early versions of GIS allowed for field designation and which field was being calculated within a given raster was a simpler process to realize. With such values assigned to both rasters and the raster completed, they were simply added together and produced a set of codes as shown below that would then translate into one of four different possibilities that could then be assigned a value from the S-Factor amplification classification system. The combined values are indicated as Class code (Clss_code) in the tables (Tables VI.1 and VI.2), and their corresponding S-Factor is indicated as S_Factor_1 in Table VI.1 and S-Factor in Table VI.2.

With this achieved, a new column was then added to the resulting table, and manually edited to designate an amplification factor according to the S-Factor classification
system. The codes produced in the calculation could be readily paired with one of the 4 classifications of the UBC S-Factor system, and a value of 1, 1.2, 1.5, or 2 was manually paired with the codes and entered into the tables. GIS then has the ability to switch between values being represented and can change between columns of a given raster to map different associated values of the same raster cells. For instance, it can switch between a code that was produced to a newly assigned column that now would represent the S-Factor. Likewise, GIS through its symbology representation has the capability to group, map and classify based on certain values. Similar values of one amplification factor would be mapped one color, and similar values of another amplification would be mapped a different color. The resulting map would then indicate the degree of amplification based on soil composition and depths from the data provided.

After the raster work was done, the intensity and amplification factors of an earthquake could be clearly seen within the GIS. The work then moved onto how these factors would affect various infrastructure. Vector data was then incorporated into the project such as roads, dams, and railroads that could be overlain to see how they may be impacted during an earthquake. As well, some new data layers were developed through the digitizing process that utilized some of the data rich geological quads that included symbology of schools, buildings, and various other infrastructure that could be utilized in the overall analysis. Simple point data and digitizing was developed for this infrastructure and overlain of the seismic hazard analysis.

With these procedures complete, the process of discussion and analysis of results could begin. Earthquakes produce a tremendous destruction on civilized society, and we can only guess when they will hit, but this mapping process enables us to predict that when
they do, where it would most likely produce the worst results and what if any valuable infrastructure that we have in those areas. Most importantly, it allows us to plan where would be the safest places to be in light of these earthquakes and to locate safety infrastructure from the mapping process that would be suitable for evacuation were such an earthquake to occur. The analysis process also lets us find infrastructure that could be at risk and forward our results to state hazard mitigation authorities and engineers that can determine if any mitigation plans could be put in place to sure up such structures, or to consider rebuilding if necessary to prevent worse case destruction were an event of this kind to happen within the next 50 years or sooner.
CHAPTER VI
RESULTS

Microzonation Analysis Results

The combined raster analysis of Ouray indicates a deep deposit of alluvium in the central part of the city, as is highlighted in red on the following map. This would be the area of greatest ground motion experienced in this small town during an earthquake, and where most of the geotechnical investigation should occur to ensure that building structure is safe and would be able to withstand ground motion of that intensity.

The areas highlighted in yellow would experience a more moderate intensity of amplification, and while structures in these areas should also be monitored for structural integrity, they may not be of the same level of concern as those found in the areas marked as high ground motion intensity. In the eastern portion of the city is an area that also is designated as landslide on geological maps and this area as well would be of considerable concern for ground motion and destruction during an earthquake (Figure VI.1). A deposit of talus as well intrudes into the deeper alluvium (this can be seen in green in the lower southeast portion of the city and as well indicates how the combined rasters are different than the soil depth rasters alone), and this area is indicated as moderate ground motion and not severe because of the rocky and more firm nature of the talus deposit. Areas in green on the map would experience the least amplification and would not be a high consideration in a geotechnical investigation. The areas in green typically represent an exposed bedrock layer or a soil depth to bedrock that is less than 20 feet and does not indicate a significant level of amplification in this analysis. The data distribution
indicates a mean of 1.266 for S-Factor and a σ of 3274, and the frequency of S-Factor 1 at 185128 and S-Factor 2 at 29829 (Figure VI.2).

Figure VI.1. S-factor analysis of Ouray Colorado.
Table VI.1. S-factor table of Ouray with combined depth and geological composition codes and corresponding S-Factor.

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<td>35</td>
<td>1200250</td>
<td>21257</td>
<td>1.5</td>
</tr>
<tr>
<td>36</td>
<td>1200260</td>
<td>12505</td>
<td>1.5</td>
</tr>
<tr>
<td>37</td>
<td>1200270</td>
<td>13243</td>
<td>2</td>
</tr>
<tr>
<td>38</td>
<td>1200280</td>
<td>16586</td>
<td>2</td>
</tr>
</tbody>
</table>

Figure VI.2. Data distribution of S-Factor for Ouray, Colorado.
The analysis of Grand Junction Colorado for seismic wave amplification indicates a different geological structure compared to Ouray, and is marked by more extensive alluvial deposits stretched out over this city. It can be seen from the map, that two major alluvial deposits exist in the city, one to the northern part and the other to the south. This deposit is likely from the sinuosity of the Colorado River that has meandered through the valley over the ages and changed course at times, leaving behind extensive alluvial deposits throughout that valley. Both areas are of significant concern in the Grand Junction area as the soil depth in both locations indicates a soil depth of over 60 feet of a loose and more clay like deposit. The deepest part of these deposits would indicate an amplification factor of 1.5 to 2 for these deeper parts of the alluvial deposits, and would create considerable ground motion and danger for people in those areas and for building structures, especially if the earthquake was of an Mw 5 or greater (Figure VI.3). The distribution of the data indicates that most of the values mapped for S-Factor are in the 1 S-Factor range with a mean of 1.145 and the value of \( \sigma \) at .2776 (Figure VI.4).
Figure VI.3. S-Factor raster of Grand Junction Colorado

Table VI.2. S-Factor table with combined codes for depth and soil type and related S-Factor.

