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Spatial Variability of Soil-Rock Interface in Chennai using Geophysical and Geotechnical data

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Abstract. Mapping surficial and subsurface conditions play an important role in analysis and design of geotechnical structures and facilities. Spatial distribution of depth to soil-bedrock interface has a prime significance in developing input ground motion at the surface and estimating damage potential of an earthquake. This paper deals with the evaluation of spatial variability of soil-bedrock interface in Chennai, south India using Multichannel Analysis of Surface Wave (MASW) test and Standard Penetration Test (SPT) data. The MASW tests have been carried out at selected locations in Chennai city using 24 channel Geode and shear-wave velocity profiles are developed. Based on the MASW test results, a shear wave velocity (Vs) of around 300 m/s is obtained for weathered/soft rock, and a value of 700 m/s for hard rock in the present study. Depths corresponding to these velocity ranges are identified to estimate the position of soil-bedrock interface in the study area consisting of IIT Madras campus and its surrounding area.

In addition, nearly 85 borelogs have been used to identify the main soil types and variation in depths to bedrock in the study area. A comprehensive geo-database containing all subsoil information has been designed to create three-dimensional borelog information and depth to bedrock interface. The spatial variability of depth to soil-bedrock interface at the locations where field measurements are not available has been mapped using spatial interpolation technique called kriging. The developed bedrock map indicates that the depth to soil-rock interface varies from 2 to 18 m in the study area. The evaluated depths to soil-bedrock interfaces have been compared and validated with the subsurface profile information obtained from a few selected borehole data and MASW test results. Further, the available SPT data can effectively be utilized for developing shear wave velocity distribution maps at different depths along the soil profile using the correlation between Vs and SPT-N values for different categories of soils of the study area. These maps will be of immense use for ground response studies and development of microzonation maps.

Keywords. Spatial variability, MASW, Shear wave velocity, SPT, Geo-database, Kriging, Bedrock map, Microzonation.

1. Introduction

A knowledge of subsurface conditions is vital in the analysis and design of geotechnical structures and facilities. In addition, it also helps in planning and execution of soil exploration programme. The depth to bedrock from the ground surface is an useful parameter in foundation studies and in ground response analysis. Determination of rock depth based on near surface velocity measurements using Multichannel Analysis of Surface Wave (MASW) test is an efficient and non-destructive way of measuring shear wave velocity and provides accurate information about the depth to bedrock. Shear wave velocity (V_s) is an important parameter representing the stiffness of the soil layer and influences the amplification behaviour of the site. The shear wave velocity can also be used for seismic site classification and microzonation studies.

The knowledge about the spatial variability of soil-bedrock interface in a particular area plays an important role in providing the complete three-dimensional (3-D) subsurface information. This data can be used to advantage in 3-D ground respond analysis for obtaining ground surface motions to estimate the damage potential of an earthquake. Hence it is necessary to determine the depth to bedrock from the ground level. In this study an attempt has been made to evaluate the spatial variability of soil-bedrock interface in the study area using Standard Penetration Test (SPT) data and measured shear wave velocities from the MASW tests.

2. Description of the Study Area

The study area has been selected in the Chennai city i.e., IIT Madras campus and its surrounding regions as shown in Figure 1. Chennai is the India's fourth largest metropolitan city, covering an area of 176 km^2 and is located between 12.75°–13.25°N and 80.0°–80.5°E on the southeastern coast of India. The city is a low-lying area, situated at an average altitude of 6.7 m above the mean sea level (MSL). The general geology of the city comprises of mostly sandy clay, shale and sandstone as depicted in Figure 1 (GSI, 1999).

From geology, the subsurface of the study area comprises of Archean crystalline metamorphic rocks (consolidated) and Coastal deposits. The major part of the study area is covered by marine sediments of thickness varying from 4 to 12 m.

