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Developing a geotechnical database to improve slope stability assessments in Quito, Ecuador

Développement d’une base de données géotechniques pour améliorer les évaluations de la stabilité des pentes en Quito, Equateur

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ABSTRACT: Quito, Ecuador, is a city at risk of many hazards including earthquakes, volcanic eruptions and landslides, compounded by the widespread presence of problematic volcanic soils known as Cangahua. This paper presents the preliminary results of data analyses undertaken on a new geotechnical database for Quito, compiled from a variety of sources. It is envisaged that this database will be utilised primarily for improving our understanding of landslide hazard drivers in communities in and around the city. The preliminary statistical analyses include probability density functions and regression models for soil parameters. A difference in geotechnical variability between the north and the south of the city was observed. The study also presents data from unmanned aerial vehicle (UAV) mapping of an informally constructed hillside community in Quito, identifying house-scale slope features (e.g. cut slopes and house loading) that may affect local landslide hazard processes. Together, the statistical analyses of these datasets will provide the inputs for physics-based stochastic slope stability modelling. Recommendations for future data collection are given to support the development of a higher resolution Quito database and facilitate the improvement of community-scale slope stability assessments.

RÉSUMÉ: Quito, en Équateur, est une ville exposée à de nombreux risques, notamment des tremblements de terre, des éruptions volcaniques et des glissements de terrain, aggravés par la présence des sols problématiques d’origines volcaniques, "Cangahua". Cet article présente les résultats préliminaires des analyses entreprises sur une nouvelle base de données géotechniques pour Quito. Il est envisagé que cette base de données soit principalement utilisée pour améliorer notre compréhension des moteurs de l’instabilité des pentes dans la ville et ses environs. Une analyse statistique préliminaire est présentée, comprenant la création de fonctions de densité de probabilité et de modèles de régression pour les paramètres du sol. Une nette différence de comportement géotechnique entre le nord et le sud de la ville est mise en évidence. Une expédition de véhicule aérien téléguidé pour la cartographie d’une communauté informellement construite sur le flanc d'une colline est décrit, dans l'objectif d’identifier les éléments à l’échelle locale qui peuvent effectuer les glissements de terrain (e.g. la longueur et l'inclinaison de la pente, la charge structurale des maisons). En combination, l’analyse de ces bases de données des sols et des pentes fournira des contributions pour la modélisation stochastique et physique du stabilité des pentes. Des recommandations pour la collection des données géotechniques sont formulées dans le contexte du développer une base de données à plus haute résolution, menant l'amélioration des évaluations de stabilité des pentes à l'échelle communautaire.

KEYWORDS: geotechnical database, slope stability, UAV mapping, urban landslides

1 INTRODUCTION

1.1 *Geological and multi-hazard setting*

Ecuador’s capital, Quito, is located within the Inter-Andean Valley (IAV), a structural depression orientated approximately NNE to SSW, extending approximately 400km (Villagómez, 2003). The IAV is flanked to the West by the Cordillera Occidental and to the East by the Cordillera Oriental, surrounded by several volcanic complexes (O’Rourke & Crespo, 1988). As a result of this geological and tectonic setting, Quito is exposed to hazards such as earthquakes and volcanic eruptions, and hydro-meteorological hazards such as high intensity rainfall and landslides (Bucheli & Alvear M, 2018). The Quito Metropolitan District (DMQ) is home to nearly three million inhabitants, many of whom live in landslide-prone locations such as the steep soil-mantled slopes surrounding the city. Even small changes to natural slope surface cover, topography, drainage, and loading can decrease stability (Anderson & Holcombe, 2013). Within this multi-hazard environment, rapid urban expansion onto such slopes is potentially increasing the risk to life and infrastructure.

1.2 *Data for landside hazard assessment in Quito*

The soils in Quito are highly variable. Traditionally, soil testing undertaken at the numerous national engineering consultancies and universities has focussed on strength testing using the quick undrained triaxial method (e.g., ASTM, 2015) which provides estimates of total strength parameters. For rainfall-induced landslides the drained soil conditions are most relevant (e.g. Leroueil, 2001) and effective strength estimates are required for slope stability models such as the Combined Hydrology And Stability Model, CHASM (Wilkinson et al., 2002; Almeida et al., 2017). This type of soil testing may be accomplished by direct shear box (DS), consolidated drained (CD) triaxial, and consolidated undrained (CU) triaxial if pore water pressures are measured. However, dynamic hydrology-stability modelling is not often used in Quito, and the required soil tests are not routinely undertaken. Therefore, little such effective strength data exist for the DMQ.

