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Regional Geotechnical Mapping Employing Kriging on Electronic Geodatabase

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Featured Application: The development of a regional geotechnical map allows quick and easily obtaining information regarding soil formation and allowable bearing capacity. In addition, this map will help in preliminary studies, feasibility studies, and land use policies.

Abstract: A regional geotechnical map was developed by employing kriging using spatial and s geostatistical analysis tools. Many studies have been carried out in the field of topography, digital elevation modeling, agriculture, geological, crop, and precipitation mapping. However, no significant contribution to the development of geotechnical mapping has been made. For the appraisal of a geotechnical map, extensive field explorations were carried out throughout the geotechnically diversified plateau spread over an area of approximately 23,000 km^2. In total, 450 soil samples were collected from 75 data stations to determine requisite index properties and soil classification for the subsequent allowable bearing capacity evaluation. The formatted test results, along with associated geospatial information, were uploaded to ArcMap, which created an initial input electronic database. The kriging technique of geostatistical analysis was determined to be more feasible for generating a geotechnical map. The developed map represents the distribution of soil in the region as per the engineering classification system, allowable bearing capacity, and American Association of State Highway and Transportation Officials (AASHTO) subgrade rating for 1.5-, 3.0-, and 4.5-m depths. The accuracy of the maps generated using kriging interpolation technique under spatial analyst tools was verified by comparing the values in the generated surface with the actual values measured at randomly selected validation points. The database was primarily created for the appraisal of geotechnical maps and can also be used for preliminary geotechnical investigations, which saves the cost of soil investigations. In addition, this approach allows establishing useful correlations among the geotechnical properties of soil.

Keywords: GIS in geotechnical; geotechnical mapping; Potohar Plateau; geostatistical analysis

1. Introduction

Geotechnical investigation is considered to be a pre-requisite for any civil engineering project. It ensures the safe execution of the project and improves its feasibility, planning, and design phases. There is an increasing challenge for geotechnical engineers to quantify ground properties by considering potential variability between the sampling points. To assess the variability of soil properties at a site, it is essential to consider the correlation structure of soil properties. This study was meant to be an aid by providing an electronic geodatabase and ready-to-use geotechnical map for an economical preliminary investigation. This approach may reduce the cost and time required for such investigations and provides reasonable accuracy. A comparable work has been carried out in the field of topography, digital elevation modeling, and agriculture soil mapping. Geological, crop health, and precipitation mapping are also of interest to the researchers. However, in the literature, there are no significant contributions to the appraisal of geotechnical mapping. Engineering soil classification is not only important for preliminary recommendations on the feasibility of proposed projects but also plays a vital role while selecting identified material sources for the proposed projects. The American Association of State Highways and Transportation Official (AASHTO) classifies soils on the basis of their relative suitability as a subgrade material, which ranges from excellent to poor (A-1–A-7, in descending order). This rating considerably affects the selection of routes and alignment of motorways and highways. In addition, subgrade rating greatly affects the cost of these megaprojects. Subgrade rating can even lead to the selection or rejection of a particular route for the proposed highway. In addition, it can identify potential problems on a specific route. The well-developed maps containing information on engineering classification and subgrade rating can serve as an excellent tool for engineering planers. The generation of such maps requires an extensive exposure to soil formation, geological processes, topographic features, field exploration, and laboratory testing along with a reliable data analysis, interpretive and mapping tools. Thus, a desk study was performed, which evaluated the available topographic, administrative, and precipitation data, location, and route of water bodies in the area.

In total, 75 locations were selected for drilling and collection of samples to determine requisite properties to be incorporated into the proposed geotechnical map. Reconnaissance survey was conducted on the sites chosen to acquire initial information about ground condition, e.g. visual soil classification, observation of geological features through examination of outcrops, tentative water table, suitable equipment for drilling at each site, equipment access to the selected site, nature of nearby water bodies if any, and social and cultural issues of the area. The reconnaissance outcome was systematically compiled. Finally, the exact location of 75 sites was selected for boring and collection of samples in a mesh grip pattern scattered throughout the geotechnically diversified plateau spread over an area of approximately 23,000 km^2. In total, 450 soil samples were collected from 75 data stations to determine requisite index properties and to be used for subsequent engineering evaluations. Laboratory tests were performed according to relevant American Society for Testing and Materials (ASTM) standards, and the results were compiled to create a database for further processing.

ArcGIS is an emerging software for the analysis of datasets. It consists of diversified techniques for the interpretation, analysis, interpolation, and extrapolation of parameters. The test results were converted to form a geodatabase and uploaded to the ArcMap software. Among the numerous available data interpolation techniques, the kriging technique of geostatistical analysis was determined to be more suitable for the evaluation of target geotechnical mapping. Kriging is a geostatistical interpolation technique that considers both the distance and degree of variation between known data points when estimating values in unknown areas. A kriging estimate is a weighted linear combination of the known sample values around the location to be estimated. The weighted average of the data available on nodes fixes the weight of all the nodes on the basis of the spatial variation and distance from the cell under consideration to determine the output value for each cell. The main strength of kriging is its unbiasedness and ability to predict the spatial distribution of uncertainty [1,2]. The validation of generated maps was carried out through confirmatory tests at arbitrary selected additional ten points.

Input parameters for modeling and mapping soil properties often consist of samples from preselected spatial locations, although samples are collected at several different soil depth intervals. However, it may be of interest or the conditions may require to assess the properties of soil at the locations other than the sampled locations or between the sampled locations. It is the task of the data analyst to put the data together in such a way that useful and reliable conclusions can be drawn for the soil depths of practical interest [3]. The effect of spatial variation on geotechnical properties of soil has been studied, and depositional environment has been reported to affect these properties [4]. The spatial modeling of geotechnical parameters has been utilized to assess the geotechnical properties by creating 3D models for the construction of the Lavrion Technological and Cultural Park [5]. Soil stratigraphic profiles were generated by employing algorithms that use individual cone penetration test (CPT) sounding as an input. These stratigraphic profiles have been reported to reduce ambiguity in generated profiles [6]. Memory-based learners and machine learning algorithms were determined to perform better than other regression analysis techniques, as reported in [7,8].

The probabilistic approach has been ranked higher than deterministic approaches in geotechnical engineering owing to its better incorporation of uncertainty. Geotechnical uncertainty can be quantified through the statistical analysis of the database or on the basis of the judgment of an engineer performing the analysis [9]. A 2D Bayesian compressive sampling approach is developed to address uncertainties in the interpretation of spatially varying smaller geodatabase; this approach is compared with the kriging interpolation method for geostatistical analysis described in [10,11]. The site variability modeling of cone penetration resistance has been determined to facilitate geotechnical engineers to better understand site conditions and produce a design with higher reliability [12]. A framework to predict soil behavior by modeling two significant sources of uncertainty, which are the measurement error and spatial variability, has been developed [13].

