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Building 3D subsurface models and mapping depth to weathered rock in Chennai, south India

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Abstract: Three-dimensional (3D) solid models thoroughly and completely define the stratigraphy of the subsurface including complex boundaries. They are particularly useful for practical geotechnical analysis and engineering design. In recent years, there are many sophisticated subsurface investigations have been planned and undertaken for various infrastructure projects in Chennai city, India. The 3D subsurface modelling, analysis and assessment of soil characteristics are needed to support the decision making in the execution of all developmental projects with regard to urban planning and hazard studies. This study aims to build 3D subsurface models for Chennai using borehole data and geostatistical kriging in a framework of Geographic Information System (GIS) using a software, Arc Hydro Groundwater (AHGW). Nearly 400 borehole data have been used to construct the 3D soil stratigraphic system for the study area, Chennai city. In addition, a spatial variability of depth to weathered rock has been mapped for the study area which has a prime significance in foundation engineering studies, underground space utilization and seismic ground response analysis. The developed map indicates that the depth to weathered rock varies from 2.8 to 30 m in the study area. The evaluated depths to weathered rock have been compared with the subsurface profile information obtained from Multichannel Analysis of Surface Wave (MASW) tests. The proposed methodology of building subsurface models in an integrated 3D environment and mapping the soil class zonation at different depths will help in better interpretation and management of the subsurface information for future development in Chennai.

Keywords: 3D solid models, Borehole data, Geostatistical kriging, GIS, Depth to weathered rock, MASW test

1. Introduction

Global A knowledge of subsurface conditions plays an important role in geotechnical analysis, design and in planning and execution of the soil exploration program. The stratigraphy and pertinent properties of the soil underlying a specific site are defined by constructing a three-dimensional (3D) solid models utilizing various geotechnical data and modelling techniques. The 3D solid models are considered to be an effective way of representing and interpreting the subsurface information to enhance the visibility and accuracy in the analysis and design of geotechnical structures and facilities. Spatial variability of depth to weathered rock from the ground surface is needed for numerous applications in geotechnical engineering and urban geosciences. The depth to rock surface in a site is a crucial parameter in foundation design and ground response analysis. Local site conditions such as depth to bedrock, soil layer information, location of water table and various geologic parameters are the factors influencing the amplification of earthquake ground motions which induce earthquake-related hazards. Therefore, building 3D subsurface models with all layer information and mapping depth to weathered rock is needed in order to make informed decisions regarding the underground space utilization and hazard and risk assessment studies.

Over the past three decades, a series of modelling theories and techniques have been presented by several researchers to construct the 3D solid models for stratigraphic systems using various geotechnical data (for example: borehole data, geological maps, geotechnical survey records, cross-sections, structural information etc., and geophysical data in most favourable conditions). However, the utilization of such unorganized subsurface information gives rise to many difficulties. They are: the data often not easily accessible, abundant, heterogeneous and the inherent uncertainties associated with the stratum information. The subsurface modelling process involves three essential steps: standardization of modelling data, sustainable data management in the database and construction of 3D subsurface solid models.

The standardization of modelling data focuses largely on the design of data standards and code systems for the geotechnical data as reported in the previous studies. For example, Chang and Park (2004) suggested a standard form of borehole data and implemented in a web-based Geographic Information

System (GIS) system. Similarly, Simmons et al. (2013) developed a standard called CoalLog by upgrading the collection and coding of geotechnical data in compliance with Australian and international standards to provide services to the coal industry. For compilation and effective management of the vast amount of geotechnical data, robust management systems and processing procedures were developed (McCarthy and Graniero, 2006; Turner, 2006; Sun et al., 2014). Several approaches have been developed for generating 3D solid models from different types of geotechnical data and applied within a framework of GIS (Camp and Outlaw, 1993; Ichoku et al., 1994; Lemon and Jones, 2003; de Rienzo et al., 2008; Kaufman and Martin, 2008; Ming et al., 2010; Yan-lin et al., 2011; Zhu et al., 2012; Ghiglieri et al., 2016; Yeniceli and Ozcelik, 2016). In practice, boreholes are the most common source of data used in the subsurface modelling as they are simple, intuitive, exact and detailed for practical users. Several modelling methods involving the construction of individual stratigraphic layers using surfaces interpolated from control points of the borehole data with subsequent blending of these units into single solid model have been proposed and applied (Kaufmann and Martin, 2008; Gallerini and De Donatis, 2009; Marache et al., 2009; Akiska et al., 2013). These methods have their own advantages and disadvantages based on the use of interpolation algorithms and their ability to represent missing and discontinuous surfaces in three dimensions. However, the accurate rebuilding of the complex 3D subsurface structures from the discrete geotechnical data remains a challenge.

In this study, a methodology is developed for constructing 3D subsurface models using borehole data and geostatistics in the GIS environment. The developed methodology is applied for the suburbs of the Chennai city, south India to present and reliably estimate the subsurface profiles and their associated properties. The study starts with the geotechnical characterization of the study area, standardization of borehole data and development of the spatial database. The spatial database is then interfaced with the GIS to build the 3D subsurface model using geostatistical kriging. In addition, the spatial variability of depth to weathered rock in the study area has been evaluated and compared with the Multichannel Analysis of Surface Wave (MASW) test results. The 3D subsurface information will be of immense use to engineers, policy and decision makers for future infrastructure development of the urban centres.