In addition to soil properties, slope stability modelling requires data on natural slope angles, local slope cuts and fills, drainage conditions, loading by houses, and vegetation cover (Holcombe et al., 2016; Bozzolan et al., 2020). Where communities are informally constructed (i.e. without planning or engineering design) many of these localised slope characteristics may be undocumented on official maps. Here, aerial photography could potentially provide such information at a scale that will enable the localised drivers of urban landslides to be represented.

1.3 *Study Aims*

This study aims to mitigate the problem of data scarcity affecting slope stability assessments at community scales in Quito, with the following objectives:

(i) compilation of a preliminary database of available geotechnical information to support studies of urban landslide hazard drivers across Quito;
(ii) aerial mapping of a typical landslide-prone informal community and characterisation of local urban slope features affecting stability;
(iii) statistical analysis of the collated datasets to provide inputs for future stochastic slope stability model simulations.

2 QUITO SOILS AND THE NEW DATABASE

2.1 *Key features of Quito soils*

As a result of Ecuador's complex geo-tectonic evolution, the soils of the Quito Metropolitan District are highly variable. Much of the northern portion of the Inter-Andean Valley and the Southern Colombian Andes is dominated by volcanic soils pertaining to the Cangahua Formation, attributed to both volcanic and glacial processes, and is formed from altered tuffs, intercalated with ash deposits, pumice, lapilli, paleosoils and occasionally mudflows and alluvium (Villagómez, 2003, Hall & Mothes, 1997). The term "cangahua" or "cangagua" (a Quechuan word meaning "sterile ground") is frequently used to describe a particular volcanic soil type, rather than the Cangahua Formation as a whole. This term has been used in various ways: generally, it may refer to any indurated volcanic soil, without any consideration for its origins or diagenesis. More specifically, cangahua may refer to an indurated volcanic soil, derived from cemented ash deposits. Vera & Lopez (1992) define cangahua as a soft, porous rock, whilst Colmet-Daage, in descriptions of profiles in of the equatorial Sierra (made between 1974 and 1984), considers a cangahua as any hard layer encountered within the profile (Colmet-Daage 1974-1984). When attempting to compile geotechnical information from a range of diverse sources it is likely that there will be inconsistencies in the identification of soil types.

Cangahua-type soils may be highly variable due to their origins, evolving from ash depositions from the late Pleistocene to the Holocene, when the IAV was subject to steppe-like conditions (Hall & Mothes, 1997). Typical thicknesses of horizons are of the order of 10m to 30m (Iriondo & Kröhling, 2007), but may be up to 100m (Zebrowski, 1997). This variability is likely to be the result of transportation and weathering. Cangahua Formation depositions are often considered to have been reworked, such that they were scattered by wind and then settled under a humid climate, covering 20,000 km^2 of the Inter-Andean Valley (Iriondo & Kröhling, 2007). These soils are rich in volcanic material, poor in organic material, and are very stiff in dry zones, but much softer at higher altitudes subject to greater humidity (Zebrowski, 1997). Similarly, they may be easily excavated during the winter months, but not in the summer months (Gaibor Lombeida & Guano Zambrano, 2012). Although cangahua soils frequently form near-vertical slopes in valleys, they show very little resistance to weathering processes.

Qualitative information from observations and local knowledge is very useful for creating a holistic understanding of the hydrological and stability processes affecting cangahua soil slopes. The cemented soil structure does not readily allow the transmission of water, especially at depth (Creutzberg et al., 1990). As such, water runs off during heavy rainfall, eventually leading to erosion (Podwojewski and Germain, 2005), which then facilitates the wetting of the soil horizon. Upon wetting, cangahuas tend to disintegrate by slaking, since they are low in organic matter (Creutzberg et al., 1990), the presence of which tends to minimise slaking (Chenu et al., 2000). Studies have shown that the strength of cangahua soils is directly negatively affected by its degree of saturation, prompting authors to state that it is essential that local moisture conditions and rainfall scenarios are considered in slope stability assessments (O'Rourke & Crespo, 1988). It can be inferred that slopes built in cangahua soils may be considered stable after initial construction, but that stability is likely to be highly affected by weathering. Therefore, it is imperative that signs of weathering or other disturbance are addressed in a timely manner.