The prediction of various soil properties or soil classes on the basis of soil sampling over small area by employing numerical modeling techniques reduces their effectiveness owing to limited spatial variability incorporation. Digital soil mapping is an emerging technique to overcome the above-mentioned limitation in soil surveys [14]. Different approaches have been employed to model soil depth in France, and multi-resolution kriging has been reported to produce smoother maps compared to straightforward digital soil mapping and regression modeling [15]. The Illinois State Geological Survey (ISGS) has illustrated the workflow for the generation of 3D geologic mapping in ArcScene [16]. Geotechnical and geological characterization of a region in Portugal and geophysical and geotechnical approaches for micro-zonation studies for Hispaniola Island has also been appraised [17,18].

An ordinary kriging technique has also been used to generate top sand thickness and seabed surface [19]. The prediction of soil properties from terrain attributes using various forms of the kriging regression analysis technique has been reported to perform well [20,21]. Kriging has been evaluated as an unbiased and least error-prone optimum reserve estimation method to reduce or avoid ambiguities in plotting geological cross-sections on the basis of engineering geological properties and data from exploratory holes [22]. Among the eight data interpolation techniques available under the spatial analyst tool in the ArcMap software, the inverse distance weighting (IDW) method has been reported to produce more accurate zonation maps. Standard penetration resistance maps for various depths have been generated and compared with the actually measured values for Surfers' Paradise in Australia [23]. The mapping of soil properties is a time consuming and costly process, especially for diverse topographic conditions [24]. The estimations of soil moisture content using ordinary kriging, IDW, kriging with external drift (KED), and spline were compared, and KED has been reported to produce better results [25,26].

The engineering properties required to correlate with their parent materials irrespective of the diversity in the soil and the parent materials have been reported and are assumed to be applicable for all types of parent materials [27]. Multicriteria decision analysis (MCDA) has been performed using GIS software to develop geotechnical micro-zonation models using various soil properties [28]. The geotechnical database has been processed using GIS to generate soil types and standard penetration resistance maps to ease data interpretation [29]. Most of the soil investigations are being carried out without the use of GIS in this region. The current study on the geotechnically diversified region is the first of its kind. This work is an effort to introduce the integration of GIS-based field explorations and subsequent development of geotechnical maps, which has not been practiced in the region. A correlation between Standard Penetration Test (SPT) N values and index properties of soil was evaluated using artificial neural networks and another correlation between relative compaction and allowable bearing capacity has also been appraised

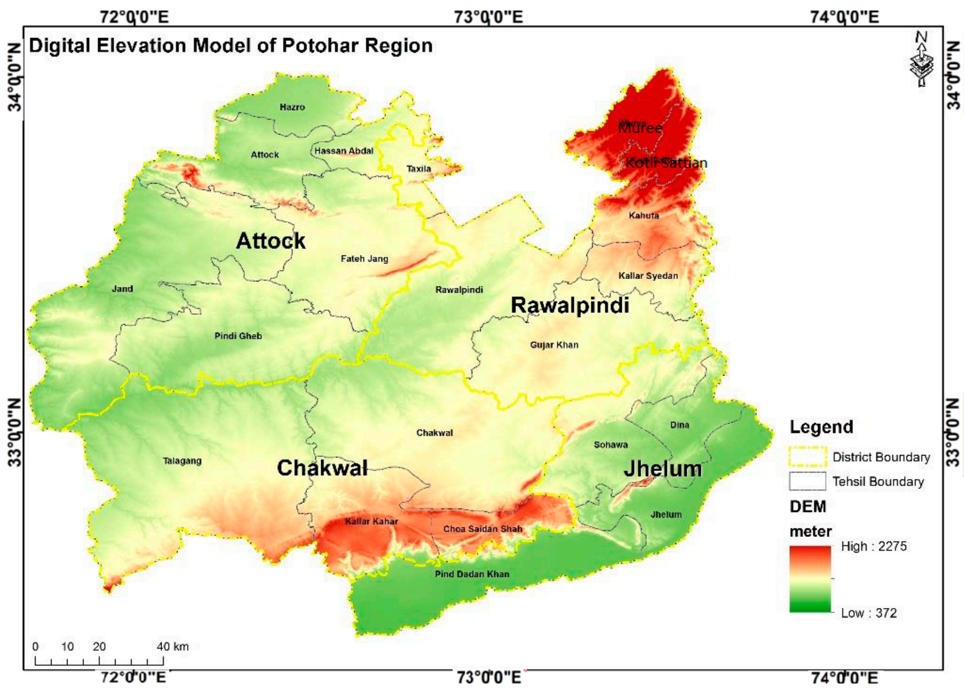
The development of a regional geotechnical map provides a quick and easily obtaining insight regarding soil formation and allowable bearing capacity. In addition, this map will help in preliminary studies, feasibility studies, and land use policies.

2. Materials and Methods

In the first phase, available data related to topography, geologic settings, precipitation, and land use patterns were explored. Concise discussion on these parameters is presented to establish a baseline for field explorations.

