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Measurement of field hydraulic conductivity for a Quito soil

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ABSTRACT: In Quito, Ecuador, landslides present a significant threat to communities settled on hillsides and ravine slopes, and geotechnical data is needed to assess slope stability. Saturated hydraulic conductivity is a key input parameter for mechanistic modelling of rainfall infiltration and the pore water pressure conditions that can trigger landslides. This paper presents field data of in-situ saturated hydraulic conductivity by working with communities to conduct field measurements on the cemented volcanoclastic soils found in Quito. The new field data is then compared with predictions from recently established geodatabases of hydraulic conductivity obtained from laboratory tests on fine-grained and granular soil.

1 INTRODUCTION

Rapid urbanisation is predicted to increase landslides worldwide in the coming decades (e.g. Holcombe *et al.* 2016 & Ozturk *et al.* 2022). However, slope stability assessment and urban landslide risk reduction presents a challenge in regions with limited financial and technical resources for geotechnical data gathering and meeting slope design standards (e.g. Anderson & Holcombe 2006, 2013). In Quito, Ecuador, landslides often occur in the volcanic ash Cangahua soils that are found in the inter-cordillera valley from southern Colombia to central Ecuador at altitudes of 2200 to 3000 metres (Winckell & Zebrowski 1992). This is a multi-hazard environment in which rainfall can trigger cascading landslides, debris flows, and floods. Hydraulic conductivity (k) is an important soil parameter for geotechnical engineers. Saturated hydraulic conductivity (k_{sat}) is used to calculate rainfall infiltration and saturated groundwater seepage and to derive unsaturated hydraulic conductivity, for example using the Millington–Quirk formulation (Millington & Quirk 1959) in slope hydrology and stability models (e.g. CHASM, see Wilkinson *et al.* 2002).

To support the investigation of rainfall infiltration and landslide initiation, this study has the following aims: (i) present new field data of k_{sat} obtained via citizen science activities; (ii) compare the new data with values predicted from previously established transformation models. The study is part of the Tomorrow's Cities project on urban disaster risk reduction (see Galasso *et al.* 2022 for a discussion of the aims of the wider project).

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2 MATERIAL AND METHODS

2.1 *Geological setting of the study site*

The study site is part of the Conocoto Giant Landslide (CGL) located on the eastern flank of the Puengasí anticline, uplifted by a segment of the Quito reverse fault system, in the southwestern part of the Metropolitan District of Quito. This relict landslide is estimated to have occurred between 165ka to 10ka and has a 3700 metre semi-circular scarp (Noroña Muñoz 2021). The deep colluvial strata are comprised of Cangahua – a volcanic ash soil produced by partial diagenesis of fine explosive volcanic material cemented primarily by amorphous clayey material, silica, iron oxides or calcite (see Vera & Lopez 1992, for a detailed description of Cangahua).

2.2 *Soil sampling and index testing*

In collaboration with community residents, undisturbed soil samples were taken from a continuous Cangahua material layer. The soil samples were denoted as S1 and S2 from 200mm and 500mm sample depths respectively. Granulometric analysis and SUCS classification were carried out on both samples, following the standard ASTM D2487 (ASTM 2011). To carry out the soil classification tests of the soil samples (using ASTM 2017a), the laboratory used the material that passed through Sieve No 40 (see ASTM D6913 for the ASTM sieve sizes) (ASTM 2017b).

2.3 *Estimation of saturated hydraulic conductivity using a double ring experiment*

In this study ASTM D3385 (ASTM 2018) was used to measure k_{sat} at the sampling point located on the ridge of the CGL, in collaboration with community residents. The experiment was carried in a half-metre deep pit during the rainy season. The double ring system was filled with water for two hours to allow saturation conditions to develop. A long-term test was then carried out in which infiltration measurements were taken every 15 minutes for 2 hours, and then every 24 hours for the following three days. The soil conditions were assumed to be near saturation. For natural Cangahua, O'Rourke & Crespo (1988) indicated a natural degree of saturation (S_r) ranging from 32% to 56%.

3 TEST RESULTS

The k_{sat} measurements obtained from the field testing show an order of magnitude range (Table 1). The soil samples (S1 and S2) collected for this study have a SUCS classification of type CL (following ASTM 2011), with a predominance of fines (see Tables 2 and 3). Table 3 also shows the computed specific surface area per volume (S_A) which can be computed using the soil grading curve (see Chapuis & Légaré 1992, Feng 2022).

Table 1. Double-ring infiltrometer test results for three-day experiment.

Time (min)	0	60	90	120	150	1590	3030
Infiltration (cm)	0	0.4	0.2	0.2	0.2	9.4	5.8
k_{sat} (m/s)	0	4.72x10^{-6}	3.61x10^{-6}	2.78x10^{-6}	2.50x10^{-6}	1.09x10^{-6}	6.71 x10^{-7}

Table 2. Laboratory grain size analysis results.

ASTM sieve no.	3"	2"	1½"	1"	3/4"	3/8"	4	10	40	200
Aperture (mm)	75.0	50.0	37.5	25.0	19.0	9.5	4.75	2.0	0.425	0.075
% passing (S1)	100.0	100.0	100.0	100.0	100.0	100.0	99.5	99.2	92.5	60.7
% passing (S2)	100.0	100.0	100.0	100.0	100.0	100.0	100.0	99.8	94.6	64.0

Table 3. Laboratory results for soil samples.