2. Description of the study area

Chennai is the India's fourth largest metropolitan city, the capital of Tamil Nadu state, situated on the southeast coast of India and in the northeast corner of Tamil Nadu, characterized by coastal plains of the Bay of Bengal. Chennai city covers an area of 178.2 km2 and it is located between 12.75° − 13.25° N and 80.0° − 80.5° E.

Building 3D subsurface models and mapping depth to weathered rock in Chennai is attempted as part of the present study. The city is a low-lying area and the terrain is very flat with contours ranging from 2 to 10 m above the mean sea level (MSL) with a few isolated hillocks in the south-western part of the city. The general geology of the city comprises mostly of sandy clay, shale, and sandstone as depicted in Figure 1 (GSI, 1999). The city is underlain by various geological formations comprising of ancient archaean crystalline metamorphic rocks (consolidated); upper gondwana composed of sandstones, siltstones, and shales; and coastal and river alluviums (unconsolidated). The geology of the city consists of shallow bedrock on the east and south and gondwanas below the alluvium in the north and west. The coastal region of the city is entirely covered by marine sediments.

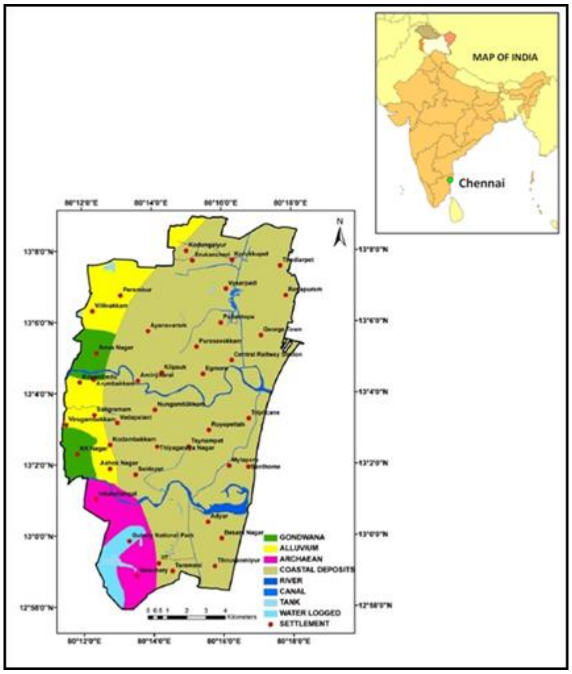


Figure 1: Geological map of Chennai

3. Data collection

Various data sources are included in the process of collecting the information for the present study. Nearly 400 borelogs have been collected from the geotechnical agencies and engineering unit of IIT Madras, Chennai to establish the subsurface profile of the study area. Details of the borehole locations and their corresponding coordinates are obtained from the field. Borehole data along with the index and engineering properties of the subsoil layers are collected for different locations in the study area as depicted in Figure 2. The elevation values of the study area are obtained from the CartoDEM data with 2.5 m spatial resolution. The elevation data have a horizontal accuracy of 15 m and a relative vertical accuracy of ± 5 m.

The city has an average elevation of 6.7 m with the lowest and highest points being 1 and 60 m from the MSL. A base map of the study area is prepared using ArcGIS® software, ESRI (Figure 2). 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.

4. Three - dimensional subsurface modelling

4.1 Methodology

A three-dimensional subsurface model integrating original geotechnical data like borehole information promotes expert understanding and support in decision making during the implementation of various geotechnical projects. Consequently, with advances in computer technology, studies on subsurface stratigraphy using the framework of 3D subsurface modelling has recently become a core research topic to resolve the complexities associated with the subsurface. The three-dimensional subsurface modelling is often exercised to construct solids for any spatial information systems regarding environmental and geological problems. Lemon and Jones (2003) proposed the original horizons method, which can be used to construct the geological subsurface model directly from boreholes and additional cross-section data. Similarly, several researchers focused on generating 3D solid models using boreholes (Gallerini and De Donatis, 2009; Touch et al., 2014;) along with the mechanism to handle the missing and discontinuous strata information (Zhu et al., 2012).

