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Applications of GIS in Geotechnical Engineering: Some Case Studies

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Abstract— *Geographical Information System is a very effective tool for capturing, displaying and analyzing geographically referenced data. GIS has shown a very important role in various aspects of geotechnical engineering including preliminary site investigations, identification of potential project barriers (like mines etc), interpolation for obtaining data at inaccessible locations, data visualization, data processing as well as preparation of post processing graphs and charts. This paper highlights some of the case studies ranging from soil survey planning to soil management, and furthermore, hydrologic response unit generation using GIS. The results illustrate the vast potential of GIS towards effectively resolving geotechnical engineering problems under diverse scenarios. Future research is being carried out in the areas of soil mapping using GIS, expert knowledge and fuzzy logic.*

Keywords— *Geographical Information System, geotechnical engineering, site investigations, project barriers, hydrological response unit generation.*

Disclaimer— *The views expressed in this paper are strictly individual views of the author and do not, in any way, represent the views of the department/organization where they are presently working.*

I. INTRODUCTION

Geographical Information System is a very effective tool for capturing, displaying and analyzing geographically referenced data. GIS is different from other Information Systems insofar as it contains geographically referenced data consisting of spatial data component which defines location, and attribute data component which defines characteristics (Chang, 2006). GIS has shown a very important role in various aspects of geotechnical engineering including preliminary site investigations, identification of potential project barriers (like mines etc), interpolation for obtaining data at inaccessible locations, data visualization, data processing as well as preparation of post processing graphs and charts. Geotechnical information acquired from site and laboratory tests are vital for a safe and economical design of building and infrastructure works especially in land development projects (Mohamad and Ghani, 2011). Hence GIS finds its applications at all the stages of a geotechnical engineering project.

II. GIS APPLICATIONS IN GEOTECHNICAL ENGINEERING

In geotechnical practice, GIS can be used in at least four ways: data integration, data visualization and analysis, planning and summarizing site activities, and data presentation (Player, 2006).

Data Integration

In geotechnical practice, the conventional approach to data integration for working site model creation can be an arduous task. Existing data sources are found in a variety of hard copy, electronic, and paper formats such as maps, plans, reports, books, aerial photos, etc. Integrating these data together with photos, notes, borings, and other site-specific data can require a significant effort. Less time may be spent on data analysis and acquisition than on data integration. Also, making copies of the work may take as much time as the initial production and yield unprofessional looking or illegible results. Using GIS as a tool can greatly improve the efficiency and effectiveness of these efforts.

GIS provides tools for integrating these multiple data types such as raster format data (e.g. photos and scanned maps) and vector format data (e.g. computer-aided drafting (CAD) files, northing and easting point files, drainage lines, etc.). This data may consist of readily available existing information such as soil surveys and topographic maps, or project specific information such as proposed centerlines, project extents, survey points, aerial photos, and site investigation results. Many federal, state, and local agencies provide wide-ranging types of GIS data for download on the Internet.

When integrating data from various sources, two important considerations are data limitations and data coordinate systems. Each data set has inherent limitations. The source of the data must be considered; positional accuracy may vary from tenths to hundreds of meters, and the applicability of the data to their intended use also needs to be considered. The site model is only as accurate as its components. In some cases, the data accuracy may be inadequate for detailed design, however it may be more than adequate for preliminary investigations.

For disparate data sets to be integrated, each must be converted to the same base coordinate system. Readily available data sets may utilize a coordinate system such as the Universal Transverse Mercator (UTM) with varying datums. Project specific data sets may use a standard coordinate system (such as State Plane) or a project specific system. Most GIS programs contain routines for performing coordinate transformations relatively simply to enable integration of data sets having different coordinate systems.

Data Visualization and Analysis

After data has been integrated into a working site model, the model can be used to visualize site data and analyze the site. This model is continually refined as more information is gathered and integrated into the existing model. One of the primary benefits of using GIS in this effort is its flexibility. Data layers can be combined and turned on and off as needed. Data can be symbolized to graphically represent relationships and queried to filter out extraneous information. Spatial queries can be performed to identify the relationships between features and help to determine engineering conclusions. For example, buffers of varying distances around features can be created to identify other features within critical proximity (e.g. drinking water wells within a specified distance from a leaking underground storage tank) or create an exclusion zone (e.g. not advancing soil borings within 8 meters of a sensitive wetland).