<table>
<thead>
<tr>
<th>OBJECT ID</th>
<th>Class code</th>
<th>Count</th>
<th>S_Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1200020</td>
<td>113648</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>1400020</td>
<td>981348</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>1400030</td>
<td>850189</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>1400040</td>
<td>334921</td>
<td>1.5</td>
</tr>
<tr>
<td>5</td>
<td>1400050</td>
<td>119561</td>
<td>1.5</td>
</tr>
<tr>
<td>6</td>
<td>1400060</td>
<td>122553</td>
<td>2</td>
</tr>
</tbody>
</table>
Figure VI.4. Data distribution of S-Factor for Grand Junction, Colorado.
According to the map (Figure VI.5), significant infrastructure also lies in these areas that could be considered for geotechnical investigation to ensure structural integrity. There are office buildings, the VA Hospital, and Mesa College all on foundations that would likely incur significant ground motion during an earthquake. The only areas that would not have this level of concern and likely have less amplification would be the areas in the northern part of the city that are marked by bedrock outcroppings. The location of St. Mary’s Hospital (upper northwest corner) is one such structure in the area that would be in a more stable zone, and could be considered for an evacuation center in the event of an earthquake, as it may suffer less damage and as well may be subject to less ground motion making it a safer environment during an earthquake event.
Figure VI.5. Seismic wave amplification and building structures in Grand Junction Colorado.
Grand Junction, because of its significant size and population would be a good candidate for a long term geotechnical investigation that would take into account its propensity for severe ground motion during an earthquake, as well as to develop a comprehensive earthquake response plan for its residents. The alluvial deposits that mark the city would certainly be at risk of severe ground motion for an earthquake of an Mw 5 or higher and older infrastructure bridges and overpasses should be evaluated for structural integrity. As well, the city is surrounded by several major bedrock outcroppings that would offer locations for evacuation and can also be considered for rebuilding plans that would take into account more stable foundations for critical infrastructure and public buildings such as schools, hospitals, and administrative buildings.

**UBC Classification System, Shortcomings and Suggested Interpolation**

The UBC S-Factor system is a reliable system that is sufficient for the determination of seismic wave amplification based on geological soil types and composition. The difficulty of the system is applying it to any and all geological conditions that exist in reality. While most soil conditions and depths could be matched to some classification in the system, the methodology leaves some gaps that may be experienced in reality as seismic waves propagate through a given area. For instance, in the UBC system the S-Factor 1.2 can only exist if the soil depth is over 200 feet. Nowhere in this study were depths of soil of 200 or more feet found. Therefore, there is a gap between the S-Factor of 1 and 1.5 in this study if the UBC S-Factor classification is strictly adhered to. Would this mean that there is a jump between amplification between 1 and 1.5, skipping 1.2
amplification and other values in between? In reality, these gaps are likely to be smoothed by such middle values, and therefore some interpolation between this gap is presented in the following suggested model for Grand Junction, where one of the S values of 1 is replaced with a 1.2, creating a more continuous wave amplification progression without sudden jumps (Figure VI.6). While the real emphasis of this modeling is to find the areas of intense amplification probability, which it has, the shortcomings and suggested improvements to the model are evaluated in the Discussion section of this work.
Figure VI.6. S-Factor Interpolation grid, using 1.2 amplification factor interpolation.

Table VI.3. S-factor Interpolation grid table. Column S_Fct_Inpl, includes new value of 1.2.
CHAPTER VII
PLANNING CONSIDERATIONS BASED ON SEISMIC MICROZINATION

Role of Planning and Scientific Data

While scientific data is valuable, data and findings that exist in isolation and are not implemented into the reality of our communities and civilization are not of much importance. Geologic hazards are an area of serious importance, and they are often neglected because of their intermittent nature, only to be nature’s worst such hazards when they do occur and are particularly destructive when planning considerations are not implemented to prepare and mitigate for such disasters. Recent earthquakes worldwide have totaled more $300 billion dollars alone from earthquakes in Japan, Mexico, and South America, and 2011 had over 21,000 earthquake related deaths with many of them from the Magnitude 9 earthquake in Japan that year (USGS, 2011) Even countries that have gone through all efforts possible still find themselves devastated when earthquakes as what occurred in Japan happen and devastation is total.

The gap between real science and research and the role and extent that government can play in response to that knowledge is often blurred and confused, and seemingly opposite in nature. The following, however, explains and fills that gap and underscores not only their dependence on each other of scientific research and public backing, but also clarifies that without a proper coordination between the research being presented and proper hazard planning response, the public is at risk. The goal we would like to have is to have our scientific data, mapping, and geotechnical engineering evaluations incorporated as far into society as possible which does not only include scientific findings, but suggested
responses to the findings, as well as a suggested framework for the working relationship that must exist between scientist, engineer and community planner for an appropriate response to exist and the public to have the greatest benefit from this knowledge.

The importance of this work is that it provides a general map of predicted hazards on a city wide level. It allows city planners, engineers, and the community to be aware of this hazard and conduct further investigation particularly in areas that are marked as high potential for destructive ground motion during an earthquake and to plan accordingly. In particular, we would want to flag older buildings and critical infrastructure that is in these areas of high ground motion potential and have them investigated with confirmation borehole drillings and foundation inspections to verify the degree of risk that these structures would be in during an earthquake. Geotechnical investigations may confirm the depth of soil and risk and may find that structural improvements could be useful or that in some cases that adequate foundations may have already been put in place during its construction that seem to protect the structure even in the event of an earthquake.

Typically structures in Colorado are not planned for earthquakes, but it does not mean that inadequate foundations would exist in all cases. We would be particularly concerned about structures such as decaying bridges or dams that may have been built in areas of a deep soil profile and could be subject to severe ground motion particularly in an earthquake above an Mw 5 or higher. Bridges and overpasses that have been subject to 50 or more years of weathering processes may exhibit weakened and rusted steel, and even foundational settling and cracking that may render the structure as a hazard subject to various motion and vibration.
Even though it would be ideal to roll back time, and build such structures with improved foundations based on our current information and data, we must deal with the structures that exist and mitigate with what we have. Where such structure has decayed to the point where it is beyond a mitigation improvement, it can be considered to rebuild the structure entirely particularly if the structure is flagged in an area of highest potential wave amplification and would have higher levels of potential community destruction were an earthquake to take place. One must also consider that were an earthquake to take place, what would be the method of evacuation or infiltration into the site of troops or help were a major bridge or overpass to fail on a major transportation corridor, as is common during earthquakes, and people can neither leave nor help brought in during such a disaster.