Broadly, a division can be made between the mechanical properties of cangahua deposits in the north and south of Quito (Guerrón Andrade and Tacuri Silva, 2012). This division is a function of differing volcanic conditions between the two zones: cangahua horizons in the north are suggested to have formed from primary ash deposition and pyroclastic flows, whilst those in the south are derived from mudflows and secondary (reworked) deposits (Vera and Lopez, 1992). These differences are reflected in the compositions of the different materials, such that northern deposits are andesitic to dacitic in nature, whilst southern deposits are dacitic to rhyolitic (EPN, 2019).

2.2 *Database assembly*

For a geotechnical database supporting rainfall-triggered slope stability assessments, the compilation of quantitative soil data was centred around the search for effective strength parameters (i.e. effective friction angle, ϕ', and cohesion, c') in published articles, reports and dissertations. Different testing apparatus and shear modes are present in the assembled database, including the results of direct shear (DS) and consolidated drained and consolidated undrained (with pore water pressure measurement) triaxial tests (TX). Data from these two broad test categories are denoted in this paper by the subscript "TX/DS". Quick (unconsolidated) undrained triaxial test data are denoted by the subscript "UU". UU data describe the total stress condition which is not directly relevant to rainfall-induced slope instability. That said, such data may be useful for other assessments e.g. short-term slope stability and therefore such data were included in the database. Table 1 lists the sources of the data that were included in the database. Table 2 gives details on the key geotechnical parameters including the best fit probability density functions (PDFs).

Cangahua soils are characterised as being highly sensitive to remoulding (Marín-Nieto et al., 2009), therefore, only strength parameters obtained from undisturbed samples were included (accepting that some degree of disturbance is almost inevitable). This consideration had the result of reducing the available dataset. As described in section 2.1, the term "cangahua" has a broad range of definitions according to the author and the context, therefore, most data entries are listed as cangahua, which may not necessarily reflect varying soil types within the area. Additionally, certain entries were described as "cangahua retrabajada", indicating that they were reworked or weathered, however, it cannot be assumed that other entries which do not specify this describe primary, unweathered cangahua soils.

2.3 *Data processing*

For each of the datasets, the number of datapoints with non-zero values (n) and the number of zero values present in the dataset (z) are noted in Table 2. For both the PDFs and regression models, the minimum number of data points required was set to 20, with the assumption made that datasets with fewer data points could not be meaningfully modelled (Minitab, 2017) using the approaches described herein. All geotechnical data were georeferenced, thereby allowing the data to be split into north and south Quito subsets, to investigate the suggestion of distinct geotechnical behaviour between the two regions, as described in section 2.1. To this end, a northing of 9976470 was used as the threshold for separation. Given that this study compiles a preliminary database, no outlier removal was undertaken (e.g. high effective cohesion values observed from Figure 1(b)).

Table 1. Quito geodatabase sources with test type and number of available datapoints. CD: consolidated drained triaxial test; CU: consolidated undrained triaxial test; UU: Unconsolidated undrained triaxial test; DS: direct shear test.

Source	**Type**	**n**
Crespo (1987) (see also O'Rourke & Crespo (1988))	CD	2
Montatixe Chicaiza & Chango Alvarez (2018)	CU/UU	7/12
Guadalupe Maldonado (2015)	DS/UU	9/3
Pachacama Caisaluiza (2015)	CU/UU	12/12
Jiménez (1999)	CU/UU	5/27
Bucheli & Alvear M (2018)	DS	1
Tenesaca Illescas & Caiza Flores (2019)	DS	42
Betancourt Campuzano (2018)	UU	1
Monereo Perez (2014)	UU	44
Flor Arroyo (2016)	UU	8
Cordovillo Flores (2018)	UU	3
Gaibor Lombeida & Guano Zambrano (2012)	UU	16
	Total	204

2.4 *Statistical Analysis*

For the parameters described in Table 2, various distribution types were fitted: normal (N), lognormal (LN), exponential (E), and Weibull (W). For datasets containing zero values, only non-zero distribution types could be fitted, i.e. normal and exponential distributions (indicated in Table 2 by *).