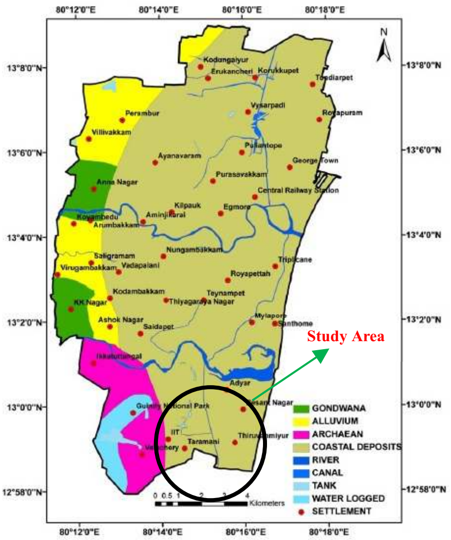

Figure 1. Geological map of Chennai

3. Development of Geographic Information Systems (GIS) Based Geo-Database

3.1. Background

The vast amount of geologic information and diverse data require a database management system for storage, analysis and visualization. In practice, geotechnical engineers strive to design structures and facilities on conditions that are interpolated from the limited borehole data of a region. Hence a database incorporating comprehensive mechanism to handle missing and unsampled data will be beneficial. Thus Geographic Information Systems (GIS), a database and an information system encompassing geographic locations, have been chosen to handle spatially variable geotechnical data and to accommodate spatial complexity associated with the subsurface information in a framework of Arc-GIS.

3.2. Data Collection

There are various data sources included in the process of collecting information for the present study. Nearly 85 borelogs from reputed geotechnical agencies and Engineering unit of IIT Madras are collected to establish the subsurface profile of the study region. The details of the borehole locations and their corresponding coordinates are obtained from the field.

The elevation values of the study region are obtained from the Shuttle Radar Topography Mission (SRTM) data with 90 m spatial resolution. The elevation data have a horizontal accuracy of ± 20 m and a vertical accuracy of ± 10 m. The base map of the study area is prepared using Arc-GIS 9.3. All the elements in the map layers are georeferenced with minimum root mean square (RMS) error and projected to WGS 1984 UTM Zone 44N (World Geodetic System 1984) using the WGS 1984 spheroid.

3.3. Standardization of Borehole Data

Chennai, a highly urbanized city presently undergoing a massive infrastructure development such as construction of roads, subways, metro railways, flyovers, multistoried buildings and ports etc. Site investigations for these construction works are managed by different soil investigation agencies including government and non-government organizations. Geotechnical investigation reports from these agencies for different projects will vary in format, type of data, style and layout. The developed database is intended to cater to the diversity that sometimes exists between the geotechnical reports.

A number of borelogs and soil investigation reports of different type of projects are analyzed and compared to reveal principal components among various borehole data. According to the comparison the borehole information can be classified into three categories: (1) General information about individual borehole, (2) Stratum information and (3) Tests and Engineering properties (Chang and Park, 2004).

General information about individual boreholes includes project description (project name and company) and borehole details that comprise of (a) Drilling details (drilling method, type of sample, start and end date), (b) Borehole location (coordinates and elevation) and (c) Geometry (drilling depth, groundwater table and hole diameter). Stratum information is divided into rock and soil information. It includes (a) Details of stratum (thickness, depth, description and engineering classification) and (b) Engineering properties (N value from standard penetration test (SPT), Total Core Recovery (TCR), Rock Quality Designation (RQD), weathering, strength, fracturing, and decomposition) (Chang and Park, 2004). Tests and Engineering properties include (a) General soil properties such as grain size distribution and weight-volume relationships from various tests and (b) Results of various laboratory tests (direct shear test, consolidation test, triaxial test, permeability test, etc.).

The purpose of standardizing the borehole data from various soil investigation reports is to find a consistent method of entry for similar types of data from different projects within the database. The database with all these information helps engineers, city developers and policy makers for future development of the city.

3.4. Database Design

The purpose of the database is to organize large amount of data and to present geotechnical information in a clear, comprehensive, and efficient manner. Microsoft Access 2007 is the database software chosen to house 9 tables and user defined queries. ESRI Arc-GIS 9.3 has been chosen as the GIS software as it interacts well with the Access. Both the Access and Arc-GIS are relatively easy in operations for database users and allow for many customizable operations.