These reasons are why these hazards must be evaluated and prepared for because of the potential destruction that even an earthquake of an Mw 5 or 6 could wreak on an area if its infrastructure is in no way prepared for such an event. In mountainous areas as well, such as in the Southwestern Mountains of Colorado, overpasses are common for transporting traffic over the valleys below, and aging dams have sometimes even breached due to reaching capacity during floods such as the Big Thompson dam and flood in the mid 1970’s. Such mountain reservoirs are not uncommon in Colorado and may have passed a 100 year mark since their construction as they hold a vast yet potentially deadly volume of water for small mountain towns below.

By providing the kind of information done in this study we are generating a source of information that can be geared toward all in the community that can be affected. It can serve as a document of awareness and knowledge to the city planners that may opt for further investigation, or call for more detailed analysis to get the ball rolling in mitigating
this hazard. It can serve as a general but accurate guide for geotechnical engineers that would like to conduct studies on potential hazard sites whether from previously built infrastructure or for planned infrastructure. It can also serve as a guide for the community as well that may want to be informed of these hazards especially in the event that others in the community neglect or do not take appropriate mitigation action for these hazards or fail to have a disaster plan in place that does not account for earthquakes.

This kind of mapping is very important at the city planner level also because while more technical data is behind what made the map, the map is very readable and understandable on its face value and can be understood by someone that is neither a geologist nor an engineer. That is important because it is this crowd of planners and governing authorities that are essential to getting this kind of hazard mitigation in place and calling for further investigations and geotechnical support to evaluate this infrastructure. Without their work at the political and community levels, the kind of funding and structure necessary to move such projects forward is not realistic. Also, their level of support is important because without a hazard plan in place at their level, there is no way they can respond to such a catastrophe without any knowledge or awareness of the hazard evaluated in advance.

It is important that local, state and federal agencies coordinate efforts to have an emergency response system, not only in the event of an earthquake, but in various other catastrophic situations as well that affect large numbers of the population and community. After the geotechnical investigations have been done, it is necessary for local agencies and planners to develop a comprehensive emergency response system that accounts for earthquakes and geological hazards that could be experienced in the
community. The following is a synopsis of the emergency response system that should be in place to help save lives and speed the response of a community after a significant catastrophic event has occurred there.

Hazard Planning Response

Local Response

Local emergency response teams have a tremendous duty in the event of a natural or manmade disaster or catastrophe. Cities can vary widely in their response plans and individuals should be aware of the city plan that is in place to respond to such circumstances and knowledgeable on the strengths and weaknesses of the plan that their city has in place. Not all cities have the same available resources, and while some may be able to meet such an event with a full range of services, a smaller town in a rural area may be horribly inadequate in its ability to respond to major catastrophic events. In these cases, residents still should take it upon themselves to have an emergency response plan available and know what resources can be afforded to them in the event of a catastrophe. Local officials are responsible for police, ambulance, fire and paramedic services. They likewise should have already coordinated in advance possible solutions for evacuation shelters, likely coordinated with the Red Cross, and be aware of supply and resources that would be available during these crises (City of Littleton 2005). Also it is the duty of local officials to have verified that adequate hospital and mental health facilities and treatment are available during times of disasters. The city officials also should have an emergency command hierarchy that is clear with coordinated roles and as well backup facilities to administrate in the event of some destruction to their main administrative facilities. City officials should also as part of their emergency response plan have various response
scenarios well thought out, as well the role of the response team to crisis events (DHS 2008). Also lines of communication between local officials and the state and federal officials as needed must also be defined so that higher level resources may be called upon if city resources become inadequate. The following hierarchy at a minimum should be in place in most city administrative emergency response teams (City of Littleton 2005):

- City Manager (or Mayor)
- Assistant to the City Manager
- Police Chief
- Fire Chief
- Public Service Director
- Emergency Planning Director
- Other command personnel and support personnel as deemed necessary

**State Response and National Guard**

The State Response to natural disasters and catastrophes can open a deep source of resources that go well beyond local official ability once local resources are taxed or if the catastrophe is of a magnitude that warrants state involvement. Each state has the power to declare a state of emergency by the governor of the state, which is a powerful function that allows him or her to tap into the strength of the Army National Guard of that state. Once the power of the National Guard has been called upon, the full range of powers within the National Guard can be of service to the disaster response including the use of man power, trucks, helicopters, ambulance and medical services, bridge and engineering services and specialized abilities (Department of the Army and Air Force 2008).
Specifically legislation calls for the following duties of the National Guard:

(3) National Guard Civil Support missions are conducted to assist in:

(a) Supporting civil authorities whose capabilities or capacity is insufficient to meet current requirements with general purpose, specialized, or unique Guard forces or capabilities;  
(b) Protecting the life, property, and safety of U.S. citizens and U.S. persons;  
(c) Protecting critical U.S. infrastructure;  
(d) Providing humanitarian assistance during disaster response and domestic emergencies;  
(e) Providing support to designated law enforcement activities and operations;  
(f) Providing support to designated events, programs, and other activities.