GIS can be used to identify project constraints and potential barriers to successful project completion early in the design process. Early identification of these barriers can avoid costly and time-consuming changes after significant site design has been completed. Depending on the data sets, some potential geotechnical issues that can be identified include weak and/or compressible soils (e.g. from soil surveys); potentially unstable slopes (e.g. from topographic maps); distance to and type of borrow sources (e.g. from road networks and soil surveys); geologic hazards (e.g. from aerial photos, geologic and topographic maps, soil surveys); environmental hazards (e.g. from underground storage tank location maps); etc.

Planning and Summarizing Site Activities

After identifying in the office potential problem areas or areas needing further study, GIS can be used for both planning site activities and to integrate data collected during these activities into the site model, thus further refining it. In the GIS site model, boring and test pit locations can be planned, field reconnaissance locations noted, and maps, layouts, and figures can be created for use by field personnel. Global Positioning System (GPS) coordinates and/or project specific coordinates for investigation locations can be exported to guide surveyors and field staff in locating features and laying out investigation programs.

During field work the locations of features can be captured using GPS, swing ties, offset distances from known features, etc., which can then be imported to GIS for integration into the site model. Digital photos taken during field activities can be linked to map features. Descriptive database tables can be created and linked to boring location maps to provide searchable features or scanned boring logs can be linked for retrieval through GIS.

Data Presentation

Another benefit of using GIS is data presentation. Layouts can be created for use in reports, papers, posters, and presentations in varying page sizes and formats. Labels, symbols, scale bars, north arrows, and text can be added to maps to provide clarity and improve information transfer. This capability provides an excellent communication tool between office and field staff, consultants and their clients, field crews and utility locators, etc. Professional looking figures can be created for reports that are editable and reproducible (Player, 2006).

In the present study some of the case studies ranging from soil survey planning to soil management, and furthermore, hydrologic response unit generation using GIS have been illustrated.

III. GIS APPLICATION FOR ROADWAY ALIGNMENT

CH2M HILL was contracted by the Iowa Department of Transportation to design a bypass of U.S. Highway 34 around Ottumwa, Iowa (Player, 2006). The proposed Ottumwa Bypass corridor is located in area of actively eroding slopes and steep drainage ways feeding into the Des Moines River in Southeastern Iowa. This area also was extensively mined for coal from the late 1800s to the middle of the 20th century. As a result, potentially unstable slopes and former coal mines were concerns as the roadway alignment was being refined. A site model was created using GIS to identify areas of concern in relationship to the alignment and their potential impact on the alignment was analyzed. A database showing the locations of historic coal mining activity was obtained from the Iowa Department of Natural Resources. An 800-meter radius buffer was generated around the proposed alignment, and the model was searched for coalmines near the proposed alignment. It was determined that one mine (the Chet Akers Coal Mine) fell near the proposed location of an interchange, prompting further field investigation. Also of concern was the occurrence of unstable slopes along the alignment. Through GIS, digitized soil survey information was added to the base map and the model was queried for slopes in excess of 20%. These slopes were found at one location along the alignment within the footprint of the proposed road. This also prompted further field investigation which resulted in a realignment of the roadway to avoid the potentially unstable area (Player, 2006).

GIS was also used to in a preliminary geotechnical site investigation for the Resource Transportation Analysis (RTA) Phase II - Dalton Highway to Nuiqsut and the National Petroleum Reserve Alaska (NPR-A), performed by CH2M HILL for the Alaska Department of Transportation and Public Facilities (AKDOT&PF). The purpose of the RTA Phase II study was to identify a feasible route for an all-season road from the Dalton Highway to Nuiqsut and the resources of NPR-A. One of the major project constraints was availability of granular material for road construction. Regional geologic maps, aerial photos and satellite imagery, hydrologic networks, existing trail systems, oil field industrial roads, pipeline routes, land use, government entities, and environmental information were integrated using ArcGIS 8.2. Using this GIS model, preferred road corridors were reviewed for geotechnical considerations and, based on depositional environments and geomorphic condition, potential material sites were identified for further exploration prior to any field visits (Player, 2006).

IV. GIS APPLICATION FOR VIBRATION AND SETTLEMENT MONITORING PLAN

GIS was also used to integrate data to develop a vibration and settlement monitoring plan for the Interstate 5 (I-5) High ccupancy Vehicle (HOV) Design/Build Project in Everett, Washington, currently being designed and constructed by the Atkinson CH2M HILL Joint Venture (PLAYER, 2006). This project is located in a highly developed urban/suburban area with existing structures located close to the project right of way. CAD maps of existing and proposed features, GIS databases of local streets, parcels, structures, and other features, and aerial photos wereintegrated using ArcGIS 9.0. Threshold distances for monitoring of vibration and settlement were established and the GIS model was used to identify locations and types of proposed construction activities, proximity of existing structures, and names of potentially impacted property owners (Player, 2006).