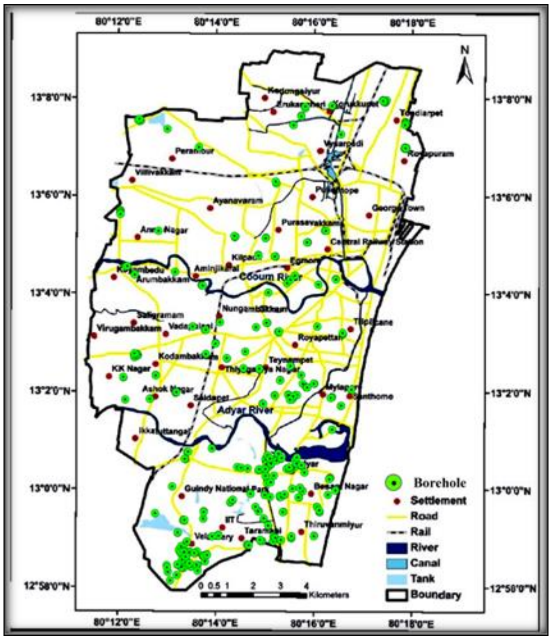


Figure 2: Borehole locations in the study area

In a highly urbanized city like Chennai, the recent years have seen many sophisticated subsurface investigation activities for infrastructure projects and underground space utilization. In order to provide an insight into geotechnical characteristics of Chennai subsoils, "horizons-to-solids" algorithm has been selected to construct 3D subsurface models using the software, Arc Hydro Groundwater (Aquaveo, 2014). The Arc Hydro Groundwater (AHGW) is a geographic data model (and a set of associated tools) for representing spatial and temporal groundwater information within a geographic information system (GIS). The AHGW expands ArcGIS software with groundwater and subsurface geoprocessing tools developed in collaboration with ESRI (Environmental Systems Research Institute, Inc.).

The horizon method (Lemon and Jones, 2003) is chosen for this study due to its simplicity and efficiency in building solid models directly from borelogs with minimal user intervention. The 3D subsurface modelling is carried out through the application of AHGW (Strassberg, 2005; Strassberg et al., 2007, 2011; Chesnaux et al., 2011) to an actual geodatabase established for the Chennai city (Divya Priya, 2016). The process involved in the horizon method of 3D modelling (Figure 3) is explained in the following sections.

4.2 Data extraction

Nearly 400 borehole information has been used in the development of a 3D subsurface model for Chennai city. The borelogs data are organized based on the developed borehole standard and stored in a comprehensive geotechnical database as a Relational Database Management System [RDBMS] (Divya Priya, 2016). The database management system ensures the availability of a single source of useful information for all developmental activities related to “urban geosciences”. This database is then integrated with the GIS as a personal geodatabase (ArcGIS format). The administrative boundary maps and shape files are prepared using ArcGIS® software by ESRI. The data or information from ArcGIS geodatabase is used for the modelling procedure by AHGW through a conceptual design. This data is then processed by AHGW software for subsequent processes to build the 3D subsurface models.

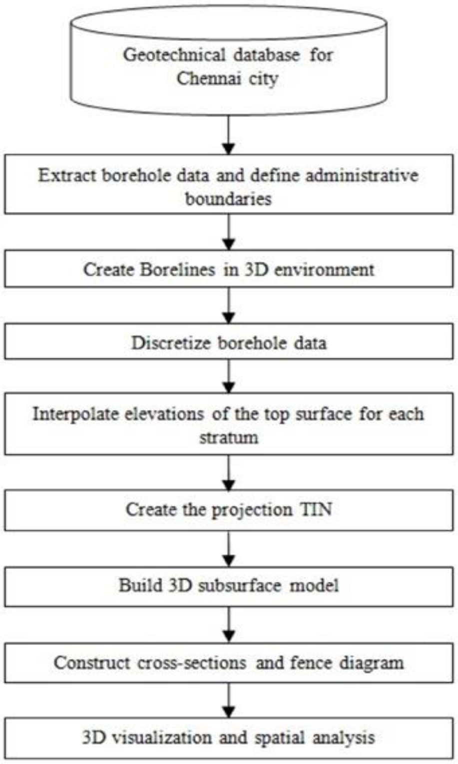


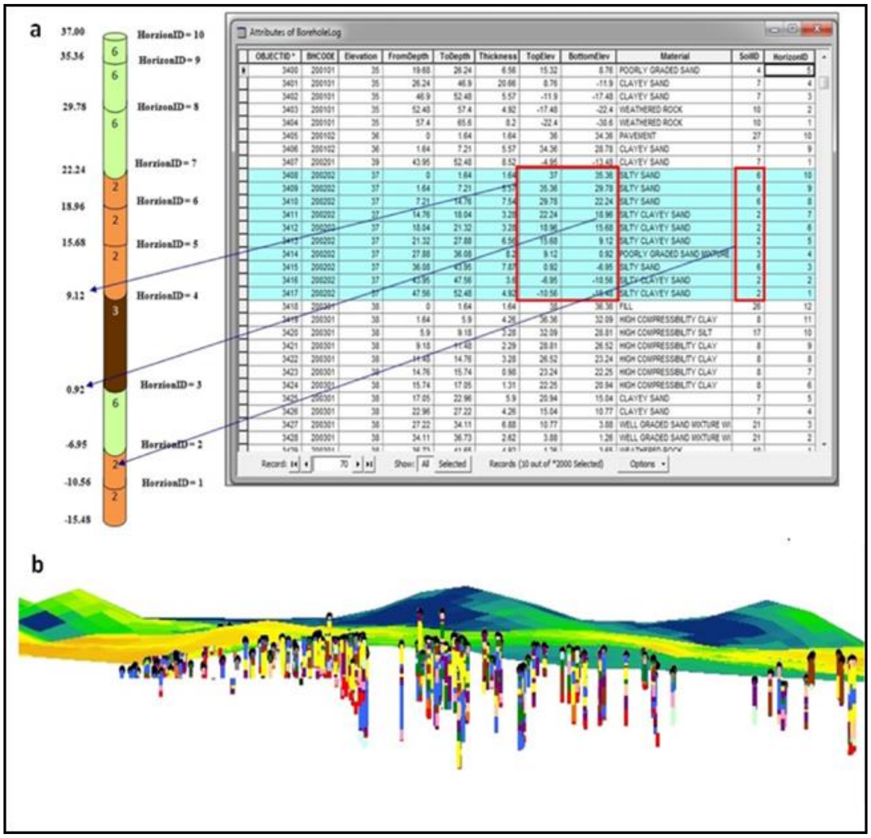
Figure 3: Flowchart for 3D subsurface modelling

