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A GIS-ENABLED APPROACH FOR THE RISK ASSESSMENT OF LEVEE SYSTEMS

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ABSTRACT

The failure of levees and the resulting flooding can have detrimental effects on human life and the economy of the affected regions. Due to the large scale physical extent of levee systems, soil investigation data is at best available at scattered intervals along the length and carries a high level of uncertainty. However, the spatial continuity of the results is particularly critical in levee systems since failure of a levee at any location could result in the failure of the overall flood protection system. Geographic Information Systems (GIS) are particularly suitable for the complex and efficient management of spatial information, georeferencing capabilities, geostatistical analysis, and output presentation. A GIS-enabled approach for the risk assessment of levees systems is presented. It uses available soil parameter data at finite locations as well as information of the underlying geology, and provides a system-level risk assessment. A levee system in Northern California is used as a pilot study for the proposed approach. Excessive underseepage and loss of freeboard due to soil liquefaction are evaluated as the two possible modes of levee failure.

Introduction

Flood protection systems are important parts of society's civil infrastructure in the United States. The vast majority of U.S. river cities, now growing at increasing rates, are protected from flooding in large part by earthen levees. Present day earthen levees are at risk from many causes of failure including seepage (both underseepage and through seepage), erosion and seismically-induced instability. Recent natural disasters like Hurricane Katrina have demonstrated the need to maintain and upgrade the aging and deteriorating flood protection systems. Furthermore, the American Society of Civil Engineers (ASCE) recently released a summary of its 2009 Infrastructure Report Card (ASCE 2009) and levees, received a D-, the lowest grade of all infrastructure.

One of the greatest challenges in evaluating the vulnerability of flood protection systems is that they are complex, interconnected, human-adaptive engineered systems requiring a

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systematic consideration of many factors as part of a rigorous and unified approach. Failure at one location means failure of the entire system. However, even though levees stretch for long distances and are in part formed through various geomorphologic processes and human activities over time, information regarding soil properties is collected only at limited point locations and can vary significantly both laterally and with depth. Hence, the prediction of the performance of levees in locations where no soil data is available becomes a limitation for system risk assessment studies. Of particular interest to seismically active regions is the uncertainty in the dynamic response and performance of levees. This response is dependent on the seismic event itself, as well as the levee geometry and the properties of the levee materials and the foundation soils.

This paper presents an approach for the risk assessment of levee systems. A geostatistical model for soil variability of levee material and underlying foundation is proposed for riverine and deltaic geologic environments. Geographic Information Systems (GIS) is used as an analytical platform for its ability to manipulate and query georeferenced data, its spatial correlation and analysis functions, integrated database, and advanced result presentation capabilities.

The direct application of GIS in studies and projects involving levees has been mainly limited to mapping and simulating the flooded areas, as well as using GIS as a database for soil investigation locations, data, and maintenance records. GIS as a tool can assist floodplain managers in identifying flood prone areas in their community, and implementing mitigation or management practices. Yamaguchi et al. (2007) developed a GIS-based flood-simulation software, due to overtopping only of river levees, that can be applied to risk assessment in adjacent floodplains. No consideration was given in modeling geotechnical failures of levees. A "Spatial Decision Support System to Optimize Inspection, Maintenance, and Operations of River Levees" was developed by Serre et al. (2006) and was applied on a limited section of levees in France. The input was from field observation cards and included items such as roots in impervious shoulder, scour, pipes going through levee, roots in body of levee, potential seepage, etc.

The Department of Homeland Security's Federal Emergency Management Agency (FEMA) has developed HAZUS-MH (acronym for Hazards U.S.-Multi-hazard); a risk assessment methodology for analyzing potential losses from floods, hurricane winds and earthquakes. However, the flooding scenarios in HAZUS-MH are a result of river water level variation and river bank or levee overtopping. Furthermore, earthquake losses do not include failure of levees, and thus do not reflect potential flooding due to such types of seismically-induced failures.

