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Technical note

Towards the digital indexation of USCS classification: Case study in Israel

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Abstract

USCS soil classification is extensively used in different engineering applications. However, being "symbolic and descriptive classification", it does not allow of an application of numerical methods for map drawing and hence hand drawn soil maps are still subjective to some degree. Application of mathematical extrapolation to soil mapping based on digitization of soil indexes significantly decreases the time taken to complete map drawing and excludes voluntarism from its production. Among other things, both these factors are of paramount importance for preliminary soil reserve estimation. This paper presents the first attempt to find a digital analogy to 17 out of 23 USCS groups (mainly poor graded soils). Examination of digitally and hand drawn vertical sections shows good correspondence between them especially where sharp transition between lithologically distant classification groups is missing from a geological section.

Keywords: USCS; AASHTO; Soil; Digital mapping

1. Introduction

Engineering geology generally defines soil as sediments or other unconsolidated accumulations of solid particles produced by physical and chemical disintegration of rocks, and which may or may not contain organic matter (ASTM D653-02). There are several other definitions similar in their sense to the above one. Soil classification is the foundation for international exchange and research in soil science (Xue-Zheng et al., 2006). For example, Hoyos-Lauredo and Macari-Emir (1999) used soil samples identification to describe an influence of field factors on dynamic soil response. Grubb et al. (2006) applied soil classification to evaluate potential use of crushed glass as a filler for urban applications. For a long time two main geotechnical classifications have been used for soil description in civil engineering applications: AASHTO (ASTM D3282-93) and USCS (ASTM D2487-00), constituents of Standard set by American Society for Testing and Materials (ASTM).

The first one is identified as "Classification of Soils and Soil-Aggregate Mixture for Highway Construction Purposes" (ASTM D3282-93) or AASHTO, abbreviation for American Association of State Highway and Transportation Officials, and confines its field of application to narrow limits — for highway and other roads

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materials only. The soils in the AASHTO are classified on the basis of the laboratory analyses only entirely excluding visual soil description. The other main imperfection of AASHTO description is a lack of clear correlation between conventional lithological soil unit names and soil groups defined by this classification. For one example, group A-7 is rated by the AASHTO classification as consisting of variations of lean and fat clays, whereas the main part of the lean clay varieties forming group A-6 includes high percentage of clayey sand soils.

The second widely used classification (ASTM D2487) known as "Classification of Soils for Engineering purposes (United Soil Classification System — USCS)" provides the basis of soil identification for a wide diversity of civil engineering purposes. This classification is based both on the laboratory test results and on an additional standard procedure for visual identification of soils (ASTM D2488-00). Moreover, group names of USCS are very close to conventional lithological definitions and thus USCS is friendly for using by geo-engineers. The above pros and cons of both classifications demonstrate that USCS classification has some advantages over AASHTO for common civil engineering purposes. Although USCS is preferable for engineering application, it is still a "symbolic classification" (all groups names are symbols) that allows of no short term computer soil mapping, e.g. for civil engineering purposes. Note that the attempts to find digital analogy to symbolic soil classification are rare in scientific literature. For example, Koike and Matsuda (2005) binary transformed triangle diagram defining granular classes in terms of the ratio of clay, silt and sand. Yet, this approach provides soil classification under two classes only (0 or 1), therefore some important lithological soil features are lost. Note that soil mapping is crucial for engineering aims, e.g. El-Rawi and Al-Samadi (1995) used soil mapping to estimate its geotechnical stability.

The aim of this work is to try to find digital indexes for several mainly sand bearing USCS groups and in doing so to save the spirit of the classification making the digital index directly dependent on granular content of soils and to exclude subjectivism from data extrapolation during slice drawing. We employed this approach in studying soil reserves on the rear site of the new Ashdod port (Israel).

2. Digital model of USCS classification

As is known (ASTM D2487-00), soils are classified on the basis of percent content of particles with different diameters. For example, affiliation with gravels is determined by the percentage of particles larger than 4.75 mm in diameter, sand – between 4.75 and 0.075 mm, clay and silt – less than 0.075 mm. USCS classification includes specific range of percentage values for each soil group (Table 1). Definition of percentage of particles of different sizes is usually followed by the calculation of curvature and uniformity coefficients to distinguish between well and poor graded materials, while clay characterization is typically carried out by using Atterberg limits. However, well graded soils were lacking on the site under study as determined by entire analysis complex in accordance with USCS requirements, whereas clays were observed to be mainly lean (see below). It enabled us to classify all granular materials on the basis of particle size only and to lump clays together as a single group.