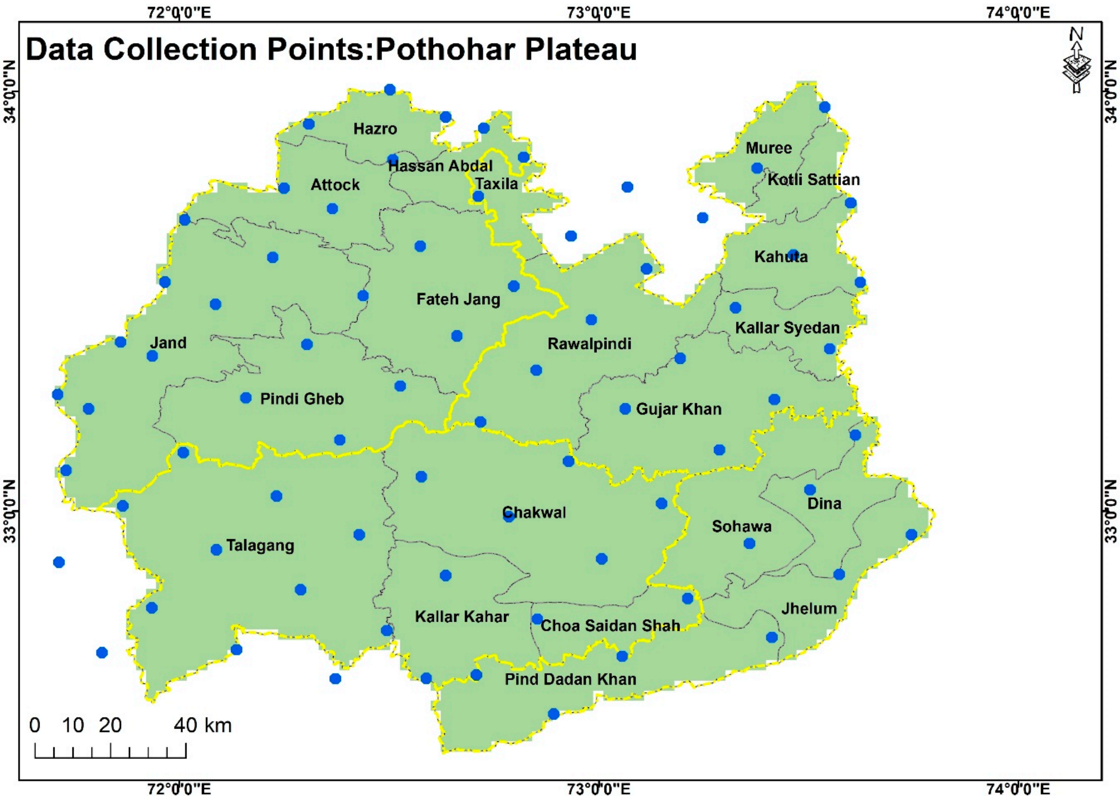
2.1. Geography

Potohar is a plateau located in the northern part of Punjab province in Pakistan. The plateau is a relatively plain area of low relief. The area is bounded by mountain ranges, Hazara and Margalla on the northern side and salt range on the southern side. On the western side, it borders the Indus River, and the Jhelum River flows on its eastern side. The highest elevation of the area is on the northern side in the Hazara range, i.e., approximately 2275 m above mean sea level; along the Jhelum and Indus river plains, the elevation is as low as 372 m above mean sea level. Most of the area has semiarid climatic conditions, and annual rainfall in the region is less than 250 mm [22]. The topography of the area shows local depressions, valleys, and ridges. Potohar stretches from latitude 32.166 to 34.150 N and longitude 71.166 to 73.916 E; it covers an area of approximately 23,000 km^2. Warwick, P.D. and Wardlaw, B.R. developed a geologic database for the Potohar region. The database shows a wide variation in the geologic setting of the region, and it is useful for various engineering studies [30]. Figure 1a presents the digital elevation map of the study area.



(a)

Figure 1. *Cont.*



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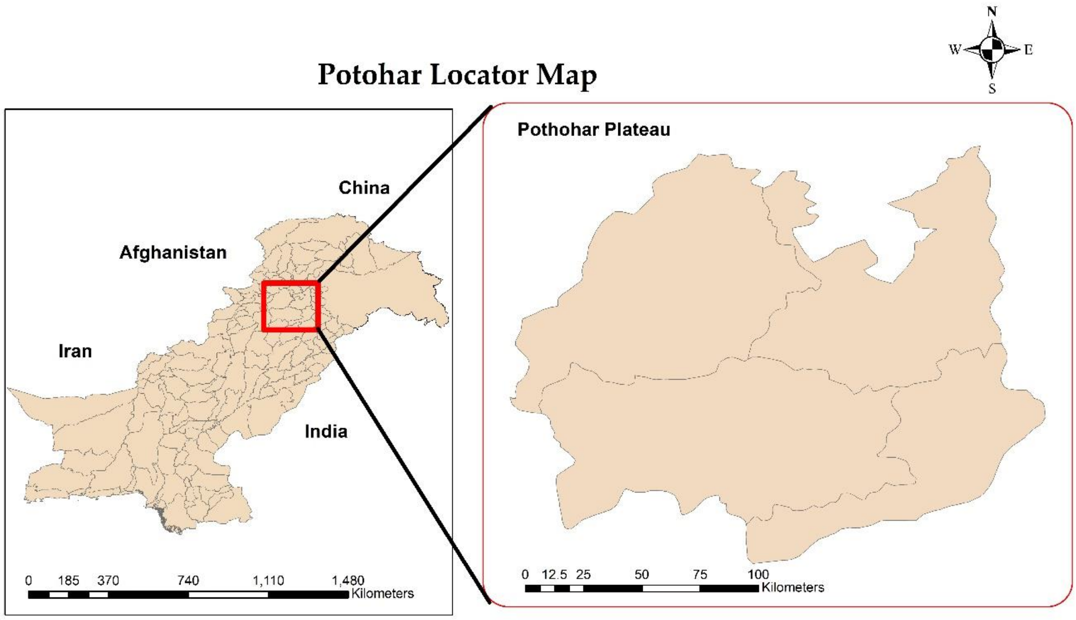

(c)

Figure 1. (**a**) Digital Elevation Model of the Study Area; (**b**) Field Reconnaissance Sites; (**c**) Locator Map of the Study Area.

2.2. Preliminary Investigations

After obtaining insight into the available parameters, the second phase was initiated by marking preliminary data acquisition stations on the map in a mesh grid pattern. The tentative coordinates of the marked points were acquired from Google Maps. The coordinates were entered into a Garmin GPS unit, and the reconnaissance phase started for the physical examination of the testing sites. The field reconnaissance survey information sheet was developed to allow field personnel to provide basic information about each site such as the visual soil classification, soil color, general geological setting, selection of suitable drilling equipment, accessibility to the testing point, nearby water bodies, and layout of testing points. The purpose-built reconnaissance survey information sheet is shown in Table 1.

Table 1. Reconnaissance Survey Information Sheet.

Site ID:-			
(N)	(E)	(Z)	
Site Address: -			
District	Tehsil	UC	
General Topography of the Area:			
Visual Soil Classification			
Soil Color			
General Geological Setting			
Vehicular Excess Source			
Nearest River			H.F.L:
Nearby Water Body:	Nature:	Distance:	Depth:
Tentative Ground Water Table:			
Elevation from the Road Level			
Nature of Ground Surface	Plain	Rolling	Irregular
Type of Built Structures (if any)	Residential	Commercial	
Visible Soil Problems			
Noticeable Soil Problems (if any)			
Other Notable information			

Tentative groundwater tables were assessed from the nearby wells. Interviews with residents were also conducted to collect information that was useful for subsequent mapping such as precipitation patterns, groundwater conditions, surface runoff storage, and landslide incidents. The locations of sampling stations are shown in Figure 1b. The locator map of the study area is presented in Figure 1c.

Geotechnical exploration included drilling, standard penetration testing, and collection of soil samples at an interval of 1.5 m; hence, the samples were collected from 1.5-, 3.0-, and 4.5-m depths and tested at a soil mechanics laboratory to determine their properties. The field reconnaissance survey and laboratory testing aimed to obtain the index and engineering properties of the soil. During the selection of field survey, testing, and sample collection sites, it was ensured that the sites were located on natural soil deposits and representative of the general setting of the area. The sites are shown in Figure 1.

In total, 75 field survey sites were marked and distributed in the mesh grid pattern throughout the region. Standard penetration tests (SPT) were performed at 1.5-, 3.0-, and 4.5-m depth at each site. Samples were extracted for gradation, Atterberg's limits, moisture content, subgrade rating, and engineering soil classification. In total, 450 SPT tests were performed in the field, and the same number of disturbed samples was collected for laboratory testing. The collected soil samples were properly preserved and transported to the laboratory for testing in a systematic manner.