4.3 Borehole visualization in 3D

The main soil types that exist in the Chennai region are identified and classified as per IS 1498 (1970) using the borelog data. Each stratigraphic unit encountered within the borehole is assigned to a unique soil identifier (SoilID) to generalize the vertical distribution of the soil strata. The set of records representing each borehole stratigraphy with their SoilID and unit properties are defined in the Boreholelog table of AHGW (Figure 4a). As each borehole contains location and elevation information (i.e. z value), Borelines are created from the Boreholelog table to visualize the boreholes in the 3D environment using ArcScene by assigning a unique colour for each SoilID as shown in Figure 4b.

4.4 Discretization of borehole data

In this study, borehole data are organized into strata and horizons. A horizon is defined as an interface between two adjacent stratigraphic units (Lemon and Jones, 2003). Each horizon is indexed with an identifier (HorizonID) in terms of depositional sequence (bottom to top). The HorizonID should start at 1 and increase from bottom up within the borehole, i.e. HorizonID 1 is associated with the surface containing top elevation value of the bottom most soil layer. Each horizon has a location (x, y, z) information, HorizonID and soil identifier (SoilID) above and below, thus representing the stratigraphy. Boreholelog table contains borehole information of the study area in which each row represents the stratigraphic unit identified along the borehole (Figure 4a). Records in the boreholelog table are indexed with a unique identifier called borehole code (BHCODE) to relate the vertical information with the specific borehole features. In addition, top and bottom elevations are defined for each stratigraphic units and each of the units is indexed with a SoilID defining the material and a HorzionID defining the ordering of the strata along the boreholes. In the next step of the modelling process, horizons of boreholes are discretized into a series of scatter points. After discretization, the horizons of all boreholes are merged into one scatter point set called Borepoints, which contains sample data with top and bottom elevation values of each stratum for subsequent interpolation process.



OBJECTID *	BHCODE	Elevation	FromDepth	ToDepth	Thickness	TopElev	BottomElev	Material	SoilID	HorizonID
3400	200101	35	19.68	26.24	6.56	15.32	8.76	POORLY GRADED SAND	4	5
3401	200101	35	26.24	46.9	20.66	8.76	-11.9	CLAYEY SAND	7	4
3402	200101	35	46.9	52.48	5.57	-11.9	-17.48	CLAYEY SAND	7	3
3403	200101	35	52.48	57.4	4.92	-17.48	-22.4	WEATHERED ROCK	10	2
3404	200101	35	57.4	65.6	8.2	-22.4	-30.6	WEATHERED ROCK	10	1
3405	200102	36	0	1.64	1.64	36	34.36	PAVEMENT	27	10
3406	200102	36	1.64	7.21	5.57	34.36	28.79	CLAYEY SAND	7	9
3407	200201	39	43.95	52.48	8.52	-4.95	-13.48	CLAYEY SAND	7	1
3408	200202	37	0	1.64	1.64	37	35.36	SILTY SAND	6	10
3409	200202	37	1.64	7.21	5.57	35.36	29.78	SILTY SAND	6	9
3410	200202	37	7.21	14.76	7.54	29.78	22.24	SILTY SAND	6	8
3411	200202	37	14.76	18.04	3.28	22.24	18.96	SILTY CLAYEY SAND	2	7
3412	200202	37	18.04	21.32	3.28	18.96	15.68	SILTY CLAYEY SAND	2	6
3413	200202	37	21.32	27.88	6.56	15.68	9.12	SILTY CLAYEY SAND	2	5
3414	200202	37	27.88	36.08	8.2	9.12	0.92	POORLY GRADED SAND MIXTURE	3	4
3415	200202	37	36.08	43.95	7.87	0.92	-6.95	SILTY SAND	6	3
3416	200202	37	43.95	47.56	3.6	-6.95	-10.56	SILTY CLAYEY SAND	2	2
3417	200202	37	47.56	52.48	4.92	-10.56	-15.48	SILTY CLAYEY SAND	2	1
3418	200301	38	0	1.64	1.64	38	36.36	FILL	26	12
3419	200301	38	1.64	5.9	4.26	36.36	32.09	HIGH COMPRESSIBILITY CLAY	8	11
3420	200301	38	5.9	9.18	3.28	32.09	28.81	HIGH COMPRESSIBILITY SILT	17	10
3421	200301	38	9.18	11.48	2.29	28.81	26.52	HIGH COMPRESSIBILITY CLAY	8	9
3422	200301	38	11.48	14.76	3.28	26.52	23.24	HIGH COMPRESSIBILITY CLAY	8	8
3423	200301	38	14.76	15.74	0.98	23.24	22.25	HIGH COMPRESSIBILITY CLAY	8	7
3424	200301	38	15.74	17.05	1.31	22.25	20.94	HIGH COMPRESSIBILITY CLAY	8	6
3425	200301	38	17.05	22.96	5.9	20.94	15.04	CLAYEY SAND	7	5
3426	200301	38	22.96	27.22	4.26	15.04	10.77	CLAYEY SAND	7	4
3427	200301	38	27.22	34.11	6.88	10.77	3.88	WELL GRADED SAND MIXTURE WI	21	3
3428	200301	38	34.11	36.73	2.62	3.88	1.26	WELL GRADED SAND MIXTURE WI	21	2