The goodness of fit was assessed using the Akaike Information Criterion (AIC), which simultaneously accounts for deviation from the model while minimising model complexity (Akaike, 1974). The standard and corrected (AICc) forms of the AIC were considered. The AICc is used for small-to-medium-size datasets, i.e. when the sample size, $n < 40$ (e.g. Hurvich and Tsai, 1989). The lowest value of the AIC or AICc describes the best fitted PDF. For verification of best fit, where $n < 40$, both AIC and AICc demonstrated the same assessment of best fit for all parameters.

The parameters listed in Table 2 were linearly regressed against each other. Different regression models were fitted: linear, power, exponential and logarithmic. The goodness of fit of each of these four models is assessed using the "r" and "p" values, which respectively describe the correlation coefficient, and the probability of the null hypothesis that the r value is zero (i.e. probability of no correlation) (e.g., Montgomery et al., 2007). The results of this analysis are discussed in section 4.1.

3 UAV MAPPING OF A HILLSIDE COMMUNITY

City-scale landslide susceptibility and hazard mapping in Quito has previously been undertaken using existing digital topography, land use, landslide inventory and seismic event maps (e.g. Jimenez, 1999). However, an assessment of localised slope features affecting slope stability in informal communities requires higher-resolution information at house plot scales. Given the covid-19 pandemic, field work by the local research team was limited and no house-to-house surveys were possible. However, mapping using unmanned aerial vehicles (UAV) has shown great applicability in disaster-prone and inaccessible regions (e.g. Daniel et al., 2009; DeBell et al., 2015 and Greenwood et al., 2019). Therefore, UAV mapping of slope features was trialled in a typical landslide-prone community situated in the north east of Quito, covering an area of approximately 20,000m^2. Aerial image processing was used to create orthophoto mosaics and a Digital Terrain Model (DTM), indicating a mean natural slope angle of 25° (maximum, 45°). Cross-sections of 90 houses and associated cut slopes were extracted from the DTM using Geographical Information System (GIS) software. Cut slope heights (mean: 4.6m) and angles (mean: 85°) and house dimensions were measured. Surface cover, construction materials (loading), household drainage and point water sources were identified from the aerial photos. Statistical analysis of selected UAV mapping data are presented in Table 2.

Table 2. Soil parameters and best fit PDF parameters (first 18 rows); selected urban parameters (last 6 rows). Params. 1 and 2 describe function fitting parameters: μ_N, σ_N and μ_{LN}, σ_{LN} for Normal/Lognormal distributions; A, B for Weibull distributions; μ_E for exponential distributions. *indicates where only non-zero distributions are fitted.

Soil property	**n (z)**	**PDF**	**Param. 1**	**Param. 2**
Effective friction angle, $\phi'_{TX/DS}$ (°)	78	N	$\mu_N = 30$	$\sigma_N = 7$
Effective cohesion, $c'_{TX/DS}$ (kPa)	36	LN	$\mu_{LN} = 4$	$\sigma_{LN} = 0.7$
Total friction angle, ϕ_{UU} (°)	116 (10)	N*	$\mu_N = 20$	$\sigma_N = 10$
Total cohesion, c_{UU} (kPa)	125 (1)	E*	$\mu_E = 60$	-
Liquid limit, *LL* (%)	51	LN	$\mu_{LN} = 4$	$\sigma_{LN} = 0.2$
Plastic limit, *PL* (%)	51	LN	$\mu_{LN} = 3$	$\sigma_{LN} = 0.2$
Plasticity index, *PI* (%)	50	W	A = 8	B = 2
Water content, *w* (%)	126	W	A = 30	B = 2
Saturation, *S* (%)	62	W	A = 90	B = 10
Bulk density, ρ (g/cm^3)	133	N	$\mu_N = 2$	$\sigma_N = 0.2$
Bulk unit weight, γ (kN/m^3)	134	N	$\mu_N = 10$	$\sigma_N = 2$
Void ratio, *e*	95	LN	$\mu_{LN} = -0.04$	$\sigma_{LN} = 0.2$
Porosity, η (%)	95	LN	$\mu_{LN} = 4$	$\sigma_{LN} = 0.09$
Specific gravity, G_s	62	N	$\mu_N = 3$	$\sigma_N = 0.06$
Sand Fraction, *SF* (%)	30	N	$\mu_N = 40$	$\sigma_N = 10$
Fines fraction, *FF* (%)	30	W	A = 60	B = 6
Altitude (m.a.s.l.)	80	LN	$\mu_{LN} = 8$	$\sigma_{LN} = 0.1$
Sample depth (m)	128	LN	$\mu_{LN} = 1$	$\sigma_{LN} = 1$
Natural slope angle (°)	90	LN	$\mu_{LN} = 3$	$\sigma_{LN} = 0.5$
Cut slope angle (°)	179	W	A = 90	B = 20
Cut slope height (m)	178	LN	$\mu_{LN} = 1$	$\sigma_{LN} = 0.5$
House height (m)	90	LN	$\mu_{LN} = 1$	$\sigma_{LN} = 0.3$
House length (m)	90	LN	$\mu_{LN} = 2$	$\sigma_{LN} = 0.5$
House orientation (°)	56 (34)	E*	$\mu_E = 60$	-