Variability and Uncertainty of Soil Parameters

Soils and rocks in their natural state are among the most variable of all engineering materials. The variability in ground properties, not only from site to site and layer to layer, but even within a single unit is a three dimensional problem that involves the vertical stratification at any given point, as well as the planar deviations within a specific layer. In the absence of unlimited resources that would permit very large numbers of boreholes and tests, geotechnical engineers find themselves most of the time having to deal with very limited site investigation data. The traditional approach in dealing with this limitation in design has been to use characteristic values of the soil properties combined with a factor of safety. However, similar type data sampled at multiple locations on a site would likely plot in a bell-shaped curve. The precision of soil parameters values depends on (a) the reliability of the sampled results, and (b) the estimation of values at unsampled locations. The reliability of measured soil specimen properties depends on the number of samples obtained as well as the testing methods and equipment used. The estimation of values at unsampled locations is done using a kriging approach that takes into account spatial clustering and correlation of known data and tries to establish trends based on other available attributes. This is achieved using the Geostatistical Analyst tools available as an ArcGIS software extension.

Objective

This paper presents an approach for a unified assessment of vulnerability of earthen levee systems by developing a GIS-based computational platform that accounts for spatial variability of the soils and includes refined slope stability and liquefaction hazard assessment models, specifically tailored to earthen levees. The main assumptions for the study include a simplified soil characterization of the levee and foundation material, as well as a simplified determination of the probability of failure. Two critical levee modes of failure were investigated: underseepage and soil liquefaction. Despite these assumptions and simplifications, the pilot study serves as an illustrative example of the application of the proposed methodology.

The seismic hazard exposure of the flood protection system in California makes the area specifically appropriate for a pilot study for both modes of failure. A representative region was chosen for the pilot study with a levee system surrounding and protecting a city in Northern California. The area is representative of the region which constitutes the greatest population density in Northern California and carries more than 25% of the nation's annualized risk (FEMA 2008).

Data Collection and Definition of Levee Components

The input data needed to analyze the response of an earthen embankment and assess the risk for the protected areas is divided in three main categories: (1) soil properties at select locations (e.g. unit weight, γ, friction angle, Φ, cohesion, c, small strain shear modulus, G_{max}, shear wave velocity, Vs, shear modulus reduction vs. shear strain curves, and damping ratio vs. shear strain curves), (2) seismic intensity measures (e.g. peak ground acceleration, PGA), and (3) study area attributes (e.g. underlying geology, river meandering and migration pattern).

The data in this study has been collected from a number of sources such as (1) national datasets for surface soil data, elevation, surface water bodies, population census data, (2) local sources for city limits and infrastructure, (3) geotechnical soil investigation reports, and (4) the USGS national seismic hazard maps.

The levee system has been defined as the collection of earthen embankments with a corresponding delineated protected area. The system has a number of nodes, or points, that define its geometry and have specific characteristics: end nodes, intersection nodes, intermediate nodes, data nodes, etc. The levee system is further divided for analysis purposes into segments, which are generally defined as a stretch of levee between two consecutive nodes. A schematic of typical cases of the proposed node classification and levee segmentation are shown in Fig. 1.

Data processing was performed using the ArcGIS platform commands and model builder feature. This consisted of digitization of the underlying geology layers from scanned hand-drawn maps of the region, digitization of soil test locations and collection of known soil properties of the levees at various test locations from a hard copy soil investigation report borehole logs and cross-sections, and finally the determination of the geometric layout of the levee centreline by tracing the highest contour lines and matching with aerial imagery and other information (Fig. 2).