Figure 4: (a) Borehole profile defined by data in the Boreholelog table; (b) Borelines associated with DEM of Chennai city

4.5 Interpolation of raster from point features

The top elevation of each stratum along the borehole is interpolated to define the solid surface at that level using the 3D coordinate information (x, y, z) in the Borepoints. Most commonly used interpolation schemes, like the inverse distance weighted (IDW), natural neighbor, Spline and kriging methods can be applied to interpolate the elevation data. In this study, the geostatistical kriging is applied as it is relatively simple, convenient, robust and commonly used technique for converting point samples into a continuous surface. A major advantage of kriging is that the value of a variable at the unsampled location is determined using the value of the same variable at sampled locations by establishing the weights based on a semivariogram. In addition, for each value estimation, the relevant associated error is calculated. Hence, for each estimated value, the relevant confidence range can be calculated. The kriging is considered as the best linear unbiased estimate and optimal for geological and geotechnical prediction in space as it uses a linear combination of weighted sample values with minimum variance (Sun et al., 2014).

In the 3D modelling process, the ordinary kriging is adopted to determine the weights. The kriging consists of the following steps: (a) Normalization of the data, (b) Evaluation of the variogram, and (c) Establishment of the experimental variogram by fitting the model. It should be noted that while selecting a model, the model that has minimum nugget effect and minimum sill with maximum effective range is chosen (Abdideh and Bargahi, 2012). After comparing the parameters of different models, the exponential model has been chosen to estimate the rasters defining each soil layers called GeoRasters (Figure 5a). The GeoRasters is a raster surface for representing the top and bottom of the stratigraphic units along with its properties (including HorizonID, SoilID and elevation information).

4.6 Creating the projection TIN

A TIN (Triangular Irregular Network) is used to define the extent and size of the solid features to be created in the 3D model. The TIN is created through a standard triangulation algorithm, in which the number of triangles on the TIN determines the amount of processing that must be carried out. The TIN used in the present study is called as projection

TIN as the elevations on the TIN are not used, only the triangles are used to define the shape and extent of the subsurface volumes. The projection TIN not only explicitly defines the outer boundary of the 3D solids, but also used to establish the topology of the solid.

4.7 The 3D subsurface model

After construction of GeoRasters and projection TIN, a solid model called Geovolume is generated by establishing a topological relationship between the stratum and surface. A solid is constructed for each stratum by looping through the horizons defined in the GeoRasters and each horizon in turn loops through the triangles of the projection TIN. All these solids are combined together as a 3D feature i.e. Geovolume for representing volumes within the subsurface as shown in Figure 5b.

4.8 Cross-sections and Geosections

Cross-sections are extracted from the borehole information through an interactive approach. As shown in Figure 6a the construction of cross-section starts by drawing a line on the map corresponding to the trace of the cross-section. Then the buffer is applied to select the particular boreholes needed to be considered for developing the cross-section in the vicinity of the line. The elevation values of the different stratigraphic layers identified in Borelines corresponding to the selected boreholes are interpolated to create a panel (a polygon feature class). A typical cross-section representing the stratigraphy of a selected section line B-B′ (west-east) is presented in Figure 6b. Several such cross-sections are constructed and exported in a 3D environment to form a fence diagram called Geosections as shown in Figure 6c.