National Guard Domestic Operations Include:

(1) Aviation/Airlift;  
(2) Command and Control (C2);  
(3) Chemical, Biological, Radiological, Nuclear, and Explosives (CBRNE) response;  
(4) Engineering;  
(5) Medical;  
(6) Communications;  
(7) Transportation;  
(8) Security;  
(9) Logistics;  
(10) Maintenance

Federal Response

Stafford Act

In 1988 the Robert T. Stafford Disaster Relief and Emergency Assistance Act was passed by Congress in order to manage and provide federal level assistance in times when state and local relief was taxed and federal relief was warranted (CCPR 2007). The Act enables the President of the United States to utilize any power of the US in response to disaster relief as the President feels warranted. A great deal of authority is enacted via FEMA which serves as an instrument of the act to pursue powers that would be necessary
from the Executive Branch of the federal government. Due to the authority that the Stafford Act enables the President, the President has virtually any resource of the United States Government at his disposal to respond to a disaster provided that the President has declared the event as a major disaster area (CCPR 2007). The Stafford Act enables the federal government to:

In Emergencies

- Utilize its resources, facilities, and personnel to assist state and local efforts;
- Coordinate disaster relief assistance;
- Disseminate warnings and provide technical and advisory assistance to state and local governments;
- Provide assistance through federal agencies;
- Remove debris;
- Provide eligible households up to $30,000 in assistance; and
- Assist in the distribution of medicine, food, and other supplies.

In Major Disasters

- Utilize, donate, or lend federal resources, facilities, and personnel to state and local governments;
- Distribute food, medicine, and other supplies;
- Remove debris, clear roads, and construct temporary bridges;
• Provide search and rescue teams; Provide emergency medical care, shelter, and needed temporary facilities;
• Disseminate warnings, information, and technical advice;
• Utilize the resources of the Department of Defense;
• Pay up to 75% of the cost of repairing or replacing state and local facilities and infrastructure;
• Provide financial assistance to private, non-profit utility companies;
• Provide eligible households up to $30,000 in assistance;
• Provide unemployment assistance, food coupons, and other assistance to eligible individuals; and
• Authorize loans of up to $5 million for local governments to supplement tax revenue lost as a result of the major disaster.

**FEMA**

The role of FEMA is to serve largely as a coordinator and disseminator of resources in response to a major disaster area. FEMA has a great deal of funds at its disposal that are largely used for in the recovery effort to a major catastrophe. FEMA’s primary job during non-disaster periods is to enable and educate state and local responders to prepare for disaster incidents and to ensure that they are fully funded so that they have adequate preparation (CCPR 2007). FEMA does not possess a great deal of substantive resources (other than financial) in itself to aid in disaster relief, but instead is to act as a liaison between the President, State, and local responders to make sure that all of the available resources are being utilized. FEMA can help in getting the US military involved in
disaster response as required if state reserve forces have met their capacity. FEMA serves as a critical financial resource in disaster response not only in individual recovery, but in state and local assistance to make sure that they can fully fund their recovery effort for as long as needed. FEMA is divided into 10 regional offices (Figure VII.1), often having disaster expertise and specialization that may be unique or required for that region such as the hurricane prone gulf states, and as well FEMA utilizes as great deal of regional and hazards mapping data such as seen below in the earthquake hazard map (Figure VII.2), to assist in its disaster and hazard response preparation (CCPR 2007).

Figure VII.1. FEMA Regions. (FEMA).

Figure VII.2. Earthquake hazard areas. (FEMA).
Response and Responsibility of the Individual

The greatest role that is expected of the individual according to the National Response Framework and Disaster Response plan is that the individual stay informed of the disaster via local radio or television stations, and that the individual plan and educate oneself in preparation for an emergency situation. Without this level of cooperation and preparation of the individual it is difficult for any response effort to be completely successful.

The National Response Framework and Disaster Response plan states (DHS 2008), Community members can contribute by:

- **Preparing an emergency supply kit and household emergency plan.** By developing a household emergency plan and assembling disaster supplies in advance of an event, people can take care of themselves until assistance arrives. This includes supplies for household pets and service animals. See the recommended disaster supplies list at [http://www.ready.gov](http://www.ready.gov).

- **Monitoring emergency communications carefully.** Throughout an emergency, critical information and direction will be released to the public via various media. By carefully following the directions provided, residents can reduce their risk of injury, keep emergency routes open to response personnel, and reduce demands on landline and cellular communication.
Staying Informed

It is the responsibility of the individual to stay informed about emergency events and to act and plan accordingly as soon as possible to prepare for the event. Common alert systems are available through the following information systems, as well new technology also can allow for text alerts to be sent to your cell phone that can be sent from any local county office or other emergency broadcasting system so that you can be aware of the situation as soon as practical (State of Colorado 2007).

- Radio; Television; Emergency Alert System; Emergency Preparedness Network (EPN) e.g., Reverse 9-1-1; Highway Message Boards; Route Alerting; Text Alerts via cell phone or email

Awareness and Immediate Response (American Red Cross 2003),

In public Areas (preparation for terrorist related activity):

- Be aware of your surroundings.
- Move or leave if you feel uncomfortable or if something does not seem right.
- Take precautions when traveling. Be aware of conspicuous or unusual behavior.
  Do not accept packages from strangers. Do not leave luggage unattended. You should promptly report unusual behavior, suspicious or unattended packages, and strange devices to the police or security personnel.
- Learn where emergency exits are located in buildings you frequent. Plan how to get out in the event of an emergency.

During an Explosion

If there is an explosion, you should:
• Get under a sturdy table or desk if things are falling around you. When they stop falling, leave quickly, watching for obviously weakened floors and stairways. As you exit from the building, be especially watchful of falling debris.

• Leave the building as quickly as possible. Do not stop to retrieve personal possessions or make phone calls.

• Do not use elevators.

Once you are out:

• Do not stand in front of windows, glass doors, or other potentially hazardous areas.

• Move away from sidewalks or streets to be used by emergency officials or others still exiting the building.

During the Earthquake

• If indoors, stay there. Get under a desk or table or stand in a corner. Stay away from windows, bookcases, file cabinets, heavy mirrors, hanging plants and other heavy objects that could fall. Watch out for falling plaster and ceiling tiles. Stay under cover until the shaking stops. Hold on to your cover – if it moves, move with it.

• If outdoors, get into an open area away from trees, buildings, walls, and power lines.