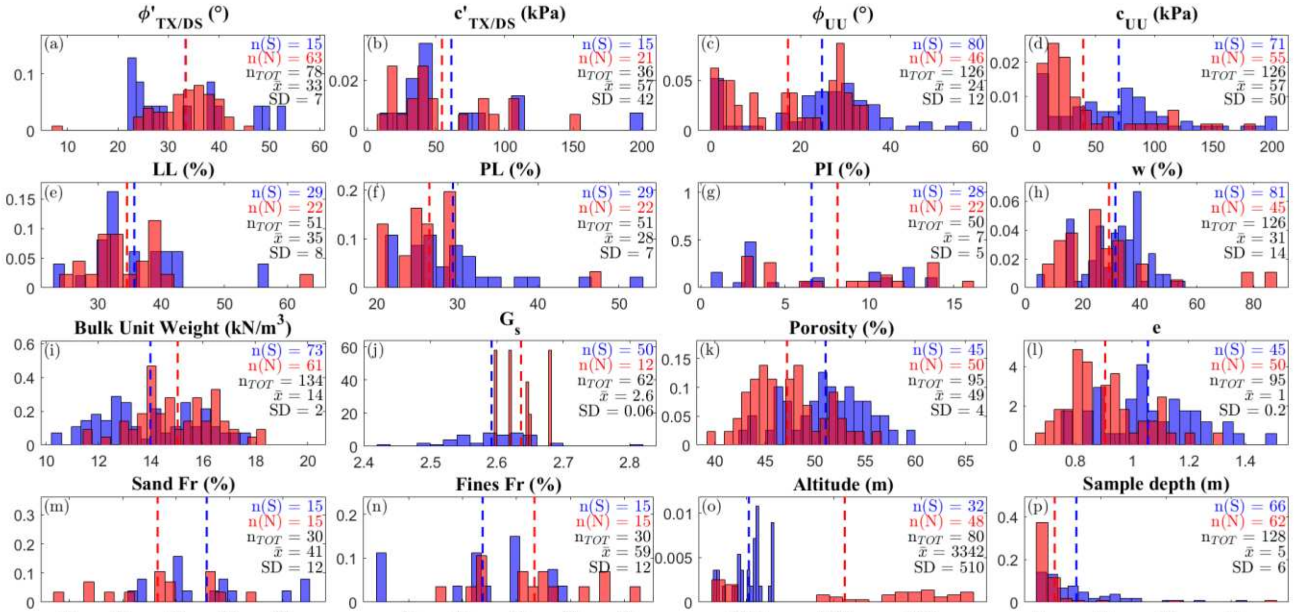

Figure 1. Probability Density Functions for Quito cangahua soils, separated according to north-south aspect (based on a northing of 9976470) [N.B. the mean values x̄ and standard deviation (SD) shown on the plots relate to the full data set for each parameters (n_{TOT})].

4 RESULTS AND DISCUSSION

4.1 *Geotechnical variability*

Table 2 shows the results of the PDF fitting analyses on the individual parameters. The $\phi'_{TX/DS}$ and $c'_{TX/DS}$ data are best represented by Normal and Lognormal distributions, respectively. Shepheard et al. (2019) showed that the soils of the Saint Lucia database had the aforementioned frictional parameters best described with Weibull distributions (although Normal and Lognormal were also good fits to the dataset). For both the Quito soils database and the Saint Lucia soils database, water content *w*, was best described with Weibull distributions.