In total, 1800 laboratory tests were performed, including 450 tests for moisture content, 450 tests for Grain Size Distribution (GSD), and 900 tests for Atterberg's limits (Plastic Limit (PLs) and Liquid Limit (LLs). GSD is an indicator of engineering properties such as compressibility and shear strength of the soil, and it is an integral part of the engineering classification of soil. Moreover, it is also essential for selecting a suitable fill material for backfills, highway embankments, and earthen dams. In addition, GSD is required for the design of seepage filters and groundwater drainage works. The standard penetration test is the most widely used test for the determination of bearing capacity of the soil, while Atterberg's limits are required for the engineering classification of fine-grained soil, mix, dusty coarse-grained soils, and AASHTO subgrade ratings. After the execution of the field survey, field and laboratory test results were processed to evaluate the parameters shown in Table 2.

Table 2. Outlines of Geodatabase Input Parameters.

Sr. No.	Input Parameters	Max. Value	Min. Value
1	Grain Size	75 mm	0.08 mm
2	Atterberg's Limit (LL)	48.148	0
3	Atterberg's Limit (PL)	27.77	0
4	Engineering Classification of Soil	CL	GP
5	AASHTO Subgrade Rating	A-1-a	A-7
6	Standard Penetration Resistance	100	5
7	Allowable Bearing Capacity	11.343	0.49

The transformation of complex tabular data into a user-friendly, easy to understand format was challenging; however, this issue was successfully addressed in this study and provided meaningful information for technical personnel, as shown in Figure 2.

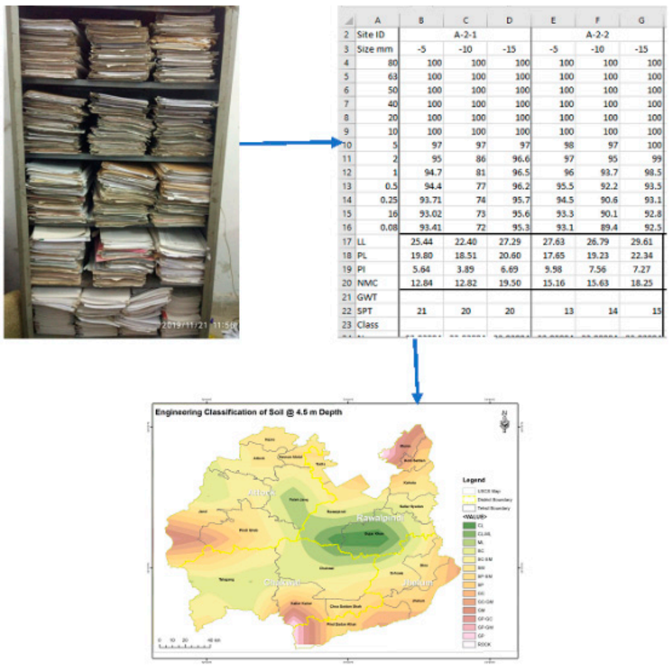

Figure 2. Data Transformation.

2.3. *Creation and Validation of Geotechnical Maps*

Electronic databases were created using the ArcMap software by incorporating these parameters. The primary electronic databases were separately created for the depths of 1.5, 3.0, and 4.5 m. Each primary database has subsets of engineering soil classification, AASHTO subgrade rating, and allowable bearing capacity. The database consists of three subsets. Subset 1 contains the test results of the samples collected from the depth of 1.5 m. Subset 2 contains the test results of the samples collected from the depth of 3 m. Subset 3 contains the test results of the samples retrieved from the depth of 4.5 m. As an improvement, compared to previous studies, this study used properly arranged data accusation points. The data stations were arranged in a mesh grid pattern to provide at least four input points for each interpolated cell.

Kriging is a multistep process; it includes exploratory statistical analysis of the data, variogram modeling, creating the surface, and (optionally) exploring a variance surface [1,2]. Kriging generates an estimated surface from a scattered set of points with z-values. Kriging assumes that the distance or direction between sample points reflects a spatial correlation that can be used to explain variation in the surface. The kriging tool fits a mathematical function to a specified number of points, or all points within a specified radius, to determine the output value for each location. The semivariogram depicts the spatial autocorrelation of the measured sample points. The goal is to achieve the best fit, as well as incorporate our knowledge of the phenomenon in the model. By considering soil anisotropy, kriging has been reported to produce reliable predictions [29].

The databases were created using the ArcMap software and processed using a spatial analysis tool. The spatial analyst extension in ArcMap was employed to develop geotechnical mapping for different depths in the study area. The point data at 1.5-, 3.0-, and 4.5-m depths were interpolated as a surface to create maps of engineering soil classification, AASHTO subgrade rating, and allowable bearing capacity of the soil. Interpolation is a procedure used to predict the values of cells at locations that lack sampling points. Because data stations were arranged in a mesh grid pattern, the kriging tool in the geostatistical analyst toolbox was employed to evaluate and fit a mathematical function by considering four data nodes on all corners of the square plus two additional nearby points. With reference to Figure 3, the values of Cells A–D are known.

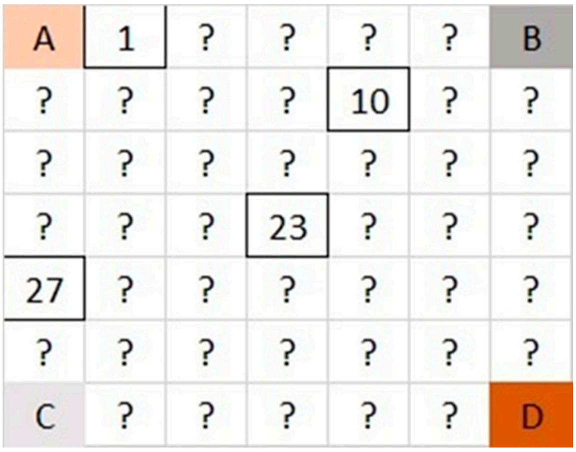

Figure 3. Kriging Analysis Explanation.

The spatial analyst tool assigns a linear weight to the values in Cells A–D to predict the value for Cell 1. The assigned weight is based on their distance from cell 1 and the known values in these cells. It is clear that, during the prediction of Cell 1, the value in Cell A l gets a higher weight compared to those of other cells.

Similarly, for Cell 10, the value in Cell B will have a higher weight compared to those of other cells. For Cell 23, the weights of Cells A–D will be equal, although their net weight may differ. After statistical interpolation and fitting a mathematical function, the analyst generated a variogram model to create a surface from these points. Figure 4 shows the flow chart of the research methodology.

The statistical validation process establishes trends and generates autocorrelation models using all of the input data, and then validates the generated maps by removing each data point one by one to predict its value using all other data points. A geostatistical method employing the kriging technique was selected for the cross-validation of generated maps. Figure 5 shows the validation flow chart.