• If driving, pull over to the side of the road and stop. Avoid areas around power lines. Stay in your car until the shaking is over.
• If in a crowded public place, do not rush for the doors. Crouch and cover your head and neck with your hands and arms.
CHAPTER VII
CONCLUSION

Geological hazards mapping continues to serve an important role in the overall response and readiness of the public for hazardous geological events that can be disastrous in consequence, although they have a somewhat intermittent nature. Landslides, floods, and even response to terrorist events often have comprehensive community plans to deal with these catastrophes and considerable funding is channeled toward their investigation. Coastal areas that have frequent earthquakes such as California, understandably, have significant response plans and scientific investigations to map and respond to earthquakes. Interior areas of the country sometimes get neglected in these investigations and response efforts, yet some areas such as Southwestern Colorado do represent pockets of activity that should not be overlooked. Such areas also represent significant clusters of population as mountain towns have grown as well as their infrastructure that must be protected and analyzed for structural integrity. The cities under study in this work, Ouray and Grand Junction Colorado, are two of these cities, which, as indicated in this work are in earthquake prone areas that have significant underlying geology that would foretell intense seismic amplification in parts of these mountain towns were an earthquake to occur there.

Mapping of earthquake hazards has been more of a gradual growth compared to that of landslides or floods, due to the complexity of seismic waves and their variability in passing through geological substrate. General maps do exist such as the one shown in Figure VII.2 that is used by FEMA to target earthquake prone regions. These overall national maps tell us little, however, about how seismic waves will be amplified in actual
geologic layers, and the past 20 years represents a higher level of seismic wave amplification investigation and mapping processes that aim to define particular at risk geologic structures that will intensify ground motion experienced in earthquakes, as was modeled in this study. This more finely tuned approach to geological mapping of earthquake prone regions serves an important role for the readiness of the public, community planners, and as well can serve as a useful guide for engineers investigating aged infrastructure or future development efforts that should take into account some degree of earthquake readiness in the design and building of important structures.

GIS is developing into a high level spatial database that is able to combine a flurry of data structures, maps and even CAD data that can be integrated into an overall analysis process that was previously unaccomplishable due to the lack of sophistication and resources available to generate such work. Often, these mapping efforts of seismicity were either one of very general mapping with little defined geological structure, or the opposite, very defined investigations that would typically look at the earthquake readiness and foundations of specific structures. This form of mapping using this microzonation approach instead is offering an accurate picture of seismic amplification without becoming overly generalized, and detailed enough to guide city planners and geotechnical engineers to the key areas that could cause potential danger or harm during an earthquake. The quality of this microzonation mapping in GIS will lend itself well to many areas of the world such as Mexico, Chile, or Japan that are frequented by earthquakes and may have some general maps of faults and where earthquakes are likely to occur, but they may not have sufficient microzonation mapping that can detail the hazard potential of specific geological structures.
CHAPTER IX
DISCUSSION

While this mapping process used cross sections provided by the USGS to interpolate soil depth and is sufficient for this mapping purpose, more detailed analysis can also be obtained in the following method, however it can require a great deal of time as well as money if further geological investigation is required. Another method of raster generation to determine soil depth would be to use water well or possibly even oil or gas well drilling logs. If a sufficient number of drillings have taken place over a given area and the logs are reasonably well recorded, depth to bedrock can be specifically determined for these drilling locations. The more points, the more accurate this method would be which is also the problem with the well log/data point approach because often sufficient records do not exist over an entire area, and more drilling may be required to have sufficient points. Once the soil depths have been determined over say a minimum of 100 points, a raster interpolation can be developed in GIS that will combine and interpolate between soil depths providing a highly accurate picture of the soil depth of a given area. Fortunately, however, sufficient cross sections of soils depths do exist for many areas that have been mapped for geological purposes, and typically those cross sections were developed from knowledge and findings of borehole and well drilling investigations. Another possible shortcoming in this investigation and all microzonation mapping at the present is the lack of specific knowledge applied to exact geological structures and the required further development of seismic amplification classification schemes as the one presented in this model using S-Factors.
Resolution, Purpose, and Resources

Current classification systems that have been introduced, such as the International Building Code 2012 (IBC 2012), do bring a more detailed level of classification, however not without increased complexity that more often than not will require a team of on-site geotechnical investigations in order to fulfill the data parameters of the model. This leads us to a discussion as to what is the main purpose of the mapping that is to be conducted, and the degree of data resolution and data collection required to achieve that resolution.

When conducting any kind of geological hazard mapping, the question of resolution of data is always of importance. Resolution would determine to what scale the data is useful and accurate, and some resolutions are not applicable for certain site specific characteristics. For instance, the maps produced in this study would indicate the degree of seismic hazard potential of a given earthquake for a regional area on maps of a 1:12,000 scale or 1:24,000. For resolutions of more detailed, say a 1:500 scale in situ geotechnical data collection is required and specific site evaluations must be conducted. The purpose of such maps would also be different. It would be for the purpose of determining specific stresses and forces that would impact a building or buildings for certain blocks. Past UBC 91, more current classification systems have been developed, however, they are more practical for site by site (block by block) analysis because of the level of detail and field study required rather than for applications of general hazard mapping.

Furthermore, mapping at scales of 1:250,000 also require a less detailed requirement of data classification, as seen in the FEMA map in Figure VII.2. These kinds of maps can actually simply require the general location of where earthquakes occur without going
into the detail of site soil characteristics because such soil characteristics cannot be visible or discernible at that level of scale. A map at that level typically, can only tell us where earthquakes occur and where they do not.

The IBC 2012, and other similar systems past UBC, such as IBC 2000, differ significantly from the older system, and approach a level of complexity that demands site specific data to be retrieved from the area being worked on. More specifically, the shear wave velocity (Vs) must be determined for each bedrock and soil type at the given area. The problem with this however, is that while Vs tables do exist, they are general tables that may not be applicable for the area under study, especially when looking at soil conditions which are the most important aspect of this study. Soil conditions vary widely, so when exact velocity requirements are necessary; it also mandates a geotechnical field study. As Dr. S.K. Ghosh described it clearly when presenting the UBC system compared to some of the newer classification systems,

Soil Profile Types $S_1$ through $S_4$ were qualitatively defined in UBC and documents based on the UBC. The structural engineer, after reviewing the soils report, typically determined the Soil Profile Type.