Figure 1 presents PDFs for the data from Table 2, separated according to their northern or southern locations in Quito. A clear offset is observed from the total strength parameters (ϕ_{UU}, c_{UU}), showing elevated values in the south relative to the north (n = 126, for both). This trend is less obvious for the effective strength parameters ($\phi'_{TX/DS}$, $c'_{TX/DS}$) (N.B. the sample size is lower: n = 78, 36). Other soil parameters also indicate a difference between the north and south of Quito (i.e. natural water content *w*, bulk unit weight γ and void ratio *e*). The change in *e* values may be the result of differing volcanic ash deposition leading to differing particle size distributions (sand and fines fractions). This analysis supports the suggestion of distinct geotechnical behaviours in north and south Quito (Guerrón Andrade and Tacuri Silva, 2012) and provides an example of the application of the geodatabase for identifying soil subsets once sufficient data has been added.

Regressions between effective friction angle $\phi'_{TX/DS}$, and water content, *w*, and void ratio, *e*, have been identified (Figures 2 and 3). Figure 2 shows that for the same water content the Quito soils tend to exhibit a higher value of effective friction angle than Shepheard et al. (2019), who presented a negative linear correlation (for some Saint Lucian soils); the analysis presented in this study results in a power relationship (Equation 1):

$$\phi'_{TX/DS} = 53.276w^{-0.147} \tag{1}$$

From Figure 3, a negative linear relationship is observed between effective friction angle, $\phi'_{TX/DS}$, and void ratio, *e*, given by the following equation:

$$\phi'_{TX/DS} = -18.417e + 52.396 \tag{2}$$

Effective friction angle is observed to increase as void ratio decreases.

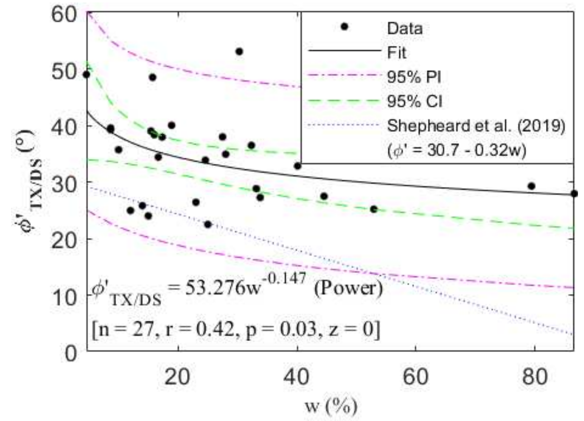

Figure 2. Effective friction angle versus water content, *w* (%).

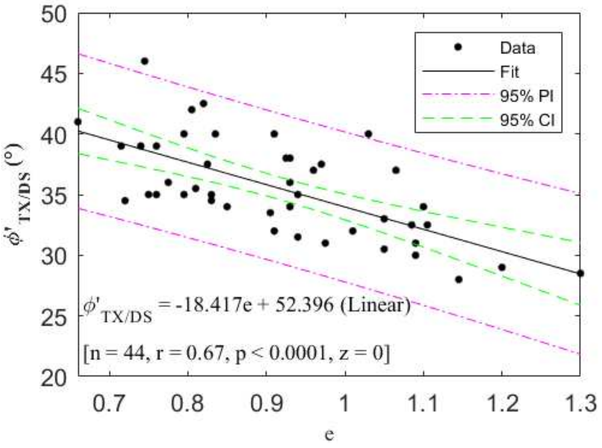

Figure 3. Effective friction angle versus void ratio, *e*.

4.2 *Urban features affecting slope stability*

Analysis of the aerial photos and DTM obtained from UAV mapping of a typical informal hillside community in northern Quito indicates a consistent style and method of construction. Statistical analysis of household-scale changes to the natural slope profile indicates the prevalence of Lognormal and Weibull distributions with low standard deviations. Cuttings in the slope material are typically almost vertical and vary in height from 3.5 to 5.5m. The mean cross-sectional length of each house (perpendicular to the slope) is less than 10m, and houses may be constructed adjacent to one another going down the slope. Rainfall is observed to trigger small landslides in the cut slopes. In conjunction with house loading estimated from construction material unit weights, number of storeys and house lengths, these UAV-derived statistical data on urban slope features provide valuable inputs for parametric and stochastic slope stability modelling (e.g. Holcombe et al., 2016; Bozzolan et al., 2020).

4.3 *General discussion*

Many studies have investigated the natural variability of soils in the field (e.g. Lumb, 1966, Brejda et al., 2000, Shepheard et al., 2019) at a range of scales. A principal aim of such studies is to improve the quality of estimations of in situ soil conditions (for example, to use in physics-based models, e.g. Almeida et al., 2017), by reducing uncertainty. Herein, a common theme exists, that of scale, whereby estimation of in situ parameters may only be as good as the statistical models from which they are obtained.