To avoid drawing limiting values diagram, the following values of characteristic diameters of soil particles were taken into account: gravel — 4.75 mm, sand — 0.425 mm (sieve 40), clayey particles — 0.075 mm (sieve 200) while limiting values of percent content were taken from the USCS classification (Table 1). All soils observed in the area under investigation (see Section 3) were divided into 17 groups under USCS classification (Table 2) while their digital indexes were calculated by the following equation:

$$DI = (PC_G{*}D_G + PC_S{*}D_S + PC_C{*}D_C)/100 \qquad (1)$$

where PC_G, PC_S and PC_C are percentages of gravel, sand and clay particles, respectively, D_G, D_S and D_C are diameters of gravel, sand and clay particles, respectively, (see above). Table 2 shows the results of digital index calculation. Note that our digital index has a unit of length and hence implies characteristic or equivalent diameter.

Integrating 17 USCS groups into six subgroups enabled us to map soils on the rear site of the New Ashdod Port area with the aim of estimating their reserves in the area for civil engineering purposes. Boundaries between adjacent subgroups were calculated as an average between minimum value of digital index of the upper subgroup and maximum value of lower subgroup. Table 2 shows calculation errors.

We conducted our numeral drawing by using the triangular with linear interpolation gridding method of "Surfer" software. Our experience led us to conclude that this gridding method is much better applicable to geo-engineering purposes than other eleven contained in "Surfer". Fig. 1b shows typical vertical section of the soils in the region drawn from our digital indexations.

3. Site lithology

Our study was motivated by the calculation of soil reserves of granular materials for civil engineering purposes (building and road construction).

More than 130 prospecting wells were drilled on the site under investigation with subsequent careful analysis of soil types under USCS classification: sieve analysis (ASTM D422-63) and Atterberg limits (ASTM D4318-00). Over 400 such analyses were carried out. Average values of geotechnical properties of several (mainly fine sandy and clayey) soil groups are presented in Table 3. In addition to these analyses, several hydrometer tests were carried out (ASTM D422-63) on representative samples from each group, average results of which were used for true soil classification along with usual (sieve and Atterberg limits) tests.

It showed that all sandy soils on the site are poor graded granular materials only. Well graded granular materials are completely lacking on the site. Fat clays (CH) are extremely rare and hence their significance is low. All exposed soils are of sedimentary genesis of Pliocene to Pleistocene age (Sneh and Rosensaft, 2004). The formation stratum of area includes clays (fat and lean) occurring in a small proportion, sands and their varieties (slightly silty sand, silty sand, sands with gravel etc.), clayey sands (close to loam), carbonate slightly cemented and weathered calcareous sandstone alternating with sand, and is termed in Israel as "Kurkar" and in Levanon as "Ramleh" (Fish, 1944).

Although our investigation is a case study conducted on the rear site of the New Ashdod Port area only, it has a wider significance because a large part of the East and South Mediterranean seashore is constituted by similar