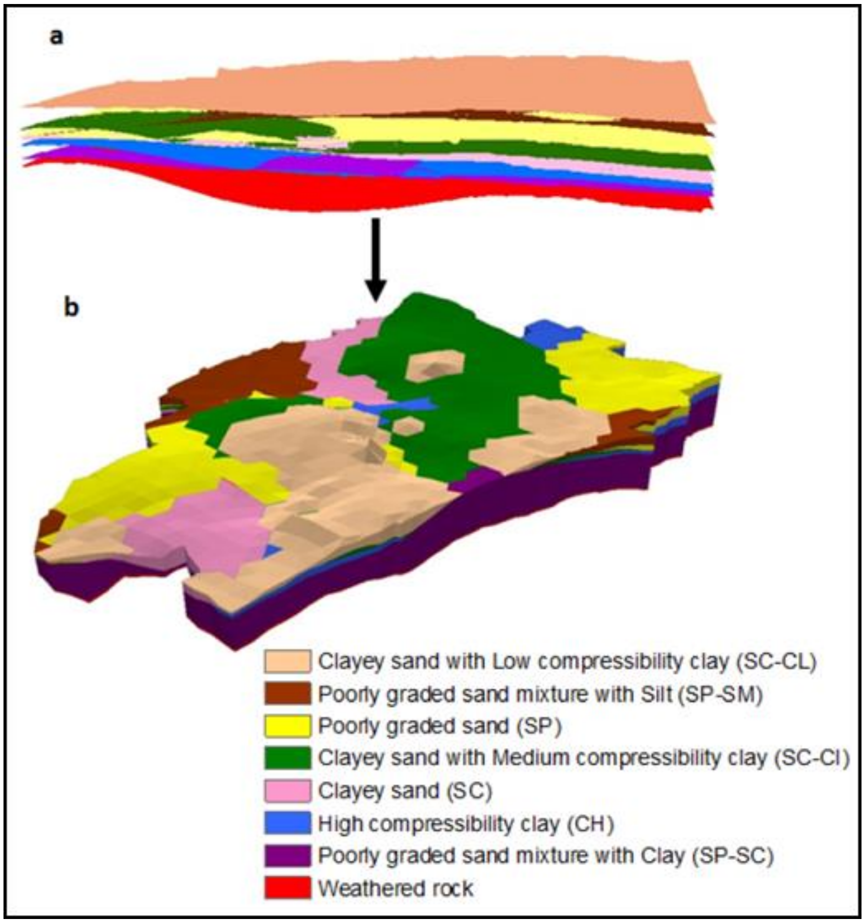


Figure 5: 3D subsurface model of Chennai city created from the interpolated rasters (a) GeoRasters; (b) Geovolume

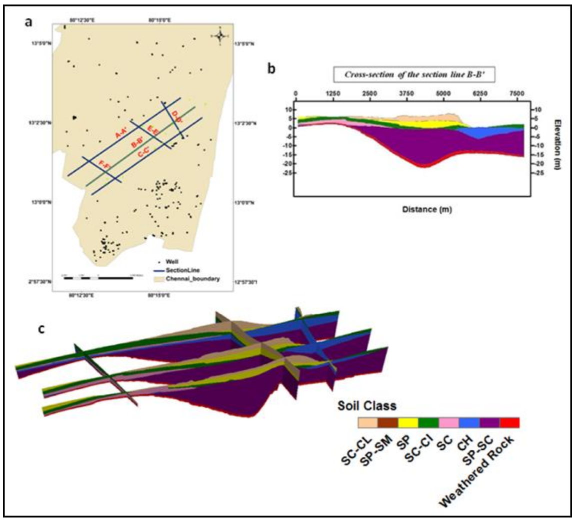


Figure 6: (a) Drawing a section line and selection of boreholes; (b) Cross-section of the selected section line B-B′; (c) Fence diagram (Geosections)

5. Application of 3D subsurface model

The developed 3D subsurface model of the study area supports to predict the types of soil and rock available and their spatial and depth variation. In addition, the model provides information about the subsurface conditions such as the thickness of the soil zone, depth to a soil-rock interface which will be of great value in foundation analysis and design, location of underground space utility structures and metros. Application of 3D solid volumes directly in engineering projects requires experts knowledge and proper interpretation. But, the two-dimensional representation of the geotechnical data in the GIS framework using thematic and contour maps provides a user-friendly and easy way of extracting useful information for infrastructure development projects. Estimating the depth to rock surface in a particular locality is important for geotechnical engineering activities and seismic ground response analysis. The 3D subsurface model is used to develop the spatial variation map of depth to weathered rock in the study area and the same is depicted in Figure 7. This map can be overlaid with the three-dimensional topographic surface features to provide a better representation of the overall surface geology.

The spatial variability of depth to weathered rock data obtained using borehole information is compared with the depths estimated from Multichannel Analysis of Surface Wave (MASW) tests. The MASW test is the most commonly used seismic method for geotechnical characterization of near-surface materials (Park et al., 1999). It is a non-invasive geophysical method which measures shear wave velocity (VS) to characterize the dynamic properties of the underlying soil, and also identifies the subsurface material boundaries and spatial variations of shear wave velocity with depth. It is widely used in earthquake geotechnical engineering for seismic site characterization and microzonation studies.

The MASW test records the Rayleigh waves in a multichannel mode. The MASW tests have been conducted at selected locations in the study area to estimate the VS profile of the subsurface. The entire procedure of MASW test consists of three steps: (i) acquiring multichannel field records (or shot gathers), (ii) extracting dispersion curves (one from each record), and (iii) inverting these dispersion curves to obtain one-dimensional (1D) VS profiles (one profile from one curve) (Park et al., 1999). The test locations are selected in such a way that the site has a flat surface with minimum surface interruptions (like buildings, roads, ditches etc.,) and also they should apparently represent the entire Chennai city for extracting subsurface information.