V. GIS APPLICATION IN SOIL SURVEY PLANNING

Soil surveys are now being created in digital format to utilize the power contained in GIS technology (NRCS, 2011). In addition, NRCS is currently converting original published surveys into digital format. This process is called Soil Survey Geographic Database (SSURGO) certification. The SSURGO surveys allow customers to utilize soils information in a variety of ways. Custom data queries and map making are just two of the advantages of using a GIS.

The Arizona Soil Survey Program is utilizing GIS technology to support the needs of many customers both internal and external. NRCS employees are now able to use the digital soil information to create highly accurate conservation plans in a more timely manner. Soil maps can be created in a fraction of the time that it used to take. In addition, custom soil data queries can be addressed easily.

Customers outside the agency are finding ways of using the digital soil data as well. In January 2000, a map depicting shrink/swell potential for soils in the Phoenix area was published in a newspaper article on construction problems associated with shrink/swell soils. This map was made available on the web and had thousands of viewers. In February 2002, a similar map for the greater Tucson area was printed and posted on the web. These GIS products are playing a valuable role in the education of consumers and developers on the issue of expansive soils (NRCS, 2011).

VI. GIS APPLICATION IN SOIL MANAGEMENT PLANNING

The objective of the project was to create a soil data base, to carry out soil management plans at regional and national level and to analyse fertilizer use and prospective fertilizer consumption (Arcak et al., 2011). The project region was located south-east of Ankara, Turkey and comprised an area of about 260 000 ha. The initial 1:25 000 semi-detailed soil maps were reduced to 1: 100 000 scale. Mapping units were great soil groups and their phases. Each unit specified the great soil group; soil depth; slope gradient; erosion degree; drainage, salinity-alkalinity class; stoniness; rockiness; land use capability class and subclass and land use. In addition to these data, each unit was examined separately for the purpose of establishing the general NPK and pH status. To begin with the 1:100 000 scale map was digitized so that polygons were formed. A total of 427 polygons were identified and tagged. Then, attribute tables were created as Microsoft Excel files. Queries were based on the above-mentioned soil characteristics. At the end of each query layers were formed for each characteristic and a map of each layer was created (Figure 1).

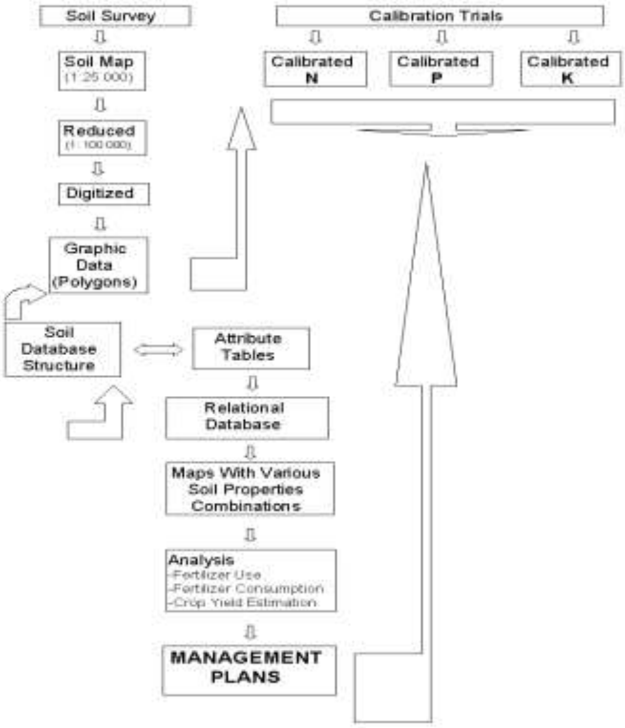

Fig. 1 Methodology of the case study

Calibrated fertilizer values for certain crops gathered by means of experiments and the amount of nutrients (NPK) available in the soil were combined to find out about nutrient deficiency in each unit and the whole area for specific crops. The soil erosion map which was generated during the course of the project has been shown in Figure 2.