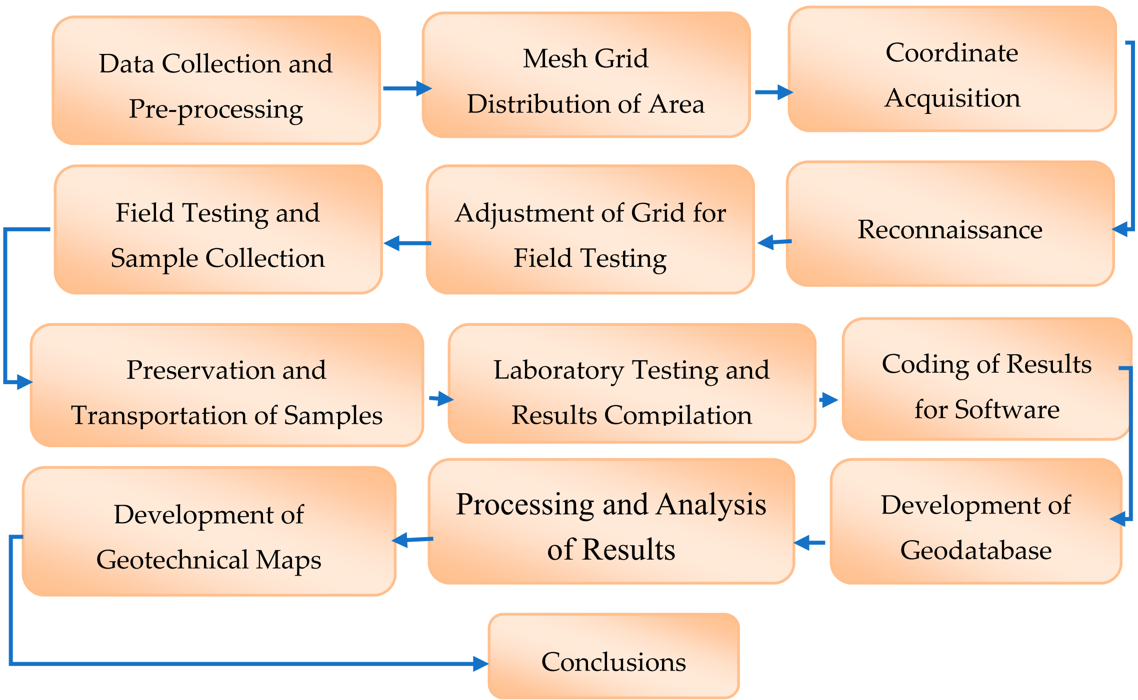

Figure 4. Flow of the Research Work.

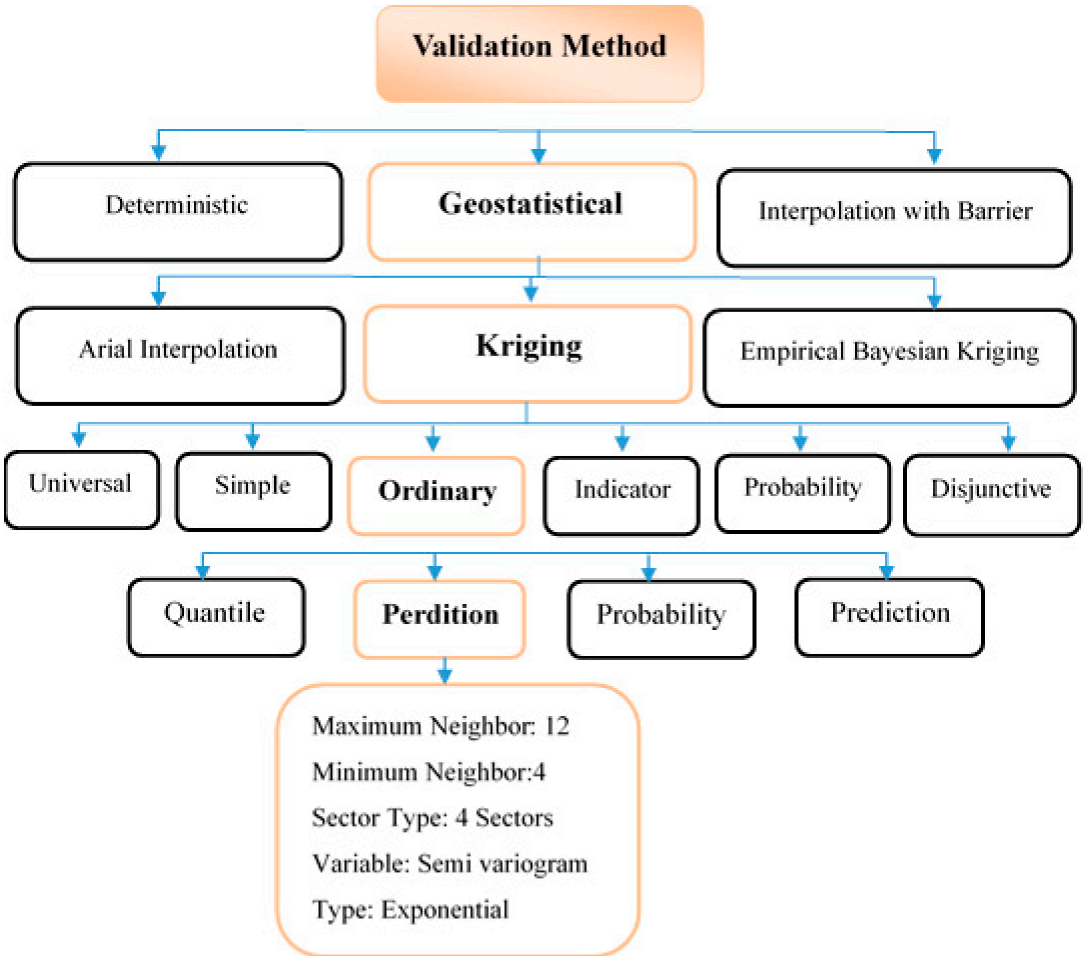

Figure 5. Validation Process of the Generated Maps.

3. Results and Discussion

The determination of engineering soil classification and evaluation of the allowable bearing capacity of the soil are integral parts of the soil exploration program for any civil engineering project. The AASHTO subgrade rating is the most important evaluation for route selection and design of highways and pavements. Testing, analysis, and interpretation of the collected soil samples led to the development of a collection of nine geotechnical maps, including three maps for engineering soil classification, three maps for AASHTO subgrade rating, and three maps for bearing capacity at 1.5-, 3.0-, and 4.5-m depths.

The maps for the AASHTO subgrade rating are shown in Figure 6. The AASHTO subgrade rating shows diversified formation in the region, ranging from excellent (i.e., A-1) to poor (i.e., A-7).