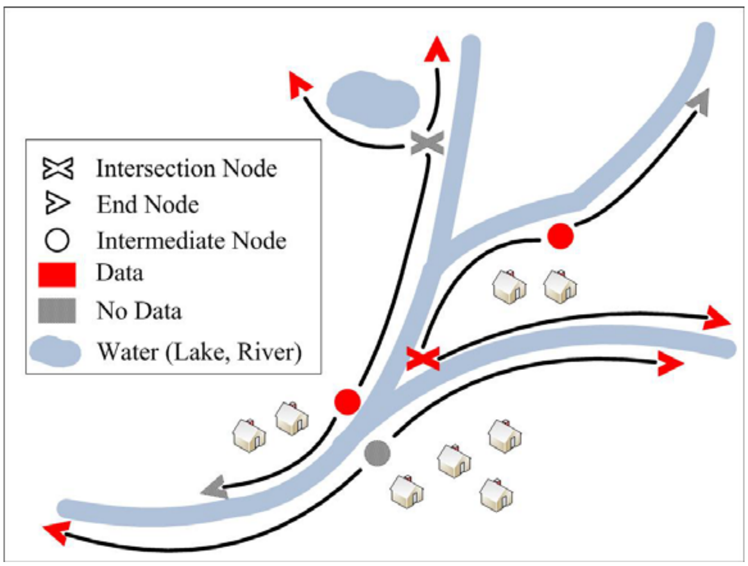

Figure 1. Proposed node classification and levee segmentation.

Geostatistical Spatial Modeling of Soil Parameter Variability

In the development of the geostatistical spatial variability model a number of factors were investigated for possible correlation with the spatial variability of the levee and underlying foundation soil material properties. The study of landforms, such as naturally formed levees, and the history of formation and dynamic processes that shape them are referred to as geomorphology. Given that, for instance, soil liquefaction does not occur randomly but is rather restricted to areas with a narrow range of geological and hydrologic characteristics, most liquefaction occurs in areas of poorly engineered hydraulic fills and in fluvial deposits less than 1500 years old (Fookes et al. 2005). In addition, natural levee development and dynamics has received relatively little fluvial geomorphic study (Kondolf et al. 2003). As such, the study of the complexity of a river's geomorphology is important in determining the type of sediments and where they were deposited, and information from the work of Helley et al. (1985) was used to determine the appropriate segmentation level of the adjoining levee system.

Furthermore, a relatively straight river section is expected to have less variability in the deposited material properties than a section that is meandered where the deposition would be irregular, justifying additional segmentation of the adjacent levees. The meander ratio, or sinuosity index (SI), is a means of quantifying how much a river or stream meanders i.e. it measures the deviation of a river path length from the shortest possible path. Because of lateral migration of meandering streams, levees should theoretically be placed at a fair distance from migrating channels (Julien 2002). However, this is not always the case, especially in urban areas where insufficient space forces the building of levees at the edge of the stream. Thus it becomes important to determine the levee parts located in the highly meandered river sections in order to give them special attention in the analyses.