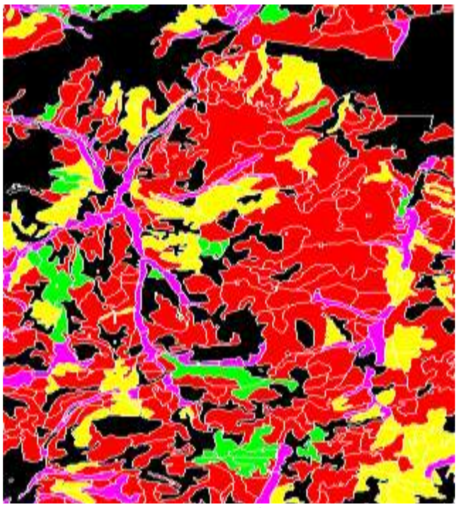

Fig. 2 Soil erosion map for the study area.

The project has demonstrated that for a successful management plan for rational utilization of land resources, Geographic Information Systems are of great importance to planners. The use of GIS in management plans results in a sound implementation in which, accuracy, reliability and easy manipulation of huge quantities of data can be attained which makes it a qualified tool to be used in this field (Arcak et al., 2011).

VII. GIS Application in Hydrologic Response Unit (HRU) Generation

Each unique combination of land use and soil class constitutes a "Hydrologic Response Unit" or HRU. Subdividing each sub watershed into unique land use and soil class combinations enables any hydrological model to reflect the differences in evapotranspiration and other hydrologic conditions for different land covers/ crops and soils. Runoff is predicted separately for each HRU and routed to obtain the total runoff for the watershed. This increases the accuracy of the water yield predictions and provides a much better physical description of the water balance.

In the present study, Cauvery basin in India has been taken as the study area (Figure 3) and the entire basin has been subdivided into 42 subbasins (Singh, 2008). There are two options of determining the HRU distribution. In case a single HRU is to be generated for each subbasin, the HRU is determined by the dominant land use class and soil type within each subbasin. However, in case multiple HRUs are required within each subbasin, a two step procedure is followed. Firstly, land uses are chosen. Once the land uses to be modeled are determined, the different soils for each land use are chosen. One HRU is created for each unique land use/ soil class combination. In the present case, since more accuracy is desired, multiple HRUs are chosen within each subbasin. After fixing the threshold levels, a total of 231 HRUs have been obtained. These HRUs have been further utilized for watershed delineation and subsequent analysis.

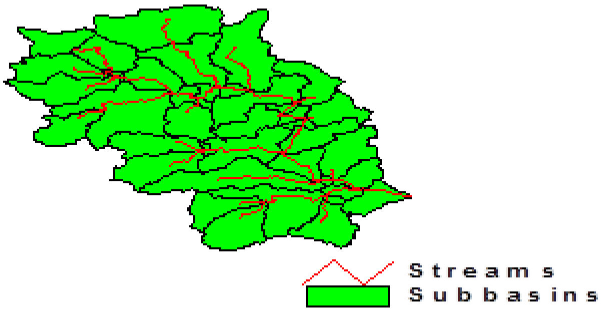

Fig. 3 Delineated Cauvery basin and its subbasins alongwith the generated stream network

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On February 28, 2001 a significant earthquake (Mw = 6.8) shaking over a The National Science Foundation-Pacific Earthquake O occurred in the Puget Sound area of western Washington. Christened the Nisqually earthquake, this intraslab subduction zone event occurred along a high-angle normal fault, due to downdip tension in the subducting Juan de Fuca Plate. It was similar in mechanism and magnitude to the Puget Sound earthquake of April 13, 1949 (Mw = 7.1) and the Seattle earthquake of April 29, 1965 (Mw = 6.7). The hypocenter for the earthquake was located 52 km beneath the southern tip of Puget Sound, about 8 km east northeast of Olympia. The Nisqually earthquake produced strong ground wide area and caused noticeable damage in the Olympia, Seattle, and Tacoma areas of the Puget Lowland in Washington. No fatalities are directly attributable to the earthquake, but damage was estimated at $2 billion (Bray, et al, 2001). Although the intensity of ground motions was not especially severe, dozens of buildings were red-tagged, and hundreds more were damaged. Observations of liquefaction were widespread in parts of Olympia and South Seattle, and several significant lateral spreads, embankment slides, and landslides occurred. The relatively long duration of the event and the relatively low cyclic resistances of some of the fills in the area are likely causes for the significant liquefaction and ground failure that was observed. Engineering Research Center (NSF-PEER) funded a team from U.C. Berkeley to make a preliminary reconnaissance and post their findings on the Internet, at http://peer.berkeley.edu/nisqually/geotech/. The Berkeley team used hand-held GPS receivers with onsite recordation to locate themselves and each digital ground photo that was imaged.