Table 1
Unified soil classification

Group	Group no.	Gravel (larger than 4.75 mm) content, %	Fines (smaller than 0.075 mm) content, %	Group symbol	Typical USCS names	Geological description of investigated soils	Unit
Gravel %gravel>%sand	1	>50	0–5	GP	Poorly graded gravel with sand	Fine to coarse calcareous sandstone (C.S.) gravel (or plate fragments) with fine sand	Lower–"kurkar"
	2		5–12	GP–GM	Poorly graded gravel with silt and sand	Fine to coarse C.S. gravel (or plate fragments) with slightly silty sand	
	3		>12	GM	Silty gravel with sand	Fine to coarse C.S. gravel with silty sand	
Sand %sand>%gravel	4	>50	0–5	SP	Poorly graded sand with gravel	Fine sand, >15% C.S. gravel	
	5		5–12	SP–SM	Poorly graded sand with silt and gravel	Slightly silty sand, containing >15% C.S. gravel	
	6		>12	SM	Silty sand with gravel	Fine sand, containing >15% C.S. gravel	
	7	1–15	0–5	SP	Poorly graded sand	Fine sand with some C.S. gravel	Lower-Kurkar" or upper-dune sand
	8		5–12	SP–SM	Poorly graded sand with silt	Slightly silty sand with some C.S. gravel	
	9		>12	SM	Silty sand	Silty sand with some C.S. gravel	
	10	0–1	0–5	SP	Poorly graded sand	Fine sand	
	11		5–12	SP–SM	Poorly graded sand with silt	Slightly silty sand	
Clayey sand soils %sand>%gravel	12	0–1	5–12	SP–SC	Poorly graded sand with silty clay	Fine sand with scattered clay lenses	Intermediate-"Terra Rossa"
	13		>12	SM	Silty sand	Silty sand	
	14		>12	SC–SM	Clayey silty sand	Silty slightly clayey sand	
	15		>12	SC	Clayey sand	Clayey sand	
Clays	16	0–1	50–100	CL	Lean clay with/without sand	Lean sandy clay	
	17			CH	Fat clay	Fat clay	

Table 2
Groups of USCS and their digital indexation

Soil group (USCS) 1	Typical name 2	Geological unit 3	Group no. 4	Limits of digital index (Eq. (1)) 5	Limits of Integrated Digital index 6	Error, % 7
GP	Calcareous sandstone (CS) fine to coarse	Lower–	1	2.48–4.75		
GP-GM	gravel with		2	2.28–4.21	4.75–2.44	5.8
GM	fine sand or silty sand		3	2.46–4.05		
SP	Fine sand to silty	"Kurkar"	4	1.06–2.59		
SP-SM	sand, containing		5	1.03–2.44	0.99–2.44	7.7
SM	15–50% CS gravel	group	6	0.9–2.26		
SP	Fine sand to silty		7	0.45–1.07		
SP-SM	sand, containing 1–15%		8	0.43–1.05	0.42–0.99	1.2
SM	CS gravel		9	0.43–1.03		
SP	"Clean" fine sand to	Lower–	10	0.41–0.43		
SP-SM	slightly silty sand, excepting "clean"	"Kurkar" group	11	0.38–0.408	0.38–0.42	0.1
SP-SC	silty sand variety, which is grouped geologically with intermediate unit	or/and Upper-dune sand	13	0.38–0.408		
SM-SC	Silty sand, clayey sand, their	Intermediate–	14	0.25–0.38		
SM	intermediate	clayey	12	0.25–0.38	0.25–0.38	
SC	varieties	soils	15	0.25–0.38		
CL	Lean and fat	group	16	0.08–0.25	0.08–0.25	1.2
CH	Sandy clays		17	0.08–0.25		

soils especially in Israel (Frechen et al., 2002), Egypt (Adeel and Attia, 2002; Bernacsoni et al., 2006) and Lebanon (Fish, 1944; Marriner et al., 2005).

These soils and rocks belong to established lithostratigrafic and geotechnical unit and are described below (from bottom to top, Fig. 1a):

3.1. Kurkar unit

Kurkar or calcareous sandstone is a bedrock of the subject structure. Obviously, in early geological period calcareous sandstone was part of a continuous paleocliff ridge running parallel to the coastline. In recent period, the cliff underwent major erosion under the action of paleostream, eolation activity, etc. Now, underground surface of Kurkar unit exhibits marked undulations of its roof elevating 5 to 15 m from the existing ground level. The Kurkar unit is cross-bedded, very slightly cemented, intensively weathered and contains alternating layers of cemented sandstone and uncemented sand varieties recovered from the boreholes as gravel with sand, slightly silty sand or silty sand. The majority of the lithological facies of Kurkar unit belong to "G" group (by USCS classification): GP, GP-GM, GM, and fall into "sand" group: SP, SP-SM, SM with gravel content up to 30–40%.

3.2. Clayey unit

Clayey unit overlies the Kurkar group with local unconformity. Some lithological types are described, such as lean sandy clay, fat clay (extremely rare), clayey sand (dominant variety), silty sand, slightly clayey silty sand (CH, CL, SC, SM, SM-SC groups by the USCS classification). All these soil types are closely related, interbedded and belong to "terra rosa" formation. Occasionally, clayey soils are separated vertically by a layer of intermediate sand varieties and cross-section in these cases attains the "sandwich" configuration.