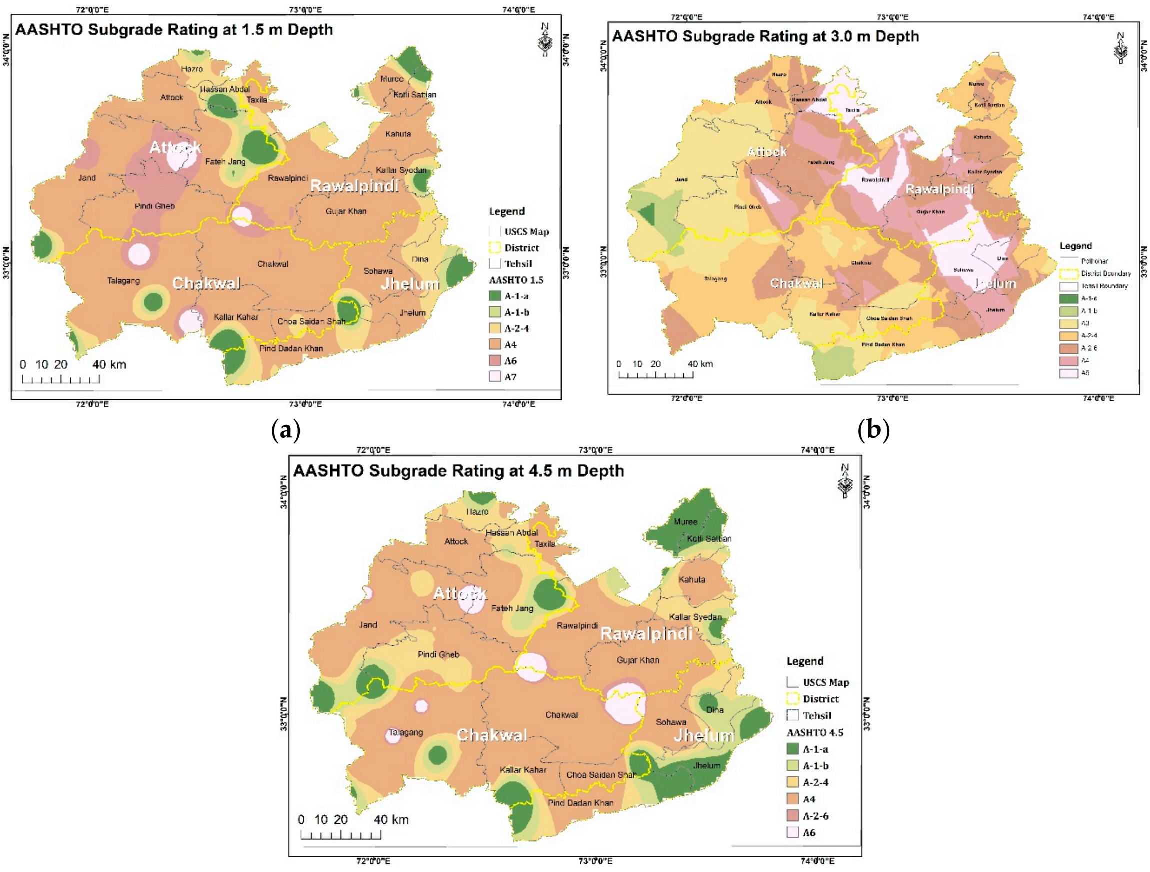

Figure 6. (**a**) AASHTO Subgrade Rating at 1.5-m Depth; (**b**) AASHTO Subgrade Rating at 3.0-m Depth; (**c**) AASHTO Subgrade Rating at 4.5-m Depth.

A-4 is the most prevalent subgrade rating at the depths of 1.5 and 3.0 m, while A-2-4 is dominant at the 4.5-m depth. These maps allow identifying potential merits or demerits of a route. Patches of problematic soils (i.e., A-6 and A-7) are visible in these maps.

Allowable bearing capacity maps are presented in Figure 7. Allowable bearing capacity in comparatively planer areas ranges from 50 to 300 KN/m^2 (0.5–3 tsf), while, in hilly terrain, it increases to 1100 KN/m^2 (11 tsf). These maps indicate a comparatively weaker or stronger soil and contribute to the feasibility assessment of proposed engineering work.

The maps for engineering classification of soil are shown in Figure 8. In addition, these maps show a diversified distribution of soil types. Fine-grained soils are dominant in the central part, while coarse-grained soils are prominent towards the edges at a shallower depth, i.e., 1.5 m. At 3.0-m depth, sandy soils overtake fine soils. Gravels are dominant at 4.5-m depth.

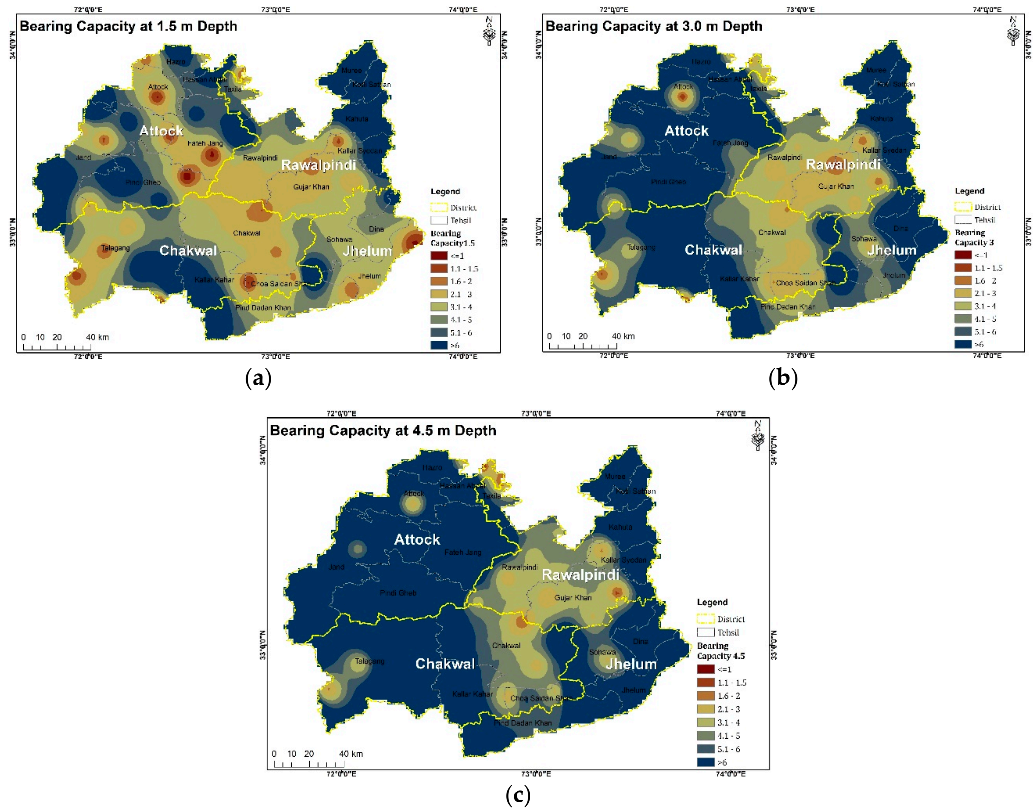

Figure 7. (**a**) Allowable Bearing Capacity at 1.5-m Depth; (**b**) Allowable Bearing Capacity at 3.0-m Depth; (**c**) Allowable Bearing Capacity at 4.5-m depth.

