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Comparison of methods for predicting regolith thickness in previously glaciated terrain, Stockholm, Sweden

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ABSTRACT

Knowledge about regolith thickness is important in several civil and environmental engineering fields. However, subsurface characteristics such as regolith thickness are difficult to determine through surface investigations and maps at regional scales. This paper presents four methods for estimating regolith thickness in a GIS environment for previously glaciated terrain with high frequency of rock outcrops: linear regression (LR) using topographical covariates; inverse distance weighting (IDW) interpolation of regolith thickness point data from well drillings; a trigonometrical approach (TA) developed for this study which uses outcrop slopes and distance between outcrops; and a simplified regolith model (SRM). The SRM is a model modified from TA which estimates the regolith thickness based on outcrops, slopes and the distance to outcrops in eight directions. The methods were compared for three study areas (Tyresö, Vallentuna and Österåker) in Stockholm County, Sweden. Based on the results in this paper, LR proved to be the most accurate method for regolith thickness estimation, measured through root mean square error values. Whereas IDW was the most accurate method in terms of error within ±2 m, which would make it a suitable model if and when large datasets of regolith point data are available. When drilling data is scarce then both the TA and SRM methods can be used for regolith estimations. However, the SRM proved to be a more accurate regolith thickness model compared to TA. SRM shows promising results and could be used at a preliminary stage in engineering projects where little or no data is available prior to detailed field investigations in previously glaciated terrain.

1. Introduction

Knowledge about regolith thickness, unconsolidated earth materials above the solid bedrock (National Resources Conservation Service, 2012), is important in various engineering fields. For instance, in the field of hydrology, regolith thickness and stratigraphy influence hydrological processes (Fu et al., 2011; Schoeneberger and Wysocki, 2005) and facilitates saturated depth ratio calculations (Ho et al., 2012). Regolith thickness is also important when quantifying the aquifer recharge, e.g. storage capacity, for instance when designing rainwater harvesting structures such as subsurface dams (Jamali et al., 2013). Physical processes such as landslides, erosion and liquefaction are sensitive to regolith thickness and slope gradient (Chartin et al., 2011; Ho et al., 2012; Shafique et al., 2011; Tarolli et al., 2008; Yamakawa et al., 2012). In the field of transportation planning (road and railway) water is the most common factor which triggers instability such as landslides, where soil depth is a major determinant of the rate of this process (Kuriakose et al., 2009; National Cooperative Highway Research Program, 2012). Hence geotechnical instability analysis and mass balance calculations are important to undertake due to costs coupled with ground stabilization measures, which can have an adverse effect on the total project cost (Loorents, 2006). Generally, project costs increase and reach a maximum value towards the finalization stage as opposed to data collection which is highest in the initial stage of planning. During the initial stage, alternative route corridors have to be determined based on available information. This available information, such as regolith thickness, rock outcrop locations and soil type are mainly derived from already existing documentation. Therefore the incitements for field investigations are low and thus seldom carried out in this context (Swedish National Road Administration, 2002). However, generally problem arises when existing documentation is lacking for an area.

Subsurface characteristics such as regolith thickness are difficult to determine through surface investigations and maps at regional scales. However one way to determine regolith thickness is to use geophysical methods such as electrical resistivity (De vita et al., 2006; Shafique et al., 2011; Yamakawa et al., 2012). Although the use of geophysical methods such as electrical resistivity can result in accurate regolith thickness estimation, depending on expert knowledge and interpretation, it is still not an appropriate method for large scale analysis; attributed to issues such as cost and time of

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sampling. Therefore, modeling and interpolation techniques are often used as an information enhancement tool. Development of Geographic Information Systems (GIS) has enabled the handling of large volumes of multidisciplinary data. This capability reduces the time, expenditure and labor needed in order to study aspects such as the hydrogeological and geotechnical conditions (Chowdhury et al., 2010; Huang et al., 2010; Kumar et al., 2008; Pandey et al., 2011; Trabelsi et al., 2011).

Modeling and prediction of regolith thickness using GIS is documented in various studies. For instance, Delmonaco et al. (2003) developed a deterministic distributed model using GIS for large-scale debris flow hazard analysis based on slope angles and soil thickness. Wilford and Thomas (2013) described a piecewise linear regression digital soil mapping approach using commonly available environmental covariates to predict soil thickness. Tesfa et al. (2009) reported the relationship between soil depth, topographic and land cover attributes for soil depth prediction using GIS through Generalized Additive Models and Random Forests. Other approaches used terrain attributes such as elevation, aspect and slope for regolith modeling through kriging interpolation techniques (Hedenström et al., 2008; Nyman et al., 2008; Penížek and Borůvka, 2006) or statistical models such as linear regression (Kuriakose et al., 2009; Tsai et al., 2001). Pelletier and Rasmussen (2009) and Crouvi et al. (2013) predicted soil thicknesses by numerical modeling whereas Rochat et al. (2012) suggested a seismic method using spectral analysis of surface waves with an empirical law derived from terrain attributes to predict soil thickness. Kuriakose et al. (2009) concluded that rock outcrops are a major controlling factor for soil depth.