3.3. Sand unit

Sand unit covers the whole of the above soil unit and is part of a large dune structure. The sand and its varieties (slightly silty sand, sand with gravel) are mainly quartz, loose and in some places, contain clay lenses.

4. Comparison of hand drawn and digital vertical sections

Qualitative analysis of both vertical sections (Fig. 1) show the presence of all three above noted geological units: sand (upper), clayey (intermediate) and Kurkar (lower), though with different accuracy. Moreover, drawing quality of two upper units (sand and clayey) is very close. Some discrepancy between them (e.g. like near borehole 172) may be due to subjective character of data interpretation by hand-drawing. Discrepancy in drawing the lower unit is higher. Fig. 2 shows zones of discrepancies (in black).

To quantify the degree of agreement between two vertical sections we calculated area size of each soil type

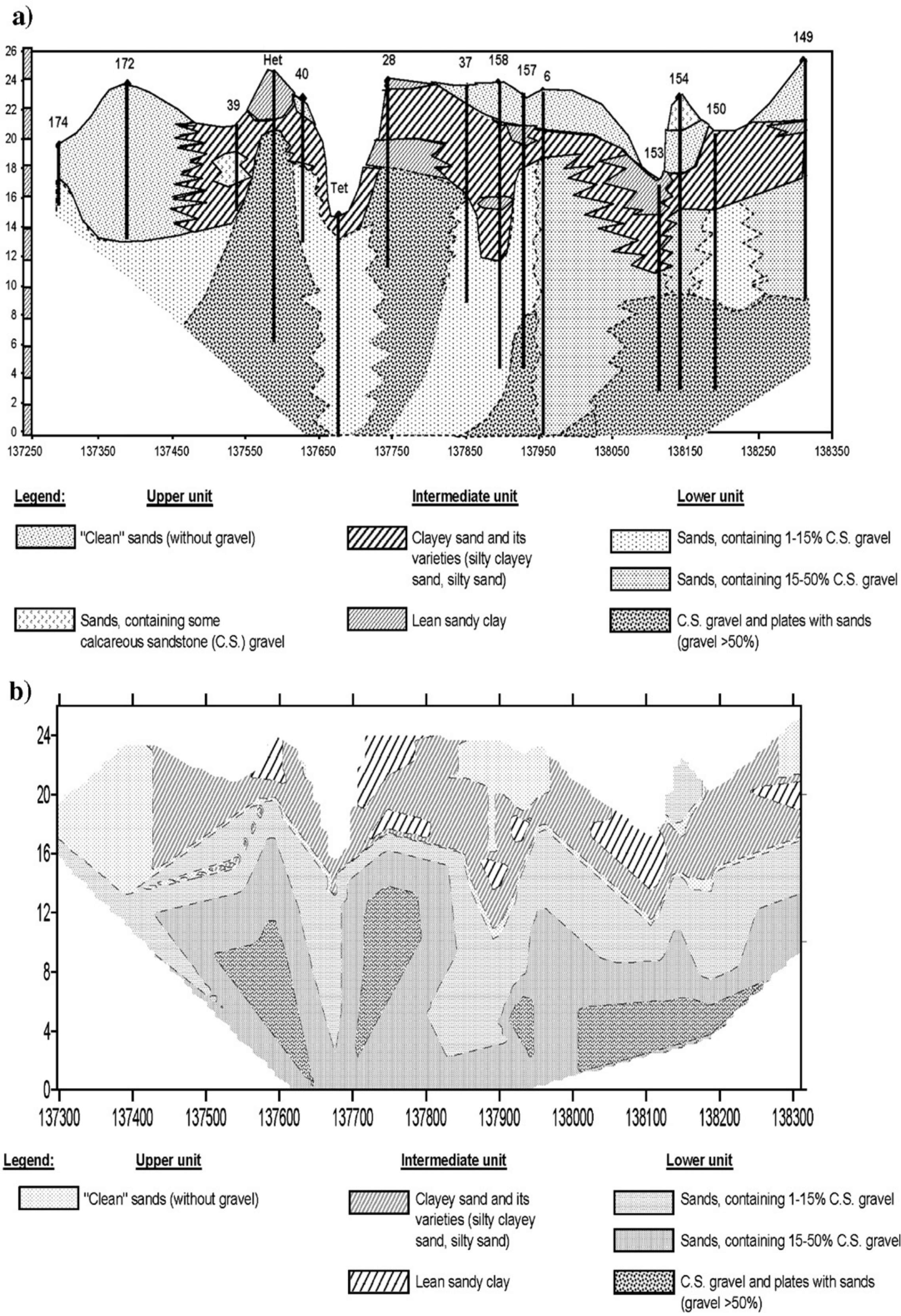

Fig. 1a. Hand drawn vertical section of the rear site of Ashdod Port. Numbers and black lines show numbers and depths of boreholes. b. Computer made vertical section of the same site as in a. Both vertical sections are drawn in the same scale, though their horizontal scale is different from their vertical scale.

Table 3
Average geotechnical properties of the sandy and clayey soil units

Soil group	Pass sieve #, %[a]				Cu	Cc	Atterberg limits, %[b]			n	Granulometric composition, %[c]				*n*
	#4 (4.75 mm)	#10 (2.0 mm)	#40 (0.425 mm)	#200 (0.075 mm)			LL	PL	PI		Sand-size	Silt-size	Clay-size	Colloid-size	
	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Sand (SP)		100	85	2.1	2.95	0.86		N.P.		85	97	2		1	6
Slightly silty sand (SP-SM)	100	99	87	7.9	3.0	0.88		N.P.		44	90	8	1	1	9