Database tables within the database are designed in such a way that the data can be broken down into simple and standard formats. Each entry within the database table has to be associated with the original borehole data at a specific location of a particular project. The structure of the database includes 9 tables containing different types of data as shown in Figure 2. The tables excluding project information table are linked to each other through a unique identifier field called borehole code (BHCODE). The BHCODE refers to the particular borehole within a geotechnical report. The Project information table is related to the borehole information through a foreign key called Project_code (the primary key of project information table). The relationships between different tables within the database can be seen in Figure 2. The tables include (i) Project information, (ii) Borehole information, (iii) Stratum information, (iv) Standard Penetration Test (SPT), (v) Rock test, (vi) Laboratory test, (vii) Grain size distribution data, (viii) Atterberg limits and (ix) Weight-volume information.

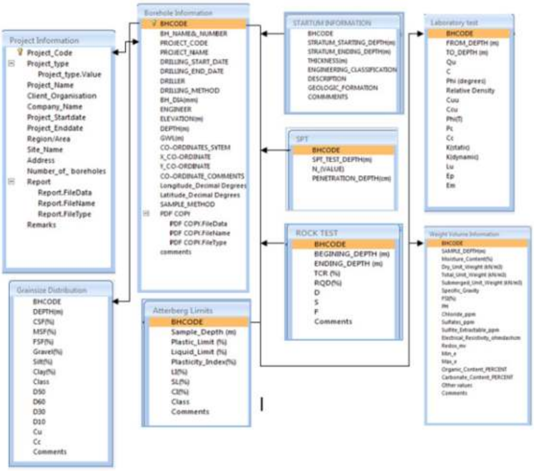

Figure 2. Database tables relationships

The geotechnical data in the database tables are analyzed and visualized through queries. The database queries are designed with the purpose of displaying table data in a GIS environment.

3.5. GIS Software

The developed geo-database has to be incorporated within the GIS software through sequence of operations. The first process involves connecting geo-database to the Arc-GIS through Arc-Catalog by setting up an object linking and embedding (OLE) database connection.

The advantage of using the database as an OLE connection is that it provides a live database connection that reflects the tables in real-time within the GIS. Therefore, as the database is updated with new information, the data within the GIS software is refreshed through the OLE connection (Lawrence, 2011). The next process is to incorporate geotechnical data points with the base map and geology map in Arc-Map. Finally, a digital elevation map is incorporated to visualize the data in three dimensions using Arc-Scene. Figure 3 depicts the process of connecting geo-database with the Arc-GIS software.

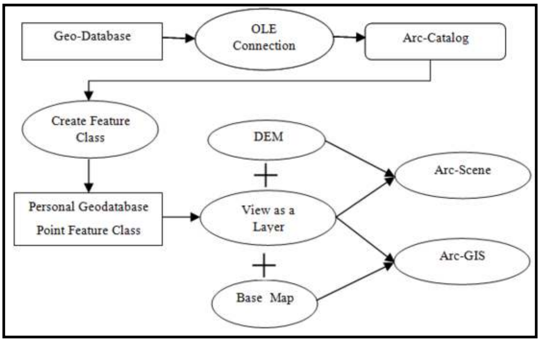

Figure 3. Database connection with GIS software

4. Spatial Variability of Soil-Rock Interface

4.1. Development of 3-D Borelogs

Three dimensional representation of geotechnical data is beneficial to understand the nature and variation of the stratigraphy with respect to location. The feature class created from geotechnical database has elevation value (z-value) with pre-defined vertical coordinate system for 3-D representation in Arc-Scene. The process involves identification of main soil types that exist in the study area from the borelogs. Then the identified main soil types are assigned with unique ID called Hydrogeologic Unit ID (HGUID) to generalize the vertical distribution of the soil strata in each log. A set of records containing information about the strata associated to the particular BHCODE defines the vertical profile of the subsurface of a site. Thus the borelogs containing geotechnical information can be created and viewed three dimensionally as shown in Figure 4.

