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Geotechnical evaluation of the alluvial soils for urban land management zonation in Gharbiya governorate, Egypt

Alaa A. Masoud

Geology Department, Faculty of Science, Tanta University, 31527 Tanta, Egypt

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ABSTRACT

Geological and geotechnical information from 534 borehole in-situ- and lab-based measured soil water conditions (Cl^- and SO_4^{-2} ion concentrations and depth to water), plasticity, unconfined compression, and consolidation parameters for alluvial clays have been analyzed. Multivariate factorial and clustering along with the geostatistical ordinary kriging techniques were used and evaluated in a Geographic Information systems (GIS) environment. The prime objective was to spatially model the geotechnical variability and to derive the loading factors along with recognition of the distinctive spatial geotechnical zones in terms of their likelihood of occurrence. Results have been, for the first time, presented for the alluvial soils of the Gharbiya governorate, Egypt with the principal management zones and their associated geotechnical risks in the main eight districts were characterized and evaluated for their favorability for construction.

Plasticity charts indicated that the soils are inorganic cohesive highly plastic clays. Geotechnical parameters showed wide ranges evidenced by their large standard deviations. Principal five factors dominated with good correlations to the swelling potential (0.90), compression index (0.74), depth to water (−0.41), soil water salinity contents of Cl^- (−0.64) and SO_4^{-2} (−0.60), and the clay layer thickness (0.59), arranged respectively in their decreasing contribution to more than 70% of the total spatial variability. Three distinctive management zones were delineated with reference to construction favorability. The first zone showed the highest favorability for construction being characterized by lowest potentials to swelling and the Cl^- and SO_4^{-2} contents and hence corrosion. Characterized by a water level approaching the ground surface, largest Cl^- and SO_4^{-2} contents violating the severity limits, and largest swelling potential, the second zone attained the lowest construction favorability and therefore safety measures should be applied. The third zone clarified intermediate favorability evidenced by the moderate severity from the Cl^- and SO_4^{-2} contents, and low swelling potential. Geotechnically at-risk areas characterized the main industrial cities; Kafr Al-Zayat, Al-Mahala Al-Kubra, and Tanta. Kafr Al-Zayat attained the most saline water (Cl^- and SO_4^{-2} contents) and hence high severity to damage associated and the most over consolidated soils. Al-Mahala Al-Kubra possessed the largest compressibility potential associated with the presence of organic silty clay intercalations. Swelling potential was largest in Tanta. The results of the employed approach can help to establish geotechnical land management zones with construction favorability for safe urban expansions.

1. Introduction

Managing environmental risks for successful rational land use planning and development in rapidly growing cities with high anthropogenic pressure require in depth knowledge and accurate modeling of the spatial variability of the geological and geotechnical properties of the soils upon which cities were built (Cendrero et al., 1990; Mendes and Lorandi, 2008; Sharafi et al., 2009; Anbazhagan et al., 2010; Kolat et al., 2006, 2012; Donghee et al., 2012). Disparate sources related to the geological and hydrogeological conditions, climatology, and the human practices that may act simultaneously with different intensities pose challenges to the accurate geotechnical variability modeling of soils (Fenton and Griffiths, 2002; Antonio-Carpio et al., 2004; Breysse et al., 2005; Chang et al., 2005; Phien-wej et al., 2006; Chrétien et al., 2007). The alluvial clays, in particular, constitute significant risk to constructions in terms of their ability to swell or to shrink and hence to volume change and are most commonly over-consolidated (Dhowian et al., 1985) that result in land subsidence, differential settlements, and building collapse (Bell and Jermy, 1994;

E-mail address: alaamasoud09@live.com

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Bell and Maud, 1995; Stavridakis, 2006; Hyndman and Hyndman, 2009). Also, the soil Cl^- and SO_4^{-2} contents of when violating the permissible limits can cause severe damages to the concrete contents of the structures (SBC, 2007; ACI, 2008). Yet, changes to the volume and the Cl^- and SO_4^{-2} contents of these clays are significant in the arid and semi-arid areas justifying their mutual analysis to disclose their geotechnical risks. In these areas, the change of the soil water content is widely related to high evapotranspiration of vegetation that sometimes exceed four times the precipitation (FAO, 1998), brought about by local site changes such as leakage from water supply pipes or drains, or associated with a pattern of short periods of rainfall followed by long dry periods resulting in seasonal cycles of soil swelling and shrinkage (Nelson et al., 2001; Cameron, 2006; Clayton et al., 2010). However, the geotechnical tests that are widely performed to understand the potential problems of soils can be time-consuming, expensive, and limited. The aforementioned challenges therefore make unraveling the accurate spatial geotechnical and geological constraints of these clays and their spatial variability imperative for investigating the land suitability for construction and for land use management on the limited soil resource. This can play a decisive role to help efficiently prioritize management zones with cost effective optimization of the construction times, efficient setting of mitigation measures, and designing projects for safe extension with appropriate and reliable foundation system to compensate for risks or over-costs (e.g. Tilford, 1994; Parsons and Frost, 2002; Hack et al., 2006; De Rienzo et al., 2008). This dictates the use of a multidisciplinary approach that can integrate the multivariate statistical and geostatistical techniques in a Geographical Information Systems (GIS) environment. These techniques proved indispensible in risk assessment of trace elements in agricultural soils in China (Chen et al., 2008), lead in mining site in Ireland (McGrath et al., 2004), and for delineation of agricultural management zones (Moral et al., 2010).