Slightly clayey sand (SP-SC)		100	90	8.8	2.88	0.92	25	14	11	9	89	2	3.5	5.5	5
Silty sand (SM)	100	99	95	23			From N.P. to 21	From N.P. to 19	From N.P. to 2	45	75	18	1.2	5.8	7
Silty slightly clayey sand (SM-SC)		100	91	34			24	18	6	30	64	20	3	13	5
Clayey sand (SC)		100	95	39			30	16	14	35	60	4	12	24	3
Lean sandy clay (CL)		100	96	59			38	18	20	15	–	–	–	–	
Fat sandy clay (CH)		100	97	74			54	23	21	6	–	–	–	–	

All tests were done in the Isotop Soil and Rock Laboratory (Israel).
LL — Liquid Limit, PL — Plastic Limit, PI — Plasticity Index, Cu — coefficient of uniformity, Cc — coefficient of curvature, n—sample's quantity.
[a] Sieving analysis (ASTM D422-63).
[b] Atterberg Limits determining (ASTM D4318-00).
[c] Hydrometer test (D422-63).

in both vertical sections (Table 4) and the error of the area computation between them.

As we noted above, configuration of sand and clayey units (upper and intermediate) produced by the digital vertical section is very similar to the hand drawn one. As is seen, zones of discrepancies are lacking for these two units (Fig. 2) while the error in the zones calculation is less than 10% for all soil types (Table 4). Note that the error was calculated as follows: $(S_{hd}-S_d)/S_{hd}$, where S_{hd} is the zone of specific soil type on the hand drawn map, S_d is the zone of specific soil type on the digital map.

General configuration of the lower (Kurkar) unit in the digital vertical section is comparable with the hand drawn one being correctly drawn under two other units, though its internal configuration has some discrepancies

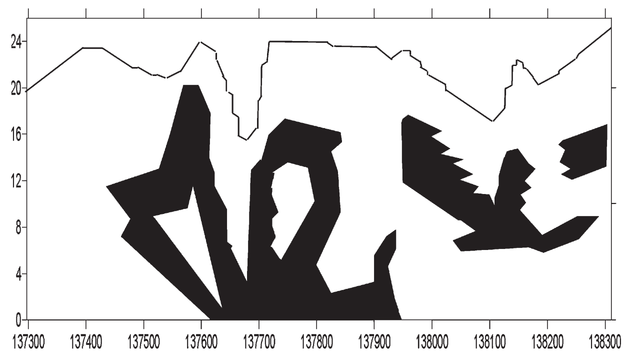

Fig. 2. Zones of discrepancy (black) between hand drawn and digital maps.