6. Comparison with MASW test results

6.1 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 shear wave velocity with depth can be found by analyzing these waves. The experimental setup consists of a source, receiver and an acquisition system as illustrated in Figure 8. The motion is generated, when a 8 kg sledgehammer (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 raw data (wiggle plot) is received by a 24 channel Geometrics make Geode and the data is stored in a portable computer. The test at each location is repeated with the 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 9. Three shots are stacked to improve the signal to noise ratio at each test location.

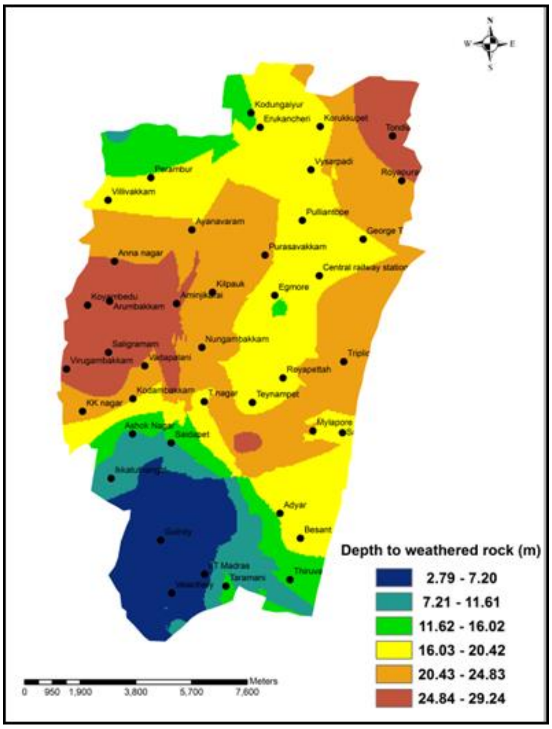


Figure 7: Spatial variation of depth to weathered rock

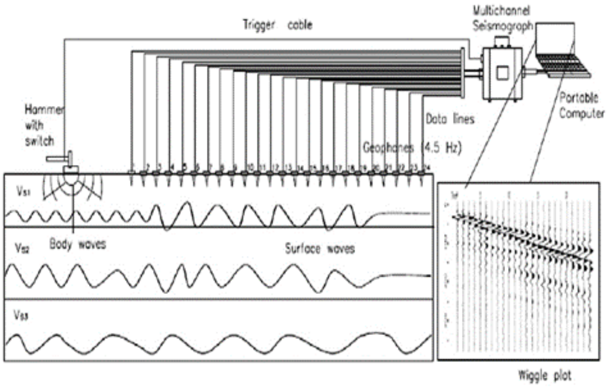


Figure 8: Schematic of MASW test setup

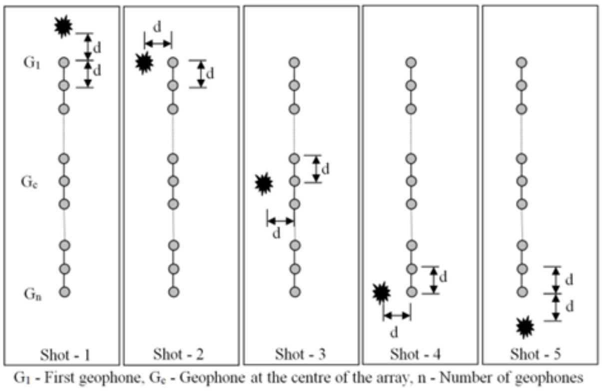


Figure 9: Shot locations for each MASW test

6.2 Data analysis and results

Raw field data (delay in travel time v/s receiver distance) is further analyzed using SurfSeis software. As a first step, the multichannel records are prepared by filtering out the ambient noise. Then they are transformed into the frequency-wave number (f-k) domain where phase velocities of the Rayleigh waves are calculated to produce a dispersion curve with high signal to noise (S/N) ratio. The calculated dispersion curve is inverted to estimate the 1-D shear wave velocity profiles at all the test locations by comparing with the theoretical dispersion curves iteratively. A typical VS profile corresponds to a location near to the C-type quarters of the IIT Madras campus is shown in Figure 10. It has been observed that the shear wave velocity of the subsurface profile is ranging from 170 to 400 m/s at the site.

As per the NEHRP (National Earthquake Hazard Reduction Programme) site classification, the very dense soil and soft rock have the 30 m average shear wave velocities [(VS)30] of 360 to 760 m/s and rock has the (VS)30 of 760 to 1500 m/s. The rock which has (VS)30 greater than 1500 m/s is classified as hard rock. Several studies have been carried out considering different ranges of VS for geomaterials (Anbazhagan and Sitharam, 2009; Trupti et al., 2012; Pegah and Liu, 2016).