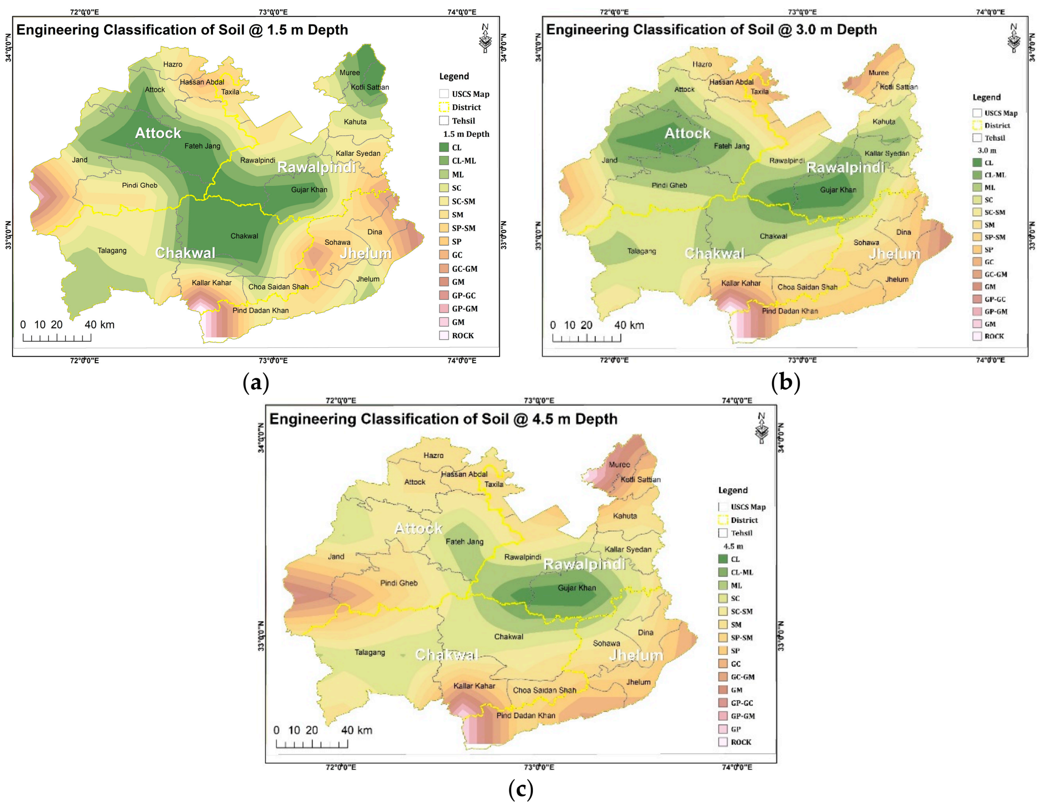

Figure 8. (**a**) Engineering Classification of Soil at 1.5-m Depth; (**b**) Engineering Classification of Soil at 3.0-m Depth; (**c**) Engineering Classification of Soil at 4.5-m Depth.

This gradual change in the gradation of soils agrees with the weathering phenomenon. Top layers are more weathered than deeper layers. This observation is also an indication of a gravity depositional deposit. The developed map is the first of its kind; it incorporates geotechnical properties of the region.

This tool is ready to be used as a design aid, especially for feasibility studies, and to improve rough cost estimates. The accuracy of maps generated using the kriging interpolation technique under spatial analyst tools was verified in two layers. Initially, a geostatistical wizard was employed to validate maps. First, the cross-validation process established trends and generated autocorrelation models using all of the input data; then, it performed validation by removing each data point one by one to predict its value using all other data points. The statistical regression function (RF) and the comparison of predicted and measured values are shown in Figure 9. The average standard error for the measured and predicted values is determined as 0.145, 0.237, and 2.396 for AASHTO, bearing capacity, and Engineering Classification (USCS) maps, respectively. Root mean square was 0.031, 0.064, and 1.858 for AASHTO, bearing capacity, and USCS, respectively.

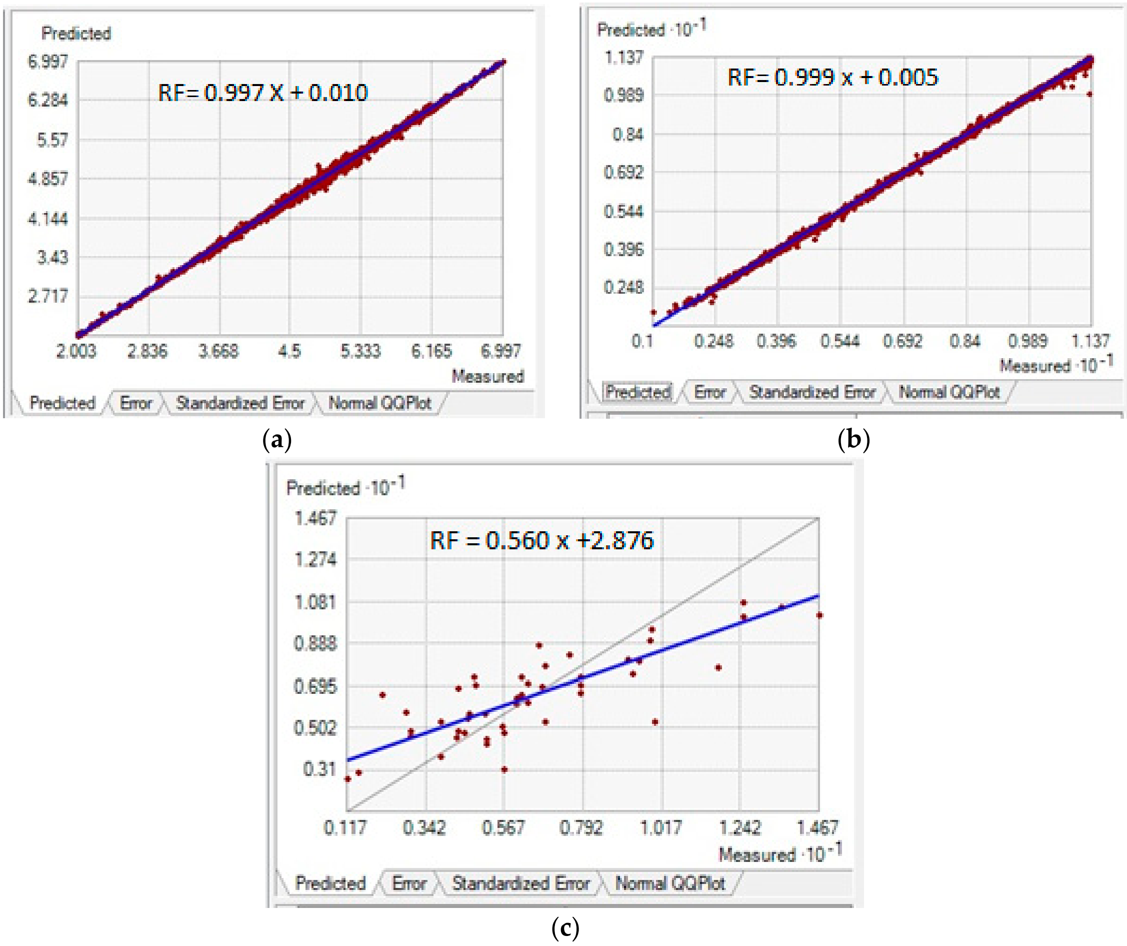

Figure 9. (**a**) Statistical Evaluation of AASHTO Map; (**b**) Statistical Evaluation of Allowable Bearing Capacity Map; (**c**) Statistical Evaluation of Engineering Soil Classification Map.