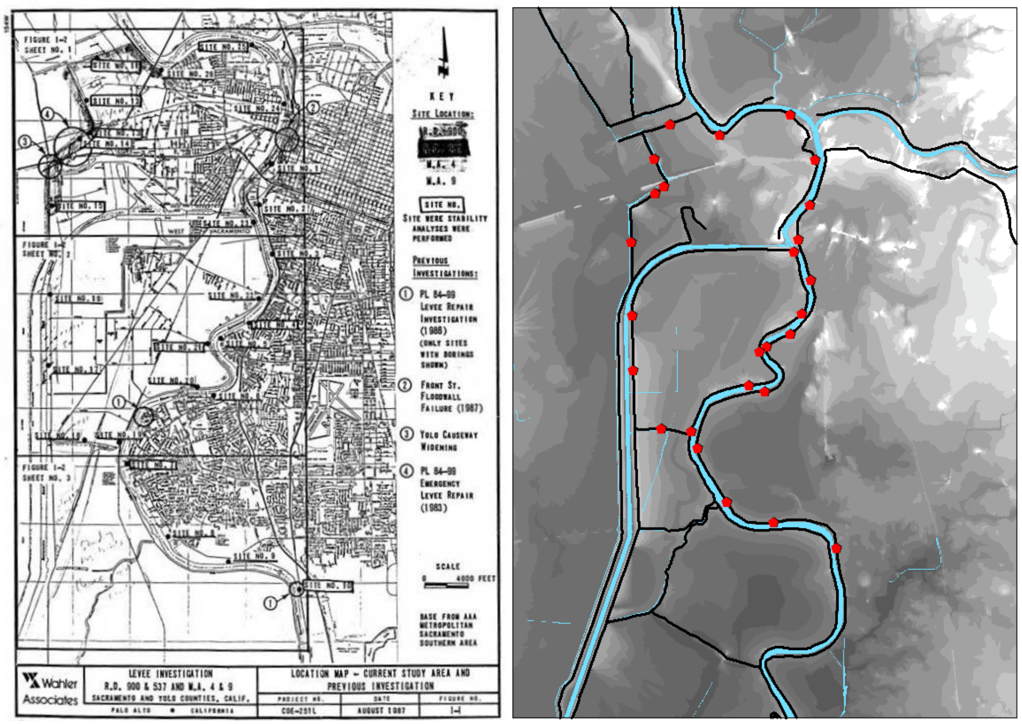

Figure 2. Levees (bold black lines) and soil test locations (red dots) represented in ArcGIS software environment with corresponding boring investigation data.

The levee system was divided into segments based on spatial correlation between the levee material and the underlying geology. The effect of the sinuosity index will also be included in future work. Estimation of soil characteristics along the resulting levee segments was done using the Ordinary Kriging approach, where, for a certain parameter, the estimated values Z^* at a location u are calculated as:

$$Z^*(u) - m(u) = \sum \lambda_\alpha(u) \left[Z(u_\alpha) - m(u_\alpha)\right] \quad (1)$$

where $m(u)$ is the estimated global mean of the parameter, α is the number of locations where the parameter is known, $Z(u_\alpha)$ are the values of the parameter at the known locations, $m(u_\alpha)$ is the mean of the known parameter values, and $\lambda_\alpha(u)$ are weights obtained by solving a system of linear equations such as to minimize the error variance σ_E^2 = Variance [Z*(u) – Z(u)]. A sample output of the kriging approach for the estimation of the shear strength of the levee foundation clay material is shown in Fig. 3.