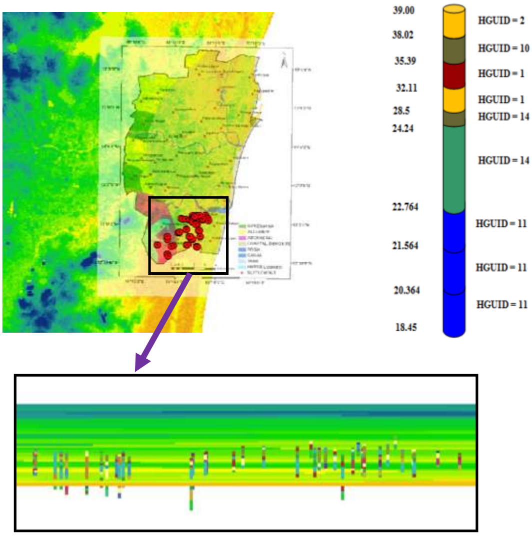

Figure 4. 3-D representation of borelogs of the study area

4.2. Spatial Interpolation Techniques

Spatial interpolation is a process of intelligent guess work, in which the investigator and the software attempt to make a reasonable estimate of the value of a continuous field at places where the field has not actually been measured (Longley et al., 2011). Spatial interpolation techniques can be grouped into two groups: (a) Deterministic methods and (b) Geostatistical methods. Deterministic methods use mathematical functions based on the extent of similarity or the degree of smoothing needed for the interpolation. Geostatistical methods rely on both statistical and mathematical models to estimate the values at unsampled locations by establishing a semivariogram. These methods have the ability to create surfaces and assess the uncertainty of predictions.

Geostatistical kriging, an interpolation technique, is considered as the best linear unbiased estimate and optimal for geological and geotechnical predictions in space because it uses a linear combination of weighted sample values with minimum variance (Sun et al., 2014). In this study, Ordinary Kriging has been adopted for predicting the depth to the bedrock in the study area. The ordinary kriging is chosen due to its simplicity in evaluating spatial variability of depth values corresponding to the top of the rock layer and nature of the available data. A spherical model has been used to get a reasonable fit to the depth values as shown in Figure 5, where the distance (h) is in km.

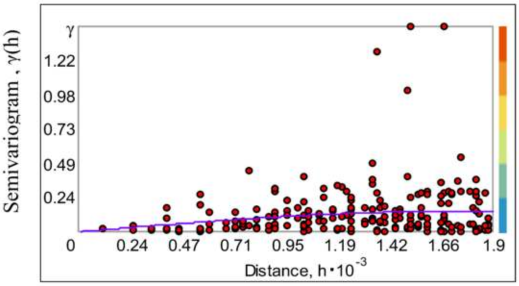

Figure 5. Semivariogram model for depth to bedrock values

Figure 6 presents the spatial variability of depth to soil-bedrock interface created from ordinary kriging using 90% of the data. The predicted depth to bedrock surface are cross-validated with the 10% of the available borelog data and found to be matching reasonably well.

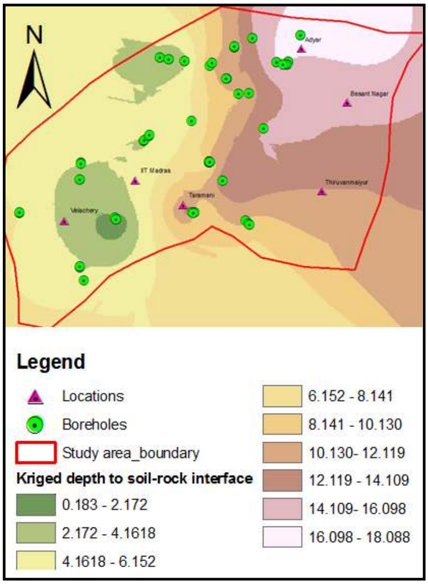

Figure 6. Spatial variation of soil-bedrock interface

5. MASW Tests

Shear wave velocity of the soil profile is an important parameter in characterizing the dynamic soil properties. The most commonly used seismic method for shear wave velocity profiling is the surface wave method. The following two methods are preferred for seismic site characterization: (a) Spectral Analysis of Surface Waves (SASW) and (b) Multi-channel Analysis of Surface Waves (MASW).

The MASW tests, that record Rayleigh waves on a multichannel mode, have been conducted at selected locations in the study area to estimate the shear wave velocity profile of the subsurface. The process involves three steps: (i) acquisition of ground roll, (ii) construction of dispersion curve (phase velocity v/s. frequency) and (iii) back calculation (inversion) of the shear wave velocity profile from the calculated dispersion curve (Park et al., 1999).