This is to be contrasted with the new situation where the distinction among the Site Classes must be based on one of three measured soil properties at the site; the shear wave velocity, the standard penetration resistance (or blow count) or the undrained shear strength (Ghosh, 2001).

In the state of California the State Mining and Geology board has developed recommendations of when a further geotechnical investigation is warranted due to the
number of seismic hazards in that state and the cost prohibitive methods required to complete the investigation. The state has opted to take what can be envisioned as an upside down pyramid approach to these investigations where, if general information clearly rules out the need for further geotechnical studies, then the study may not be warranted, if general information as well as further data warrants the investigation, such as borehole drillings that confirm a seismic hazard, or presence of landslide or liquefaction factors are present then further investigations could be warranted.

As the state agency described it in their criterion list,

The fact that a site lies within a mapped zone of required investigation does not necessarily indicate that a hazard requiring mitigation is present. Instead, it indicates that regional (that is, not site-specific) information suggests that the probability of a hazard requiring mitigation is great enough to warrant a site-specific investigation. However, the working premise for the planning and execution of a site investigation within Seismic Hazard Zones is that the suitability of the site should be demonstrated. This premise will persist until either: (a) the site investigation satisfactorily demonstrates the absence of liquefaction or landslide hazard, or (b) the site investigation satisfactorily defines the liquefaction or landslide hazard and provides a suitable recommendation for its mitigation (California, 1997).

Furthermore, the state adds that a general screening level of investigation (non site specific) should be conducted before a full geotechnical investigation is done, that would
favor mapping processes that gear the investigators to the proper sites that should be reviewed or require a more advanced level of analysis than is conducted through UBC,

The purpose of screening investigations for sites within zones of required investigation is to evaluate the severity of potential seismic hazards, or to screen out sites included in these zones that have a low potential for seismic hazards. If a screening investigation can clearly demonstrate the absence of seismic hazards at a project site, and if the lead agency technical reviewer concurs with this finding, the screening investigation will satisfy the site-investigation report requirement and no further investigation will be required. If the findings of the screening investigation cannot demonstrate the absence of seismic hazards, then the more-comprehensive quantitative evaluation needs to be conducted.

The documents reviewed should be both regional and, if information is available, site-specific in scope. The types of information reviewed during a screening investigation often includes topographic maps, geologic and soil engineering maps and reports, aerial photographs, water well logs, agricultural soil survey reports, and other published and unpublished references (California, 1997).

Once a geotechnical investigation is warranted under governmental funds, the investigation according to the State of California Board of Mining and Geology,

**Reports that address liquefaction and/or earthquake-induced landslides should include, but not necessarily be limited to, the following data:**

1. Description of the proposed project’s location, topographic relief, drainage, geologic and soil materials, and any proposed grading.
2. Site plan map of project site showing the locations of all explorations, including test pits, borings, penetration test locations, and soil or rock samples.

3. Description of seismic setting, historic seismicity, nearest pertinent strong-motion records, and methods used to estimate (or source of) earthquake ground-motion parameters used in liquefaction and landslide analyses.

4. 1:24,000 or larger-scale geologic map showing bedrock, alluvium, colluvium, soil material, faults, shears, joint systems, lithologic contacts, seeps or springs, soil or bedrock slumps, and other pertinent geologic and soil features existing on and adjacent to the project site.

5. Logs of borings, test pits, or other subsurface data obtained.

6. Geologic cross sections depicting the most critical (least stable) slopes, geologic structure, stratigraphy, and subsurface water conditions, supported by boring and/or trench logs at appropriate locations.

7. Laboratory test results; soil classification, shear strength, and other pertinent geotechnical data.

8. Specific recommendations for mitigation alternatives necessary to reduce known and/or anticipated geologic/seismic hazards to an acceptable level of risk.

Reports that address earthquake-induced landslides may also need to include:

1. Description of shear test procedures (ASTM or other) and test specimens.
2. Shear strength plots, including identification of samples tested, whether data points reflect peak or residual values, and moisture conditions at time of testing.

3. Summary table or text describing methods of analysis, shear strength values, assumed groundwater conditions, and other pertinent assumptions used in the stability calculations.

4. Explanation of choice of seismic coefficient and/or design strong-motion record used in slope stability analysis, including site and/or topographic amplification estimates.

5. Slope stability analyses of critical (least-stable) cross sections, which substantiate conclusions and recommendations concerning stability of natural and as-graded slopes.

6. Factors of safety against slope failure and/or calculated displacements for the various anticipated slope configurations (cut, fill, and/or natural slopes).

7. Conclusions regarding the stability of slopes with respect to earthquake-induced landslides and their likely impact on the proposed project.

8. Discussion of proposed mitigation measures, if any, necessary to reduce damage from potential earthquake initiated landsliding to an acceptable level of risk.

9. Acceptance testing criteria (e.g., pseudo-static factor of safety), if any, that will be used to demonstrate satisfactory remediation.
Reports that address liquefaction hazards may also need to include the following:

1. If methods other than Standard Penetration Test (SPT; ASTM D1586-92) and Cone Penetration Test (CPT; ASTM 3441-94) are used, description of pertinent equipment and procedural details of field measurements of penetration resistance (borehole type, hammer type and drop mechanism, sampler type and dimensions, etc.).

2. Boring logs showing raw (unmodified) N-values if SPT’s are performed; CPT probe logs showing raw qc-values and plots of raw sleeve friction if CPT’s are performed.

3. Explanation of the basis and methods used to convert raw SPT, CPT, and/or other non-standard data to "corrected" and "standardized" values.