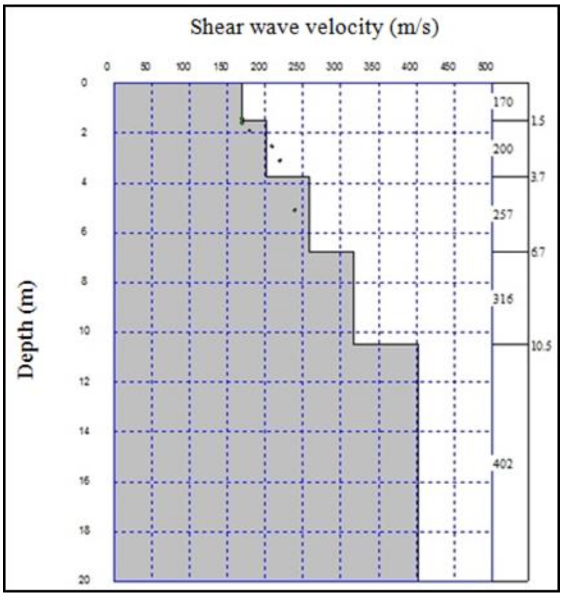


Figure 10: Typical shear wave velocity profile at IIT Madras, Chennai

In the present study, VS of 330 ± 30 m/s is considered as the criterion for the identification of weathered rock. The depths corresponding to this range are identified from VS profiles and the same depths are recognized as depths to weathered rock at test locations in the study area. The depths estimated from the measured shear wave velocities from the MASW tests are compared with those mapped using the borehole data and the differences between them are presented in Table 1. It is found that both the results agree well with each other (Figure 11).

Table 1: Comparison between depths to weathered rock using borehole data and MASW test results

Selected locations (suburbs) in Chennai city	Depth interpolated using borehole data (m)	Depth estimated from MASW tests (m)	Difference in depth (%)
Guindy	6.93	5.98	13.71
Velachery	3.02	3.70	22.52
IIT Madras	6.19	6.70	8.24
Taramani	13.15	12.50	4.95
Adyar	12.40	12.00	3.23
Mylapore	20.76	21.00	1.16
Egmore	17.02	18.00	5.76
Tondiarpet	27.56	25.00	9.30
Perambur	20.90	20.40	2.40
Vadapalani	26.80	25.81	3.70

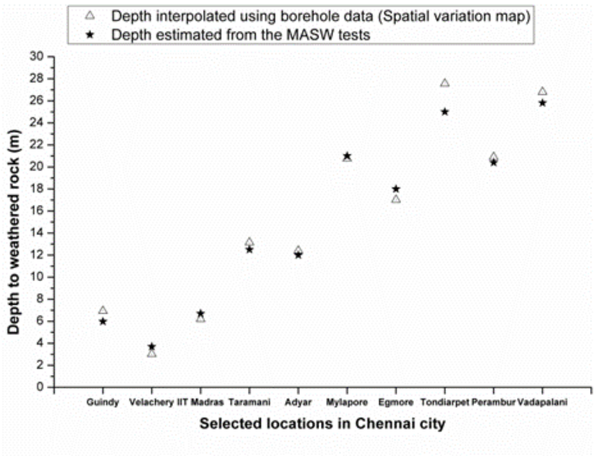


Figure 11: Comparison of depth to weathered rock

7. Conclusions

The 3D subsurface model is developed for Chennai city using borehole data and kriging in a GIS environment. The 3D subsurface model constructed with horizon approach using AHGW geoprocessing tools extended within ArcGIS software provide a platform for the integration and visualization of data from various geotechnical projects. In addition, it provides a clear representation of the subsurface characteristics with each layer information, user-defined cross-sections and fence diagram of any specific region. The information such as thickness of the soil zone, depth to rock surface are extracted from the developed 3D model for the selected regions. For example, based on the cross-sections and 3D model, it is found that the framework of stratigraphic units consists of 2 to 3 m thickness of clayey sand with low compressibility followed by a poorly graded sand with silt of 3 to 4.5 m thickness in the central parts of the city. A spatial distribution map of depth to weathered rock has been developed for the entire study area. This map provides useful information for foundation design, metro rail projects and seismic ground response studies.

The mapped depth to weathered rock obtained from borehole data has been compared with the depth to weathered rock estimated from the MASW tests and the differences between them lie in the acceptable range i.e. less than 25% indicating that both the results are in good agreement. This also represents the efficiency of the subsurface model and the MASW tests to reasonably estimate the depth to weathered rock. The spatial variability map indicates that the depth to weathered rock varies from 2.8 to 30 m in the study area. In general, the weathered rock has been found at shallow depths i.e., within 7 m from the ground surface in the southern parts of the Chennai city, at deeper depths (about 20 to 30 m) in the western parts and at moderate depths (8 to 15 m) in the central parts of the city. The spatial variability map of the depth to rock surface can also be used to extract other relevant geotechnical characteristics needed in urban geosciences activities. It is concluded that the developed 3D model with its associated subsurface information provides support for urban planning, construction and management and also aids in making informed decisions in regard to the overall development of the Chennai metropolitan area.

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