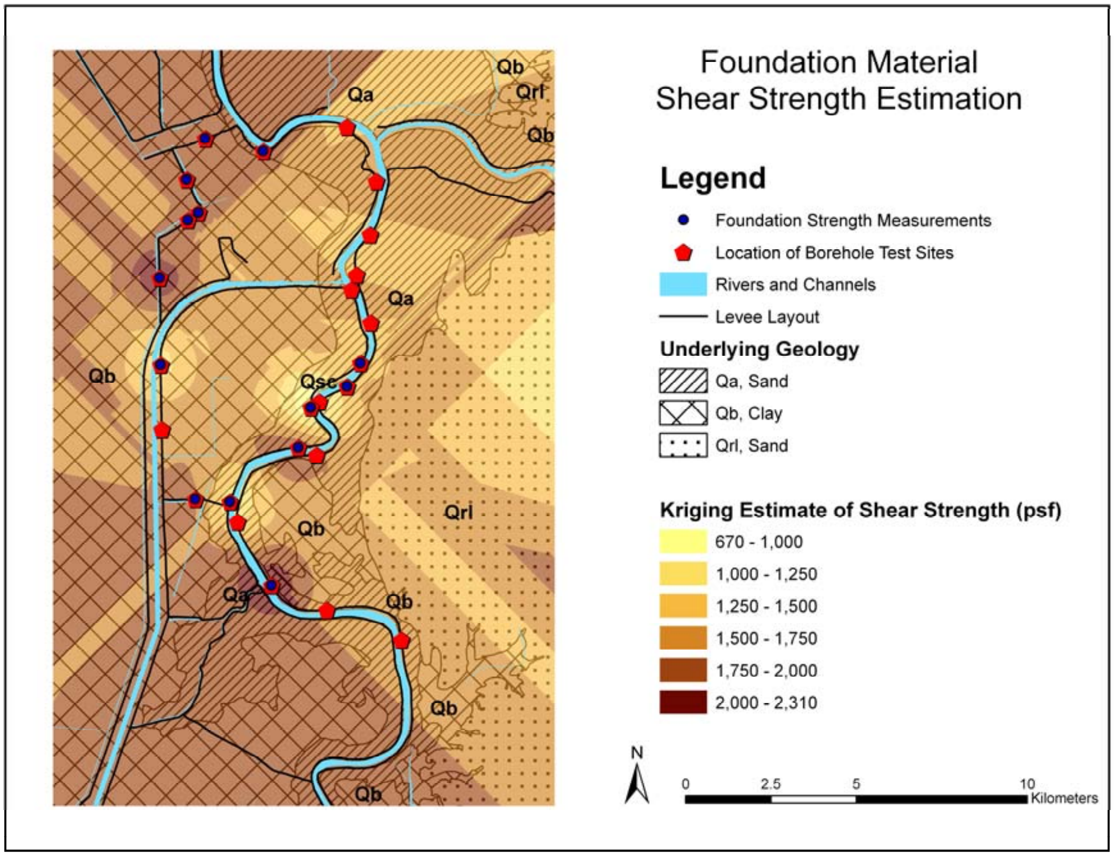

Figure 3. Kriging estimation of shear strength of the foundation layer along levee segments

Response of Levee Segments

As previously mentioned, two critical failure modes of levee failure were considered in this study: failure due to excessive underseepage and failure due to liquefaction of the levee material or the foundation soils. Spatial joins were used to combine the levee and foundation material attributes (Fig. 4). For simplicity at this stage of research, levee material was classified as a single layer (sand or clay) based on the major overall impression from soil investigation borehole data through the levee. The underlying geology map was used as the foundation layer, and similarly classified in a rudimentary manner (sand or clay).

Underseepage is one of the most common causes of levee failure that can occur either in the levee material or the underlying foundation. Sands, loose and dense, have a higher permeability than clays, and thus are more prone to this particular mode of failure. Furthermore, deeper sand layer constituting the foundation under the levee will have a higher hydraulic gradient and thus will be more critical for underseepage than the case of sand in the levee itself.

For seismic events, analysis for levee loss of freeboard due to soil liquefaction relies on pre-established typical levee cross-section analysis (Athanasopoulos-Zekkos 2008) by (1) characterizing the levee at each location as one of many typical levee cross-section profiles, (2) inputting the specific geometric characteristics and soil parameter values specific to the levee and foundation layers at that location, and (3) evaluating the distribution of the Cyclic Stress Ratio (CSR) - a measure for probability of triggering of liquefaction- for the levee cross-sections.