In this research, a preliminary geodatabase has been created for the Quito Metropolitan District, intended for use in landslide hazard assessments in around the city. Statistical analysis of the geodatabase has allowed patterns of natural soil variability to be described for Quito, which may be used in slope stability modelling software, such as CHASM, allowing city-scale landslide hazard assessments to be made. It is important to emphasise that the geotechnical parameter distributions resolved in this study are not intended for direct use in site-specific engineering design, but rather for representing soil characteristics in studies of slope stability behaviour and landslide hazard drivers at community and city scales. That said, regional geotechnical databases such as this are valuable to engineers for archiving and sharing valuable site-specific data; improving information about material parameter ranges, subsets, and variability; and providing a sanity-check for new data.

Despite the relatively limited number of datapoints within the geodatabase, a clear divide in geotechnical behaviour is observed between the north and south of Quito (Figure 1), in keeping with knowledge of local geology (as described in section 2.1). Currently, there are not enough data to warrant separate north/south modelling, however, it is envisaged that this would be possible in the future with the addition of further effective strength data to the database.

It is likely that other subgroups of soils exist within the Quito database, for example, Figure 1(b) (effective cohesion) shows two principal clusters of data, either side of approximately 50kPa. Such a division potentially describes a separation between primary and reworked cangahua deposits, as discussed in section 2.2. However, inconsistencies in data collection between the various sources mean that this cannot be ascertained with certainty. Ongoing addition of soil test data to the geodatabase would allow other geographical comparisons to be made, for example, volcanic versus rift slopes, allowing practitioners to resolve soil behaviour at the scale they require. In Figure 1(b) (effective cohesion), outlying data points are observed beyond 150 kPa, however, these have been included due to the preliminary nature of the database, such that outliers may prove significant with the addition of future data.

UAV mapping has allowed acquisition of site-specific slope geometries and house-scale urbanisation features. The outputs of this mapping have been analysed statistically. Combining city-scale patterns of soil behaviour with site-specific urban slope features is suggested as a way of tailoring assessments to specific communities and refining the spatial resolution of slope stability assessments. Such site-specific data should be combined with the highest resolution geodatabase information for which a reasonable sample size exists. For example, in future, UAV data from the case study community could be combined with soil parameter distributions describing the north of the city, when sample size allows. Considering the applicability of effective strength parameters to issues of rainfall-induced slope stability, it is suggested that there is a need for this type of data to be collected in Quito, specifically, direct shear box tests (DS), and triaxial testing which include the measurement of pore water pressure (i.e. consolidated drained, CD, or consolidated undrained, CU, with pore water pressure measurement).

5 SUMMARY AND CONCLUSIONS

This proof-of-concept study has successfully assembled a preliminary geodatabase for Quito, Ecuador, and trialled the use of UAV mapping for identifying the household-scale impacts of urbanisation on slope features. These data are intended for use in urban slope stability assessment. Three main conclusions are drawn:

(1) Development of geodatabases in data-scarce locations allows existing data to be more fully utilised by facilitating analysis of statistical patterns. Two such patterns have been found: (i) a clear offset in geotechnical behaviours between the north and the south of Quito, in keeping with the geological context and local expert knowledge (e.g. Guerrón Andrade and Tacuri Silva, 2012); (ii) regression models that suggest relatively robust relationships between effective friction angle and both natural water content (power) and void ratio (linear) for Quito's cangahua soils, following trends observed in other studies.

(2) With the development of localised rather than national/inter-national models of soil behaviour, a significant trade-off exists between spatial resolution and sample size. This may be mitigated via the gradual population of localised geotechnical databases. Additionally, site-level information obtained via UAV mapping can be combined with appropriate soil parameter distributions from the geodatabase and used as inputs for slope stability modelling. This approach allows lower resolution soil data to be combined with site-specific geometry data, allowing slope stability models to be tailored to individual sites of interest.

(3) Traditionally, studies of slope stability in Ecuador have prioritised undrained triaxial testing because of their particular applicability within seismically active areas. Given the relevance of *effective* strength to rainfall-induced slope instability, however, the collection of effective strength data for inclusion in the geodatabase (as obtained from Direct Shear tests, for example) is essential for the improvement of slope stability assessments.

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