The present research therefore aims at evaluating the integrated use of the multivariate statistical (factor and cluster analyses) and the ordinary kriging for spatial variability mapping and analysis of the geotechnical characteristics of the alluvial clays. A special focus is devoted to characterizing the geotechnical risks related to the fluctuating soil water conditions, i.e., Cl^- and SO_4^{-2} contents, water table, and the clay layer thickness, along with the soil's swelling and compressibility potentials. Integration of the adopted techniques aimed at answering the question: how can the numerous geotechnical parameters be synthesized into few spatial management zones of specific characteristics to simply assess the suitability for land development? Such study has been rarely addressed in Egypt and therefore the employed techniques have been applied to a case study area, the Gharbiya governorate, despite of the significant socio-economic impacts from the geotechnical risks where the effects of catastrophic events are often amplified by the high anthropic pressure and the ineffective land management.

2. Study area

Gharbiya governorate, located in the middle Delta region, consists of eightdistricts: Tanta, Al-Mahala Al-Kubra, Kafr Al-Zayat, Bassiyun, Qutur, Samannoud, Al-Santa, and Zefta, covering an area of about 1942 km^2 of the Nile delta (Fig. 1). The landuse varies between cultivated (1658 km^2), residential (214 km^2), and barren/utility lands (70 km^2). The governorate consists of main 8 districts, 317 villages, and 1249 small hamlets. The area overlies Holocene soils forming the flat-lying alluvial plain averaging 8.5 m a.m.s.l ranging between 11 m at the south and 3 m at its northern part (Fig. 2). The soils comprise of Bilqas Formation underlain by Mit Ghamr Formation. Bilqas Formation forms the top layer of the flood plain of the modern Nile made up of silty clay, brown at the top and gray in the lower part, constituting the agricultural soil of the delta (Fig. 3). Black and gray clays dominate in Zifta close to the Dameitta branch. Organic clay seams with coal intercalations prevail with thickness averaging 1 m in Al-Mahala Al-Kubra and 3 m in Samannoud. The clays of the Bilqas Formation are dominated by montmorillonite (Zaghloul et al., 1977), which is characterized by its high shrinking and swelling properties. Mit Ghamr Formation consists of a thick succession of unconsolidated sands and gravels deposited under continental, lagonal, fluviatile and beach environments.

The governorate is marked third (2258 person/km^2) of the highly populated governorates in Egypt (CAPMAS, 2012). The population has reached 4,439,000 in 2012, which has been doubled since 1976. This urban overgrowth underpinned with high demand for housing and lack of desert hinterland has exceeded the capacity of the governorate stressing the ability of the local government to provide serviced land. Informal settlements had accordingly proliferated, the population of which reached 30.8% out of the total population (GOPP, 2010). These have adversely affected the housing quality indicators at the level of residential units. Yet, the alluvial clays pose significant hazard to constructions that has recently resulted in the incessant occurrence of road pavement failure, land subsidence, differential settlements, and building collapse. The accurate identification of the spatial constraints of the limited soil resource is crucial to help efficiently prioritize areas with geotechnical risks or over-costs. This could help better selection and design of an appropriate and reliable foundation system for safe extension and sustainable urban development that could contribute to solving the problem of housing shortage.

3. Data and methodology

3.1. Geotechnical data analysis

The geotechnical data of the soils were collected from the schools and sewage construction projects carried out by the soil mechanics and foundation research laboratory, Faculty of Engineering, Cairo University and by the Arab Contractors company's Headquarter in Gharbiya. Geological investigations, in-situ, and lab-based geotechnical tests from 911 boreholes were filtered and 534 boreholes were selected according to specific criteria and were homogenized, classified, and archived in a GIS database thus far. Filtering criteria were based on selecting boreholes with a reliable location, a detailed measured stratigraphic logs with continuous coring vertical profile up to a depth of 20 m from the surface, and with complete in-situ and laboratory tests and statistically homogeneous with the whole data above 95% confidence level. Geospatial referencing was carried out where the borehole location and ground surface elevation was field-determined using GARMINGPSmap62SJ device.

The selected boreholes have a set of geotechnical information comprising the most relevant 16 properties—thickness of the clay layer, soil water chemistry (Total Dissolved Solids-TDS, and the contents of Cl^- and SO_4^{-2}), Atterberg consistency limits (Natural Water Content – NWC %, Liquid Limit – LL %, Plastic Limit – PL %, Plasticity Index – PI %, and the Consistency Index – C_i), Unconfined Compression Tests (Unconfined Compression Strength – UCS, and Dry Density – DD), Consolidation Tests (Initial Void Ratio – IVR, Effective Overburden Pressure – EOP, Over Consolidation Ratio – OCR, Pre-consolidation Pressure – PP, and the Compression Index – C_c). The depth to water table and the ground surface elevation was also measured and included in the analysis. Descriptive