5.1. Experimental Setup

In MASW test, a controlled active source generates the Rayleigh-type surface waves which are recorded by an array of receivers, called geophones, placed at known distances. The variation of the shear wave velocity across the depth can be found by analyzing these waves.

The experimental setup consists of a source, receiver and an acquisition system as illustrated in Figure 7. The motion is generated, when a 8 kg sledge-hammer (source) hit against the metal base plate. The corresponding signals are detected simultaneously by 4.5 Hz frequency geophones arranged in a linear array. The data is received by a 24 channel Geode (Geometrics Inc.) and stored in a portable computer.

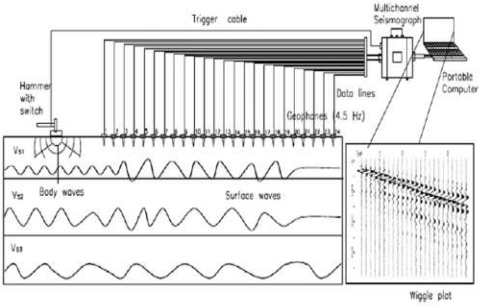

Figure 7. Schematic of MASW test setup

The test at each location is repeated with source (shots) at the front, middle and end of the receivers (an array line) to get the consistency of the field data as shown in Figure 8. Three shots are stacked to improve the signal to noise ratio.

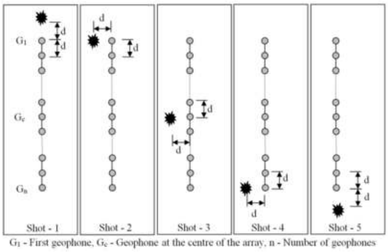

Figure 8. Shot points used at each test location

5.2. Methodology

Raw field data (delay in travel time v/s receiver distance) are transformed into the frequency-wave number (f-k) domain where phase velocities of Rayleigh waves are calculated to produce a dispersion curve with high signal to noise (S/N) ratio. Then the calculated dispersion curve is inverted to estimate the 1-D shear wave velocity profile at all the test locations. The shear wave velocity variation with depth is shown in Figure 9 which corresponds to a location near to the B-type quarters of the IIT Madras campus. It has been observed that beyond the depth of 8 m there is no subsequent change in soil properties.

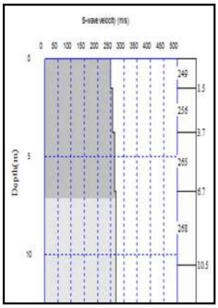

Figure 9. Typical shear wave velocity profile near B-type quarters at IIT Madras

6. Conclusions

A spatial variability of depth to soil-bedrock interface has been evaluated using geotechnical and geophysical test data for a selected suburban areas of Chennai. A comprehensive geo-database in Microsoft Access containing subsoil information has been designed based on the 85 borelogs. This geo-database is integrated into the spatial environment and depth to bedrock has been mapped using kriging in Arc-GIS. The depth to the soil-bedrock interface varies from 2 to 18 m in the study area. The mapped depth to bedrock values have been cross-validated using measured shear wave velocities from the MASW tests. A criterion to identify bedrock is adopted wherein the shear wave velocity of 410 ± 100 m/s is assigned to the bedrock. The mapped depth to bedrock matches well with the depths obtained from the selected borelogs and rock depth estimated from the MASW tests (Figure 10). The figure also depicts the uncertainty bounds. The combination of geotechnical and MASW test data can be used effectively to map the depth to bedrock. The so developed maps will be of immense use in geotechnical design and ground response analysis.

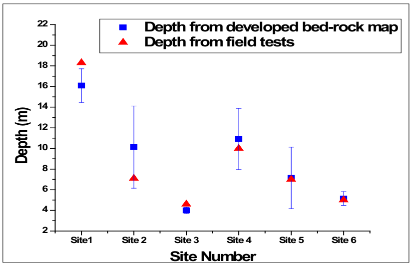

Figure 10. Cross-validation of depth values

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