Table 4
Estimation of discrepancy between hand drawn and digital vertical sections

Soil type	Unit	Area of soil in vertical section, thousands, m^2		Error, %
		Hand drawn section	Digital section	
Clean sands	Upper	1.572	1.57	0.2
Clayey sands	Intermediate	2.884	3.093	7
Lean sandy clay	Intermediate	0.693	0.728	5
Sands containing 1–15% gravel	Lower	3.885	3.516	10
Sands containing 15–50% gravel	Lower	3.094	3.605	17
Gravel (>50%)	Lower	2.797	1.071	62

(Fig. 2). Examination of these discrepancies shows that the error in the zone calculation increases from sands containing 1–15% of gravel to gravels as such from 10% to 62%, respectively.

Our analysis shows that only 40% of all drilled wells intersected lower unit and hence data volume for this unit is much smaller than for two higher units and hence insufficiency of data volume could be the first cause for errors in computer processing of lower unit (especially gravels). The second source of disagreement between two vertical sections of lower unit could be due to the difficulty in computer processing to correctly define the sharp boundary between distant classification groups located adjacent to each other in geological section, for example, between groups of gravels and sands containing some gravels (groups 1–3 and 7–9, respectively, in Table 2). An additional source of such discrepancies can be derived from the properties of USCS classification itself, where smooth transition and "uncertainty intervals" between adjacent groups are lacking. These factors cause the appearance of artificial transition groups (e.g. a group of gravels with sands) in digital vertical section instead of the sharp boundary, e.g. between gravels and sand with some gravels.

5. Limitations of the study and possible way to improve digital indexation

As we noted above our study was motivated by soil reserve calculation for construction industry, which has inherent limitations. First, although engineering behavior of silty sand and clayey sand is different, for the aims of sand reserves calculation for construction industry, integration of 17 USCS groups into 6 classes appeared to be correct enough and useful. Second, all clay varities are not only unsuitable but even harmful material for construction industry and hence their unification into the same group seems to be a proper procedure. The two last conlusions were supported by comparison between digital and hand-drawn maps.

However, the proposed digital indexation could be improved by entering special digital correction coefficients corresponding to Atterberg limits that would enable us to take into account influence of soil fine fractions on soil properties and hence significantly increase digital indexation quality.

Saving the spirit of USCS classification such a correction coefficient could be, first, dependent on both plasticity index and liquid limit used in the classification, and, second, it is bound to decrease with increasing of soil plasticity to make digital transition from unconsolidated to consolidated and from non-plastic to plastic soils more natural. That is why, the value opposite to the product of plastic index and liquid limit could be a good candidate for such a coefficient:

$$\mathrm{NPI} = 1 - (\mathrm{PI}/100)*(\mathrm{LL}/100) \tag{2}$$

It is seen that this value characterizes soil non-plastic properties decreasing as both plastic index and liquid limit of soil increase. Analysis of plasticity chart (see Fig. 4, ASTM D2487-00) shows that NPI of lean clay (CL) changes between 0.25 and 0.86, while such a range for fat clay (CH) is 0.004–0.39. Multiplication of mean values of NPI (e.g. 0.55 for CL and 0.2 for CH) by those of digital index (DI, Table 2) yields digital range for soil and enables to take into account difference in soil properties due to fine particle content. For example, multiplication of NPI of lean clay by its digital index yields digital range for such a soil of 0.045–0.1386, while such a range for fat clay (CH) will be 0.016–0.05. This simple procedure indeed allows us to distinguish between these two types of clays. Mean values of ML and MH groups obtained by the analysis of plasticity chart (Fig. 4, ASTM D2487-00) are 0.7 and 0.25, respectively. Hence, differences in silt and clay particle content could also be taken into consideration. Note that it is only one way of devising such correction coefficients. A more sophisticated treatment of the subject is a matter of further investigation.

6. Conclusions

Our attempt at digital indexation of USCS classification is aimed at creating a computer friendly method to classify granular soil material.

As our analysis showed, the digital vertical section drawn on the basis of digital indexation of the USCS classification corresponds considerably to the hand drawn one. The digital indexation quality could be upgraded by taking more subjective information into consideration (e.g. differentiation of granularly similar but originally different geological units). Entering special digital correction coefficients corresponding, say, to Atterberg limits and curvature and uniformity coefficients into our analysis will significantly increase the quality of digitization. This stage is the subject matter of a further special investigation.

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