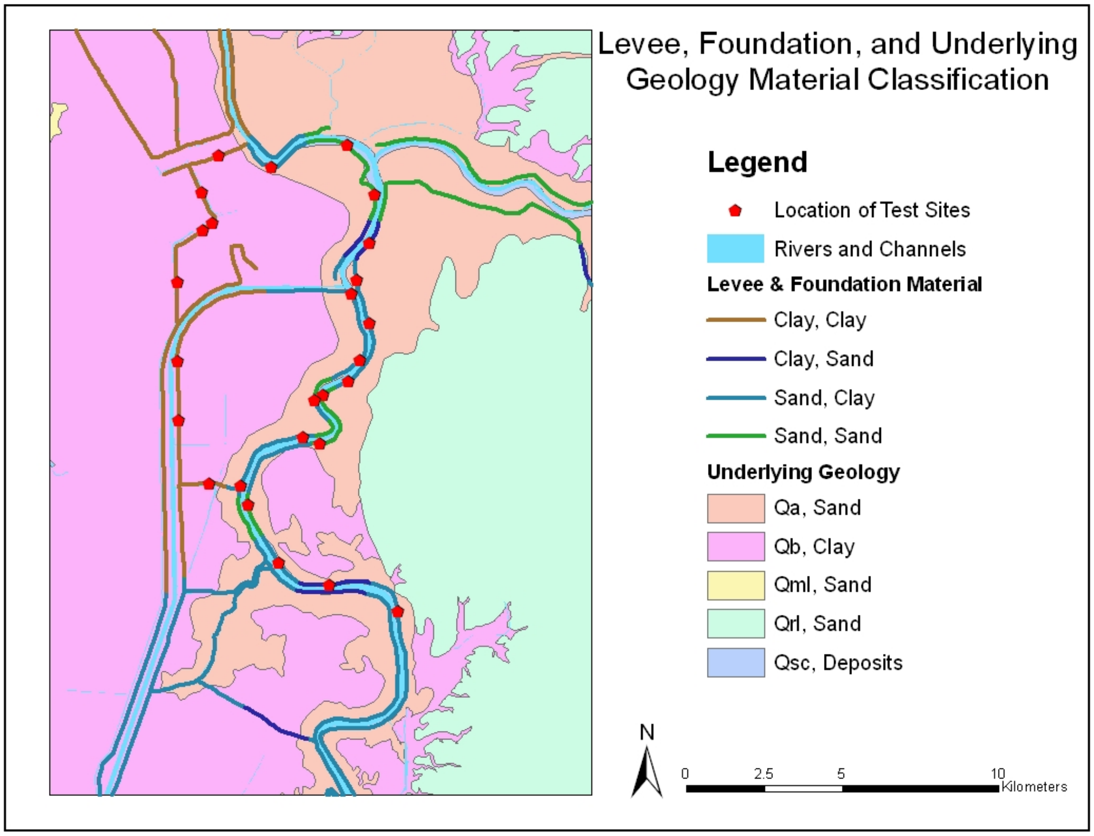

Figure 4. Levee and foundation material classification with underlying geology of the study area.

A simplistic failure probability estimation criterion was used for this first order analysis. Each soil layer combination, in this case the levee material and the foundation soil, is given a qualitative measure of failure potential due to either excessive underseepage or liquefaction. Results from the analyses are shown in Fig. 5, and the criteria used in the initial analysis maps are summarized in Table 1.

Table 1. Simplistic failure criteria used for underseepage and liquefaction.

Levee Material	**Clay**	**Sand**	**Clay**	**Sand**
Foundation Material	**Clay**	**Clay**	**Sand**	**Sand**
Underseepage	of no concern	of little concern	of some concern	of concern
Liquefaction	of no concern	of some concern	of some concern	of concern