In Sweden one important data source for predicting regolith thickness is the well archive database. Since 1976 it is mandatory to report information about new wells (Geological Survey of Sweden, 2013a) such as technical information of well depth, soil depth and groundwater levels. The well archive database contains approximately 500,000 wells for the entirety of Sweden (Geological Survey of Sweden, 2013a, 2013b). The Geological Survey of Sweden (2013c) modeled regolith thickness at regional scales using interpolation of regolith thickness values from well point data, other drillings, seismic investigations, shafts and geological maps. An additional 10 to 20 m was added to the thickness model where lineaments in the bedrock were present, in order to account for a regolith thickness known to be deeper in those areas. This SGU model produces good results but is data driven. The wells used are generally located in populated areas, thus the regolith thickness modeled is uncertain for areas without data. Therefore, a new modeling approach based on other easily attainable geological information for these areas such as existence of rock outcrops, elevation and slopes might be useful. In Sweden, digital information about these factors is available from various sources and covers the entire land surface. Modeling regolith thickness based solely on rock outcrops and slopes has not been performed previously (to the best of the authors' knowledge).

The objective of this study was to develop, test and compare a simplified regolith model (SRM) for estimating the regolith thickness in previously glaciated terrain with high frequency of rock outcrops, based on an easily available digital elevation model (DEM) and an optimized outcrop search algorithm. The SRM results were compared to the results produced by two data driven, empirical, models derived from the input of data of the dependent variable, i.e. a linear regression (LR) model using topographical covariates and an inverse distance weighted (IDW) interpolation of well archive data. The SRM was also compared to a non-data driven model derived from topographical features, i.e. a simple trigonometric approach (TA) using slope outcrops and distance between them. The methods were tested and compared in three different study areas (Tyresö, Vallentuna and Österåker) in Stockholm County, Sweden, in order to determine if the SRM can be used in a data-sparse environment with different topographical settings to estimate regolith thickness.

2. Materials and methods

2.1. Study areas

Three study areas within the Stockholm region, Sweden, were chosen based on relative differences in topographical variation (Fig. 1), geology (Fig. 2a–c) and data availability.

As opposed to the rest of the world where three quarters of the Earth's surface is covered by sedimentary bedrock (Boggs, 2009), the Swedish bedrock predominantly consists of Pre-Cambrian basement rocks (part of the Fennoscandian Shield). In the Stockholm region the basement is predominantly composed of meta-sedimentary or meta-volcanic rocks from the Svecokarelian Orogeny, 2.1 billion to 1.8 million years old (Geological Survey of Sweden, 2004, 2013d). The weathered zone of the rock is usually very thin, often less than 1 cm due to a rather short exposed period since the last glaciation.

This region had multiple occurrences of glaciation periods which led to the formation of the existing sediments. The bedrock is usually overlaid by Quaternary unconsolidated glacial (glaciofluvium and till) and post glacial (clay, silt and organic) sediments. Till is a poorly-sorted sediment that was deposited directly from glaciers with a grain-size distribution ranging from clay to boulders. The glaciofluvium deposited from glacial rivers form long ridges of sorted sand and gravel, called esker ridges, oriented roughly parallel to the ice flow direction (Andersen and Borns, 1997; Flint, 1971). When the glacier border retreated the land surface was submerged due to pressure of the ice cap. Consequently a period of rapid upheaval occurred and acting waves, from the melting water and seawater, swept the sediments overlaying the highest peaks in the topography down towards the depressions in the terrain. The removal of the sediments on the topographical peaks by the acting waves revealed the glacier polished surfaces of rock underneath, i.e. bedrock outcrops. At a landscape scale the polished rock outcrops created the characteristically roche moutonnées (rolling hills) seen across the Stockholm County.

During the submergence of the region thick sequences of post glacial sediments were deposited. Clay was deposited in the depressions in the landscape (Fig. 2a–c), often formed from fracture zones, which were deepened and widened through erosional processes (Swedish Museum of Natural History, 2012). In some valleys the clay can be up to 20 to 30 m thick. Lakes have commonly been filled with organic mud and peat. Sediments cover about 85% of the land surface in the Stockholm County. Outcrops of bedrock cover 15% of the land surface in the Stockholm County compared to the average 3% for Sweden (Geological Survey of Sweden, 2013e).

The main idea behind the use of topographical data from visible outcrops was derived from the geological processes, tectonic and erosion events, which affected the visible as well the hidden parts of the bedrock surfaces and topography. The slow weathering of the Pre-Cambrian basement rock as well as the relocation of sediments after the glacier front retreated resulted in a stable topographical environment and preservation of the bedrock topography where the visible parts of the bedrock often can be considered to reflect the hidden parts (Fig. 3a–b). Outcrop slopes can therefore be considered a reasonably stable input parameter in both the TA and SRM models.

2.1.1. Tyresö

Tyresö municipality (Fig. 1) is situated 20 km south-east (59°13 N, 18°22 E) of Stockholm, Sweden and has a surface acreage of 70 km^2 (Sveriges Nationalatlas, 2009a; Tyresö kommun, 2012). The minimum and maximum elevations are 0 and 85 m respectively. Tyresö is geologically characterized by an undulating landscape with steep bedrock ridges of either gneiss or granite, and narrow long valleys with clay, peat and till (Fig. 2a) (Tyresö kommun, 2003). Bedrock outcrops cover 52.9% of the total surface area (Fig. 4). The