To assess the accuracy of generated maps for the unseen data, another innovative technique was employed by collecting additional samples from 10 additional field survey sites and comparing the actual test results with the corresponding values in the developed maps. The statistical comparison of generated and measured cell values is shown in Figure 10.

The obtained results show that the kriging technique adequately maps the geotechnical parameters, and these parameters are similar to original measurements. From a geotechnical engineering point of view, the interpolated values were acceptable for the feasibility and planning stages of infrastructure development projects. In addition, these maps supplement each other and further strengthen the derived conclusions from individual maps. The capability of the ArcMap software to house a 1-TB-file database can considerably reduce the hazardous management of conventional printed data boxes. The database can be further converted into meaningful and ready-to-use technical information. Upon the closure of megaprojects, storage of files and data boxes remains troublesome; typically, these data, which are worth millions of rupees, are destroyed owing to the inability to physically manage them. Without the ability to manage data electronically, the quality of works suffers, and hundreds of millions of rupees worth of data is lost forever. Millions of rupees can be saved if the geotechnical data were properly managed and represented. This study is an effort to create an electronic database and generate ready-to-use maps in three spheres of geotechnical engineering.

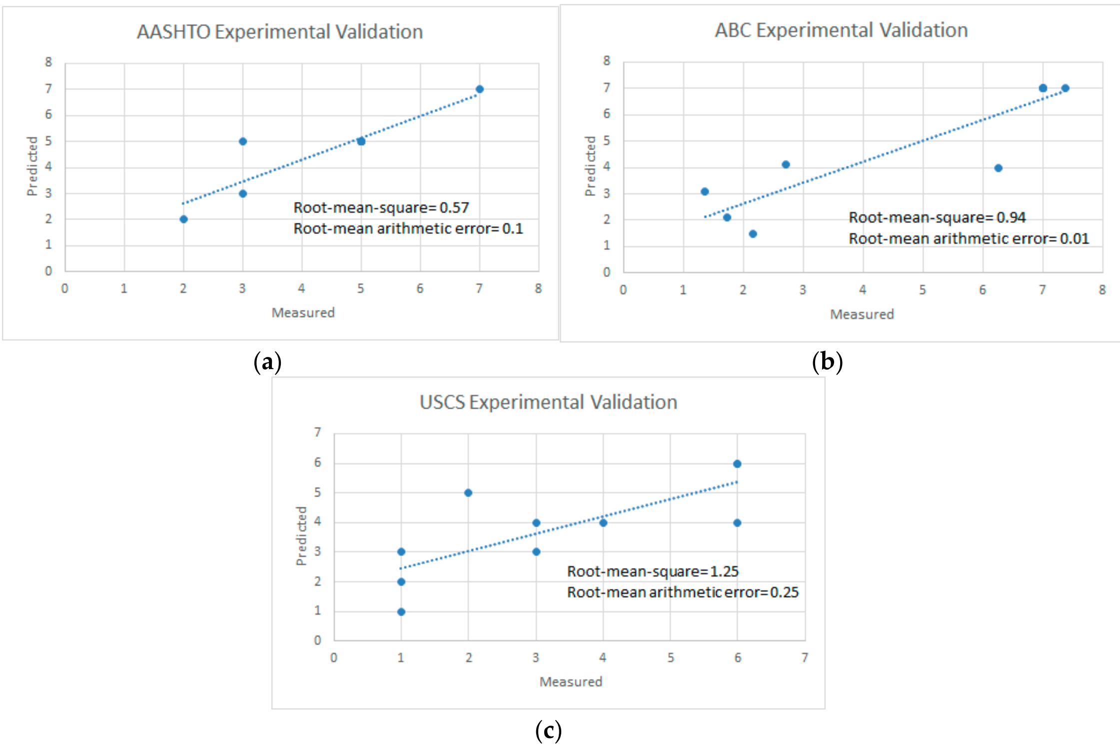

Figure 10. (**a**) Validation of AASHTO Map Using Unseen Data; (**b**) Validation of Allowable Bearing Capacity Map Using Unseen Data; (**c**) Validation of Engineering Classification of Soil Map Using Unseen Data.

After extensive field exploration, a regional geotechnical map was developed using the kriging analysis technique, which is available under spatial analyst tools of the ArcGIS software. The distribution of field survey sites in a grid pattern is also an innovative approach, which provides uniformly spaced samples for subsequent evaluations.

4. Conclusions

The geotechnical maps developed in this study demonstrate various geotechnical properties in the region. They represent the spatial distribution of soil in the region as per the engineering classification ofsoils, AASHTO subgrade rating, and allowable bearing capacity for 1.5-, 3.0-, and 4.5-m depths.

The developed electronic database can be extended to evaluate correlations between the geotechnical properties of soil. For example, the relationship between gradation and bearing capacity of soil, the correlation between soil types and bearing capacity, and the correlation between physical properties and engineering properties of soil can be developed. The developed database may also facilitate the training and testing of machine learning algorithms for prediction purposes. A-4 is the most prevalent subgrade rating at the depths of 1.5 and 3.0 m, while A-2-4 is dominating at 4.5-m depth. These maps allow identifying potential merits or demerits of a route because the patches of problematic soils (i.e., A-6 and A-7) are visible in these maps; these soils are unsuitable as supporting or construction materials, and these types of soil have to be removed from the site, owing to their swelling potential and collapsible behavior. Allowable bearing capacity in comparatively plain areas ranges from 1 to 3 tsf, while, in hilly terrain, it ranges from 3 to 9 tsf. Although kriging is now a commonly employed technique in environmental and social sciences, its suitability for geotechnical interpolations (especially for this region) was evaluated in this study. It is concluded that kriging statistical analysis is a reliable technique for the generation of geotechnical properties using available data points.

The absence of GIS-based geotechnical mapping is a particular issue for this study site, and geotechnical data are managed primarily in printed form in this region. The developed geotechnical maps will decrease the time and cost required for the preliminary investigation of large-scale projects and serve as a ready-to-use database for low rise residential units because preliminary foundation design recommendations (e.g., type of foundation, tentative allowable bearing capacity, and probable depth of foundations) may be determined using these maps. The selection of suitable routes for highways by avoiding patches of poor subgrade ratings can also be performed. These maps can serve as a tool for the selection of suitable borrow areas (by showing excellent to good subgrade rating) for highway embankments. The outcome of this study simplifies the screening process of available sites for a particular project without requiring considerable financial implications.

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