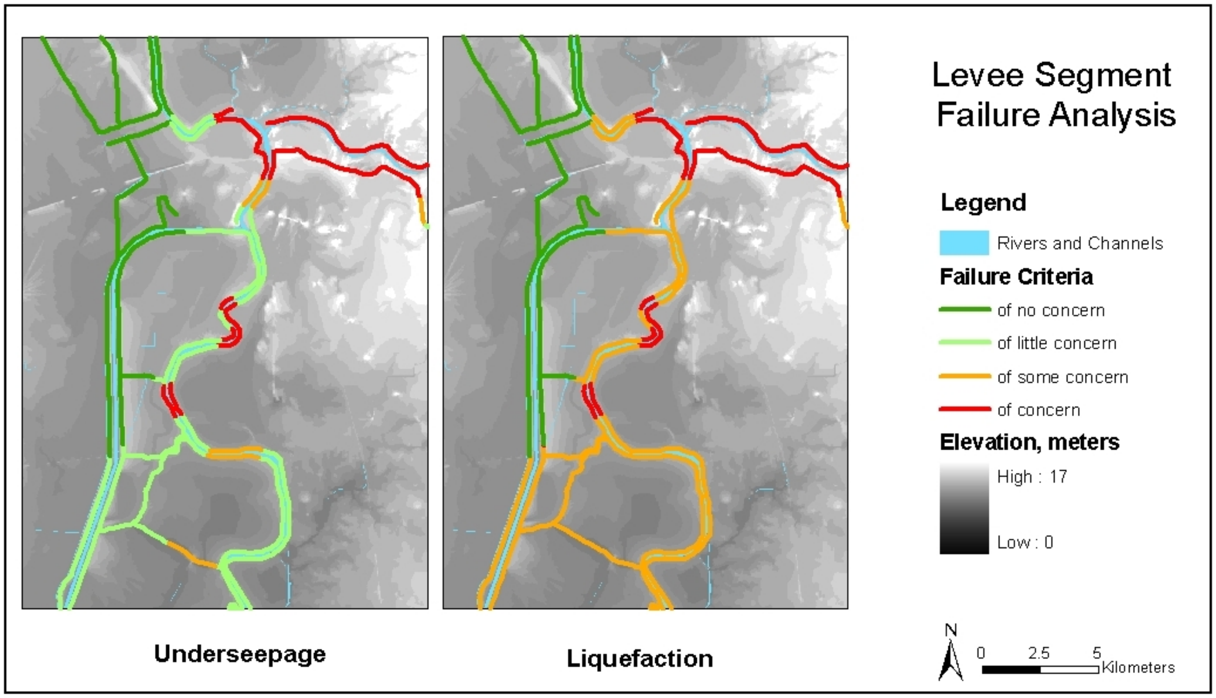

Figure 5. Results for failure analysis due to underseepage and liquefaction.

Flood Scenarios, Damage Forecasting, and System Risk Assessment

The next step consisted of modelling the possible flood scenarios for all levee segments and then using a colour code for flooding of segments of either no, little, or more concern for failing due to both excessive underseepage and liquefaction. This was done using terrain slope and flow patterns obtained by analyzing a 10mx10m digital elevation model data. This was mainly achieved using the ArcGIS watershed tool, among others, in the model builder environment. This tool calculates all the area contributing flow to a particular point at a lower level. Since levees are at a higher level than the adjacent land, and the objective is to get the area where water would flood (as opposed to water collecting downstream an area to a point), a digital elevation model was inverted, and the watershed tool was applied to it with water flowing towards the levee locations where failure would occur. The resulting flood scenarios for all levee segments, using the two considered methods of failure, were consistent with the landscape and terrain properties and are shown in Fig. 6. Note that the presented flood model does not simulate the effect of water accumulation in the flooded areas, nor does it indicate where the water would ultimately go after a steady flow for a period of time. The model assumes that all the levee section that has failed is completely non-existent physically - which is a worst case scenario, thus these calculations are conservative.

Flooded areas, as determined in the previous step, were combined and overlapped in the GIS platform with population data and presented in a 3D format using the ArcScene software. This step is performed to show the ease of visual representation and usefulness of the proposed work in helping decision makers and engineers to plan maintenance, repair, and emergency response operations (Fig. 7). Finally, individual segment and overall levee system risk measures are assessed as a function of response analysis and resulting damage estimation by developing fragility curves for a range of ground motion intensities.