4. Tabulation and/or plots of corrected values used for analyses.

5. Explanation of methods used to develop estimates of field loading equivalent uniform cyclic stress ratios (CSReq) used to represent the anticipated field earthquake excitation (cyclic loading).

6. Explanation of the basis for evaluation of the equivalent uniform cyclic stress ratio necessary to cause liquefaction (CSRliq) within the number of equivalent uniform loading cycles considered representative of the design earthquake.

7. Factors of safety against liquefaction at various depths and/or within various potentially liquefiable soil units.
8. Conclusions regarding the potential for liquefaction and its likely impact on the proposed project.

9. Discussion of proposed mitigation measures, if any, necessary to reduce potential damage caused by liquefaction to an acceptable level of risk.

10. Criteria for SPT-based, CPT-based, or other types of acceptance testing, if any, that will be used to demonstrate satisfactory remediation (California, 1997).

As can be seen from the litany of data required to do such an investigation it is understandable why such government funded level of investigation is taken on a case by case basis due to the resources required to conduct such work. Once such work is agreed to, in situ data collection must take place that can utilize a host of “black box” technologies must be incorporated into the field to determine the exact conditions at the site. Some of these analyses would include the use of a penetrometer, laboratory analysis of grain size using instruments such as a 3D optical scanner, and advanced porosity studies using tools such as a mercury intrusion porosimeter to look at the soil conditions and characteristics, determination of shear wave velocities, and liquefaction probability.

These are just a few of the field evaluations that would be required to determine a site specific seismicity that could be used to develop a mathematical deterministic model of how an earthquake would affect that particular site. In order to determine how a particular building will respond in an earthquake these exact numbers are required so that engineers can determine the best mode of action for that building. These specifics are not required however, to determine whether an overall region is afflicted with soil conditions that tend to be more hazardous in an earthquake and those less prone to these hazards as in the case of expose bedrock on the surface. As mentioned earlier in the work, W.D.
Liam Finn acknowledged the appropriateness of the UBC 91 system for general mapping and hazard planning purposes, which was the intent of this study.

In his 1991 discussion of UBC and comparison of previously existing systems, he stated, “…these parameters can be used to map relative damage potential and provide guidance for land use decisions (Finn, 1991).”

When a more general level of mapping is required, or maps that are to be used for future planning to build in less hazardous seismic regions, an analysis at the level that was done in this work would be appropriate to guide planners, reach conclusions, and save resources for other needs in the government. So, the requirements of any mapping process must always be considered, the audience, resolution, and intended purpose of the map. This hazard mapping is useful to this level of scale, at a more refined resolution more investigation would have to be done. Currently, however, more accurate mapping techniques and the ability to investigate these geological occurrences has broadened our understanding and depth of knowledge as to the behavior of these seismic events and their potential hazard being in the same spatial proximity of civilization.
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State of Colorado.


Ouray, Colorado Geology (Courtesy of USGS, 1962)
Ourray Geological Units (USGS, 1962)
Grand Junction Geological Units (USGS, 2002)

**Alluvial deposits**

- Qalc1: Youngest alluvium deposited by the Colorado River (Holocene)
- Qalg: Youngest alluvium deposited by the Gunnison River (Holocene)
- Qa: Alluvium deposited by tributary streams (Holocene and late Pleistocene)
- Qvf: Valley-fill deposit (Holocene and late Pleistocene)
- Qalc2: Oldest alluvium deposited by the Colorado River (Holocene and latest Pleistocene)

**BEDROCK UNITS**

- Km: Mancos Shale (Upper Cretaceous; Campanian to Cenomanian)
- Kd: Dakota Formation (Upper and Lower? Cretaceous; Cenomanian and Albian?)
- Kb: Burro Canyon Formation (Lower Cretaceous; Albian and Aptian)
- Jmb: Morrison Formation (Upper Jurassic)
- Jms: Brushy Basin Member (Tithonian and Kimmeridgian)
- Jmt: Salt Wash Member (Kimmeridgian)
- Jw: Tidwell Member (Kimmeridgian to latest Oxfordian)
- Qfh: Wanakah Formation (Middle Jurassic; Callovian)
- Qas: Entrada Formation (Middle Jurassic; Callovian)

**Alluvial and colluvial deposits**

- Qf: Young fan-alluvium and debris-flow deposits (Holocene)
- Qac: Alluvium and colluvium, undivided (Holocene and late Pleistocene)
- Qwpf: Pediment deposit of Walker Field (late? Pleistocene)
- Qasc: Old alluvial-slope deposit (late Pleistocene)
- Qlg: Local gravel deposits (middle Pleistocene)
- Qlg/Qt: Local gravel deposits over terrace alluvium 30 of the Colorado River (middle Pleistocene)
Graphics from Workshop: Introduction to Spatial Analysis (Berkowitz, 2005).

The workshop includes methodology for combination of 5 different thematic grids to create a site suitability index for areas of revegetation based on the following factors using an additive raster model.

1. Mean slope < 25 degrees.
2. Aspect between 135 and 225 degrees (south-facing).
3. Rainfall < 180 inches per year.
4. Solar radiation \( \geq 350 \) Calories/cm\(^2\) per day.
5. Land use not equal to 1 (urban).

Site needs for revegetation analysis. (Berkowitz, 2005)
Landuse rasters for site suitability calculation. (Berkowitz, 2005)

Site Suitability raster calculation. (Berkowitz, 2005)
Complete raster calculation tutorial workshop PDF that parallels the process in this study can be found at:


Additional example of raster math

Combining Rasters with multi thematic data

Rasters can be combined using binary data values of 1 or 0, or other codes such as 1, 2, 3 that designate a certain criterion in the raster. Say that our overall goal is to find grasslands for a particular mammal species, and the species prefers grasslands that are above 5000 ft and on south facing slopes.

Reclassify the elevation raster:

0= elevation below 5,000 ft.