Sample	Moisture content, w (%)	Liquid limit, w_L (%)	Plastic limit, w_p (%)	S_A (1/mm)
S1	35	37	23	110.57
S2	25	32	20	113.95

4 ESTIMATIONS OF HYDRAULIC CONDUCTIVITY

Feng (2022) reported a new database CG/KSAT/7/1278, with over 1200 k measurements on soils with over half of the soil grain particles larger than 0.075mm in diameter (i.e. coarse-grained soils). Equations (1a) and (1b) are a k transformation model calibrated using CG/KSAT/7/1278:

$$K = 1.693 \times 10^{-2} e^{2.283} / S_A{}^2 \tag{1a}$$

$$k_{sat} = K(\gamma_w / \mu_w) \tag{1b}$$

where K = intrinsic permeability of the porous medium (mm^2 in Equation 1a, and m^2 in Equation 1b), e = void ratio, S_A = specific surface area per volume (1/mm), k_{sat} = saturated hydraulic conductivity (m/s), μ_w = dynamic viscosity of the permeant = 1.002×10^{-3} kg/(m.s) (Kestin *et al.* 1978, assuming a testing temperature of 20°C) and γ_w = unit weight of the permeant = 9.81 (m/s^2) × 998 (kg/m^3) (density value from Kestin *et al.* 1978, assuming a testing temperature of 20°C).

Feng & Vardanega (2019) assembled a fine-grained soil database FG/KSAT-1358, which contains over 1300 k measurements soils with more than half of the particles smaller than 0.075mm in diameter and with a measurable w_p (i.e. fine-grained soils). The FG/KSAT-1358 database was used to develop a transformation model of the form presented in Feng & Vardanega (2019) and further refined in Feng *et al.* (2022) (after removal of statistical outliers), shown as Equation 2:

$$k_{sat} = 1.86 \times 10^{-9} (w/w_L)^{4.226} \tag{2}$$

where k_{sat} is in units of m/s and w/w_L = the water content ratio (where w = the water content).

By using Equations 1a, 1b and 2, predictions of k_{sat} for S1 and S2 for a range of porosities (n) quoted in various publications were made and compared with the test results. Tables 4 and 5 summarise the predicted k_{sat} values. For all the calculations, S_r is taken as equal to 1.0 and specific gravity (G_s) is taken as 2.585 (the average value from the data in O'Rourke & Crespo (1988)).

Table 4. k_{sat} at 20°C predicted using Equation 1.

	S1 (w_L = 37%)			S2 (w_L = 32%)		
Reference	$e = n/(1\text{-}n)$	S_A (1/mm)	k_{sat} (m/s)	e	S_A (1/mm)	k_{sat} (m/s)
This study	0.905	110.57	1.08 x 10^{-5}	0.646	113.95	4.70 x 10^{-6}
Podwojewski & Germain (2005) (n = 40%)	0.667	110.57	5.36 x 10^{-6}	0.667	113.95	5.05 x 10^{-6}
Crespo (1987) (n = 43%)	0.754	110.57	7.11 x 10^{-6}	0.754	113.95	6.69 x 10^{-6}
Crespo (1987) (n = 56%)	1.273	110.57	2.35 x 10^{-5}	1.273	113.95	2.21 x 10^{-5}

Table 5. k_{sat} at 20°C predicted using Equation 2.

	S1 (w_L = 37%)			S2 (w_L = 32%)		
Reference	$e = n/(1\text{-}n)$	w (%)	k_{sat} (m/s)	e	w (%)	k_{sat} (m/s)
This study	0.905	35	1.47 x 10^{-9}	0.646	25	6.54 x 10^{-10}
Podwojewski & Germain (2005) (n = 40%)	0.667	25.8	4.05 x 10^{-10}	0.667	25.8	7.47 x 10^{-10}
Crespo (1987) (n = 43%)	0.754	29.2	6.82 x 10^{-10}	0.754	29.2	1.26 x 10^{-9}
Crespo (1987) (n = 56%)	1.273	49.2	6.22 x 10^{-9}	1.273	49.2	1.15 x 10^{-8}

Compared with the measured k_{sat} data from the field testing (Table 1), the coarse-grained soil hydraulic conductivity transformation model (Equation 1) gives a significantly better prediction of k_{sat} than the fine-grained soil hydraulic conductivity transformation model (Equation 2). This may be because that while the Cangahua soil samples tested have a measurable w_P, the data in FG/KSAT-1358 are mostly pure laboratory fine-grained clays and silts and thus might not be representative for the samples testing in this work which contain a combination of fine and coarse material (see Table 2).

5 SUMMARY

This paper has presented the results of a citizen-science based project to assess saturated hydraulic conductivity in data-limited locations where rainfall-triggered landslide hazard assessment is required. New field k_{sat} measurements were made using a double-ring infiltrometer. The new data were compared with predictions from two transformation models developed from databases of coarse-grained and fine-grained soils. The field values are closer to the predictions from the coarse-grained transformation model – this is possibly because Cangahua is not a pure clay and comprises a large component of coarse-grained material.

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