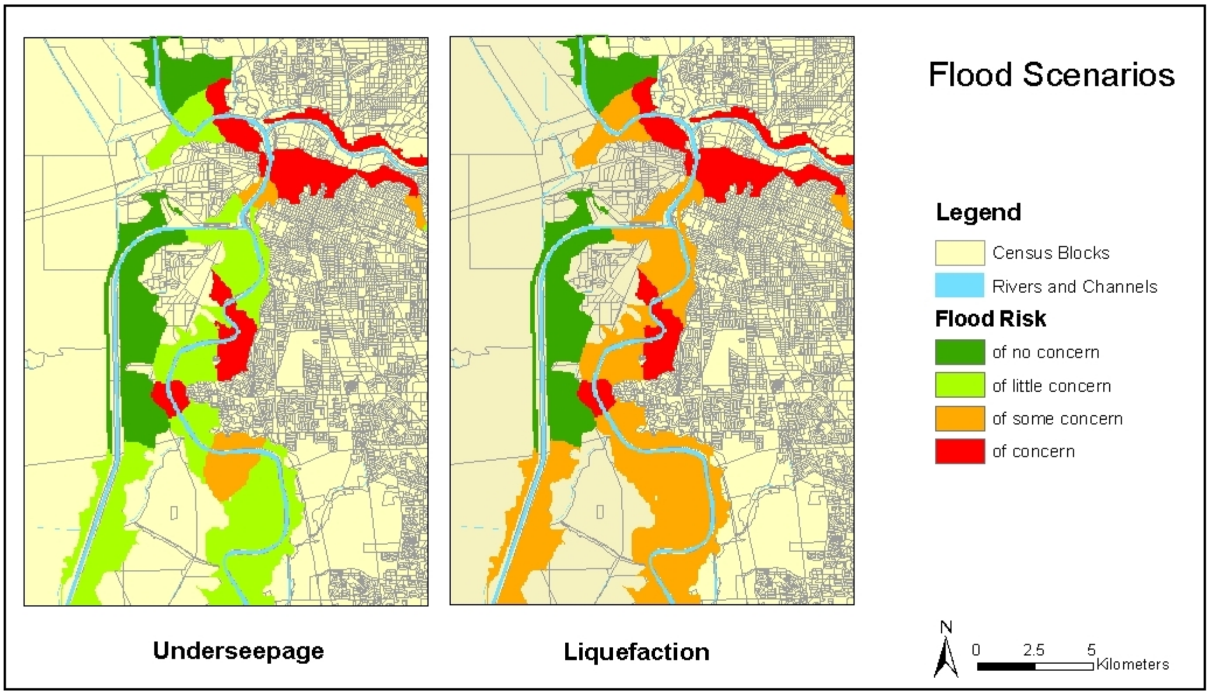

Figure 6. Flood scenarios from underseepage and liquefaction failures for all levee segments.

Conclusions

The proposed approach, even though simplified, offers a first-order estimate of the spatial vulnerability of a levee system and an efficient visualization of the results, thus enabling decision makers to quickly identify critical regions. This is achieved by combining a geostatistical model of spatial soil variability with simplified approaches for estimating underseepage and soil liquefaction levee vulnerability. Finally, GIS is used as the platform for manipulating and presenting information. A number of simplifications and assumptions have been made in order to complete the above analysis. This mainly involves the estimation of soil properties along the levee segments between the points with “known” properties, and to a lesser extent the determination of the exact flooded areas. The soil properties’ variability issue needs to be addressed using a more detailed geostatistical spatial analysis approach in the future.

More precise elevation data for the pilot study have also recently become available with an improved resolution of 1/9 arc second (~ 3 meters). The California Department of Water Resources (DWR 2009), partnering with FEMA, is assembling critically needed levee information on geometry, landmarks, test locations, history, etc for all the levees in the state. This is an ongoing project and information was not available at the time of this study, and thus the analysis relied on the manually digitized layout of levees.

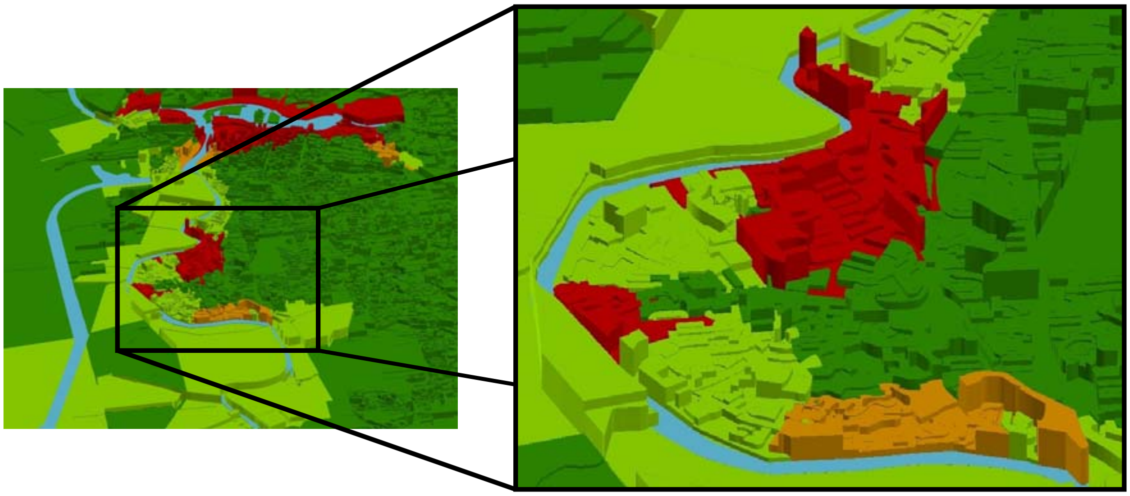

Figure 7. A 3D representation of population density (different heights) at the census block level, with flooded scenarios from underseepage levee failure (different colors)

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