1 =elevation above 5,000 ft.
Reclassify the aspect raster:

0 = slopes facing W, E, N, NE or NW
1 = S, SW or SE facing slopes

Add the two rasters together

Resulting raster cell values will be 0, 1 or 2:

0 = elevation below 2,000 ft and facing W, E, N, NE, NW
1 = elevation above 2,000 ft and W, E, N NE, NW OR south facing and below 5000 ft.
2 = elevation above 2,000 ft and south facing

In the previous raster grid the middle classification value of 1 loses some meaning in that it can be one of two completely different possibilities. Changing the aspect raster to a value of 0 or 2 creates a more clear result in the final index raster.

Rasters can be combined using multiple layers to produce a final index

Reclassify the elevation raster:

0 = elevation below 5,000 ft.
1 = elevation above 5,000 ft.

Reclassify the aspect raster:

0 = slopes facing W, E, N, NE or NW
2 = S, SW or SE facing slopes
Add the two rasters

In the resulting raster cell values will be 0, 1, 2, or 3:

0 = elevation < 5000 ft and facing W, E, N, NE or NW
1 = elevation > 5000 ft but not W, E, N, NE or NW
2 = south facing and elevation < 5000 ft.
3 = elevation > 5000 ft and south facing

Rasters can be combined to include additional thematic data such as landcover. To meet our overall original criterion of elevation, aspect, and landcover, we will begin with the previous example to obtain the slope/aspect grid.

Reclassify the elevation raster:

0 = elevation below 5,000 ft.
1 = elevation above 5,000 ft.

Reclassify the aspect raster:

0 = slopes facing W, E, N, NE or NW
2 = slopes facing S, SW or SE

Add the two new rasters together

In the resulting raster cell values will be 0, 1, 2, or 3:

0 = elevation < 5000 ft and W, E, N, NE or NW
1 = elevation > 5000 ft and W, E, N, NE or NW
2 = south facing and elevation <5000 ft
3 = elevation >5000ft and south facing

This raster will then be added to a third raster that denotes landcover. The landcover grid will make it such that any cell value of 4 combine with the above grid will create a grid that designates grassland and one of the above elevation or aspect combinations. A cell value of 0 in the landcover grid will combined with the above grid will show area that is not grassland but has one of the 4 elevation/aspect classification

Reclassify the landcover raster:
0 = everything not grassland
4 = grassland

Add the elevation/aspect raster to the landcover raster together.

In the resulting raster cell values will be 0, 1, 2, 3,4,5,6,7:
0 = elevation <5000 ft, and W, E, N, NE or NW, and not grassland
1= elevation >5000 ft, and W, E, N, NE or NW, and not grassland
2 = south facing, and elevation <5000 ft, and not grassland
3 = elevation >5000 ft, and south facing, and not grassland
4 = grassland, and elevation < 5000 ft, and facing W, E, N, NE or NW
5 = grassland, and elevation > 5000 ft, and facing W, E, N, NE or NW
6 = grassland, and south facing, and elevation < 5000 ft.
7 = elevation > 5000 ft., south facing and grassland (preferred habitat of species)

The method shown would appear to solve many problems of this kind and indeed it can, however, assume, for instance, that a more complex criterion was needed and the simple numbered index would not work. We could say, for example, that we wanted an index in the end that measured elevation in 50 ft intervals and not simply above 5000 ft or below 5000 ft, perhaps because there is a particular concentration of this species at more defined elevation values and we would like to identify that. We also want the resulting grid to reflect those values so that they could be easily discerned between the 50 ft. intervals. We could say that our starting value was 1000 ft, and we proceeded from there, 1050, 1100, 1150, 1200 and so on. Instead of having so many levels of classification in the end, we can develop a coding system that can take into account our more defined elevation values.

We could use the slopes facing as:

1000000 = slopes facing W, E, N, NE or NW
2000000 = S, SW or SE facing slopes

The elevation grid would simply be the raw elevation values at 50 ft intervals say between 1000 ft and 7000 ft.

The grassland or no grassland raster would be

Reclassify the landcover raster:
The goal here would be that all of these grids could then be added together and they would all as well retain their original coding values. So let's say we had a NW facing slope on grassland and at an elevation of 5200 ft. The final grid calculation for that cell would be 1105200. What will happen with this is that, of course not every cell will be unique, and the resulting data column in the grid can then be sorted. Some values will be the same, some will not. Then the grid can either be reclassified according to a finer level of classification, or you can simply go to the legend editor and manually define classes. Say for instance you wanted 20 classes instead of 7 in the previous example, or you wanted to take this end result and export the data of just land that was south facing, between 5000 ft, and 5500 ft, and grassland. That could easily be done by selecting the data and exporting it out into a new grid. The selected data would appear as following and would each have a number of cells associated with each classification level.

2405000
2405050
2405100
2405150
2405200
2405250
2405300
A good set of numbers. This allows for a finer resolution of data that was not possible with the previous examples. It also results in a richer and more realistic grid produced in the final calculation. The data can always be binned into smaller groups if need be using the legend editor in GIS, but most importantly, the data can also be channeled into a more defined resolution if so desired and is often needed in real world classification when very broad levels of resolution are not helpful. This way also gives the data a context so that instead of simply looking at an end sum value, at least when looking at the data table, you can view the entire definition and meaning behind a cell value. This can be added with as many factors as one would like, so long as some spacer zeros or other value separates and keeps that values unique in the final calculation.

Let’s say for instance we wanted a richer set of classifications for land type. We could have forest 1,000,000, grassland 2,000,000, swamp 3,000,000, alpine 4,000,000 and desert 5,000,000. These could then be added to the other grid themes. To see more easily how this plays out, see table 6.1 as this method is applied to the geological scenario. In that case, there were 29 possible outcomes of codes that produced between various soil types and depth. They were grouped into only 4 major categories to fit the classification system. However, the codes of the data have a rich context and meaning. While this method is not always used in raster grid calculations, it is common in most database
development where unique keys and identifiers are really a series of combined codes. For instance a person may be identified in a database by the combination of a name and zip code column, such as QU80120, where a query can combine the first 2 letters of a name and zip code or other data to produce a unique value in the final column.