Earthquake Shaking Intensity Maps (Rogers and Luna, 2004)

In 2003 the Association of San Francisco Bay Area Governments (ABAG) introduced a series of shaking intensity maps, based on the most likely earthquakes that could be generated on 18 fault segments surrounding the San Francisco Bay metropolitan area of northern California (Figure 4). These were intended to depict the general risk within neighborhoods and the relative risk of earthquake-induced shaking from community to community. Each Bay Area earthquake scenario is assumed to be caused by rupturing of a single fault or fault segment. Thus, to view an earthquake intensity map of a particular area, one simply selects an area or city of interest and then selects a nearby fault as the source of an earthquake. Aerial oblique images are valuable in providing perspective and relative elevation changes that are not easily discernible on vertical images.

Fig. 4. Example photo documenting site damage, imaged along North Deschutes Parkway showing a lateral spread toward Capitol Lake, which is to the right of the photograph. All photos were georeferenced and dated (from Bray, et al, 2001).

Fig. 5. Locations where site damage was documented by the Berkeley reconnaissance team (from Bray, et al, 2001).

Fig. 6. Earthquake fault source map displayed on ABAG's web site. The active fault segments are color-coded and listed on a table.

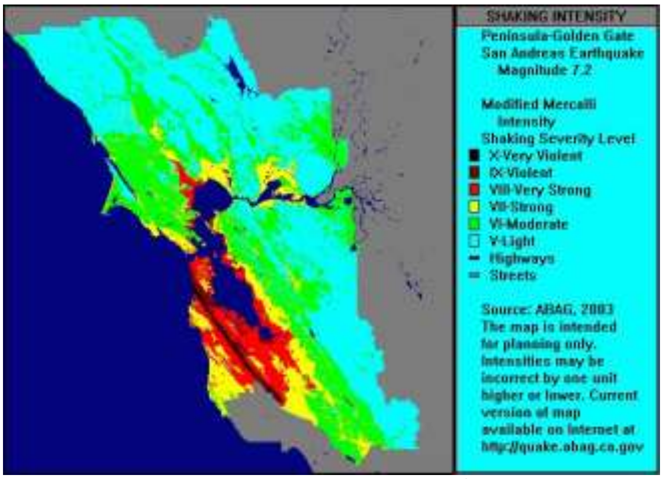

Fig. 7. Predicted earthquake shaking intensity map for Mw 7.2 quake on peninsula segment of the San Andreas fault in the San Francisco Bay area.

Figure 5 was pulled off the web and annotated to reflect locations where site damage was documented by the Berkeley reconnaissance team Each fault is shown as a color-coded line on the map reproduced in Figure 6. The most interesting scenarios are those involving multiple fault segments on the San Andreas and Hayward faults, which tend to control the peak ground accelerations expected at any given site. Figure 7 presents the shaking intensity map for an Mw 7.2 event on the peninsula segment of the San Andreas fault, similar to the type of earthquake that occurred in 1906. The linear nature of the shaking intensities is tied to the structural geologic grain of the San Francisco Bay region, which strikes northwesterly. Geologically young materials like alluvium and estuarine silt can amply ground shaking through wave impedance. These are the areas that have historically suffered the greatest shaking-related damage and ground movement. The ABAG website also presents a list of Frequently Asked Questions that includes information on the probability of various earthquakes. The purpose of the ABAG hazard maps is to educate the public, emergency response personnel, scientists, engineers, architects and decision makers about the relative risks of ground shaking in different parts of the S.

VIII. CONCLUSIONS

Geographical Information System is a very effective tool for capturing, displaying and analyzing geographically referenced data. GIS has shown a very important role in various aspects of geotechnical engineering including preliminary site investigations, identification of potential project barriers (like mines etc), interpolation for obtaining data at inaccessible locations, data visualization, data processing as well as preparation of post processing graphs and charts. This paper highlights some of the case studies ranging from soil survey planning to soil management, and furthermore, hydrologic response unit generation using GIS. The results illustrate the vast potential of GIS towards effectively resolving geotechnical engineering problems under diverse scenarios. Future research is being carried out in the areas of soil mapping using GIS, expert knowledge and fuzzy logic (Zhu et. al., 2001).

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