Vardanega, P. J. *et al*. (2023). *Géotechnique* **73**, No. 7, 648–654 [https://doi.org/10.1680/jgeot.21.00268]

DISCUSSION

Use of fall-cone flow index for soil classification: a new plasticity chart

PAUL J. VARDANEGA*, STUART K. HAIGH†, BRENDAN C. O'KELLY‡, XIANWEI ZHANG§, XINYU LIU‖, CHENG CHEN¶ and GANG WANG**

Contribution by Xianwei Zhang, Xinyu Liu, Cheng Chen and Gang Wang

Vardanega *et al*. (2021) proposed a new plasticity chart for soil classification using flow index and fall-cone liquid limit as measured from fall-cone tests. The new plasticity chart is of great significance as it allows soil classification to be performed without thread-rolling tests, which may well introduce the operator's influence. The discussers examined the applicability of this new plasticity chart to several soils containing diatoms with unique particle morphology and porous structure. The classification results based on the classic Casagrande plasticity chart and the new plasticity chart are compared and discussed herein.

Material description and test method

The soils tested herein include natural diatomaceous earth (DE) and artificial diatomite–kaolin mixtures (DKM) with varying diatomite contents. The DKM were included to investigate how diatomite content affects soil consistency limits. The particle compositions of the soils studied following the ASTM standard (ASTM, 2021) are given in Table 2. Natural DE was collected at the depth of 4·0 m from the lacustrine deposits of Shengzhou, Zhejiang Province, China. DKM were prepared by adding diatomite to kaolin clay (RP-2, Active Minerals International), with the content of diatomite being 0, 20, 40, 60, 80 and 100%. All the diatomite contents in this paper are based on the dry mass ratio. For convenience, the mixtures are labelled in the form of 'diatomite content: kaolin content'. For example, 40D:60K stands for the mixture with 40% diatomite and 60% kaolin clay. The mixture 100D:0K in fact is pure crushed DE consisting of whole and broken frustules (Fig. 7) from Changbai Prefecture, Jilin Province in China.

The consistency limits of the soil studied were determined through thread-rolling and fall-cone tests following ASTM (2017) and BSI (1990). All samples were soaked in deionised water for 7 days before the test to allow full infiltration of water into the intra-skeletal pores of the frustules. Values of the flow index (FI_c) were calculated from fall-cone test data using equation (3).

Test results and discussion

Table 2 presents the consistency limits as well as the soil classifications according to the classic Casagrande plasticity chart and the new plasticity chart. Also given in this table are the corresponding results for DKM soils from the literature. It is revealed that the classifications of both natural DE and DKM according to the new plasticity chart are identical to those following the Casagrande plasticity chart. This confirms the effectiveness of the new plasticity chart, which allows soil classification to be conducted based on FI_c from the fall-cone test as an alternative to the plasticity limit from the thread-rolling test. This has important practical implications, especially when considering the non-plastic nature of pure diatomite (100D:0K).

Figure 8 indicates that the natural DE is positioned above the A-line and corrected (adjusted) A-line, with its I_P and w_L varying considerably. In addition, the natural DE was classified as clay (CE) according to the new plasticity chart. However, the particle size analysis reveals the dominant silt-sized particles, and the soil was classified as silt accordingly. Such inconsistency between the soil classification according to the plasticity chart and the particle composition is possibly due to the high content of diatoms with extremely high water-holding capacity. Owing to the non-plastic nature of pure diatomite (100D:0K), existing methods fail to measure its consistency limits. Although some successful cases have been reported (Kim, 2012; Wiemer *et al*., 2017), they cannot be applied to the current study due to the different diatom types and their fragment levels. It is found from the plasticity chart in Fig. 8 that the increasing content of non-plastic diatomite leads to a dramatic increase in w_L and w_P, but only a slight reduction of I_P, with the data of Wiemer *et al*. (2017) being the only exception. This conclusion is different from the previous study (Shiwakoti *et al*., 2002) in which sand particles were added to kaolin clay. Although the adding of both non-plastic diatomite and sand ultimately led to the non-plastic nature of the mixture, the sand affected the w_L and w_P of the mixture differently from the diatomite. The natural DE and DKM are distinguished by the extremely high liquid limit that increases with diatom contents. However, such an increase is the result of high fluid holding capacity due to the intra-skeletal porosity of diatoms instead of plasticity (e.g. Shiwakoti *et al*., 2002; Bandini & Al Shatnawi, 2017), as proved by the very limited I_P value changes of DKM

* Department of Civil Engineering, University of Bristol, Bristol, UK (Orcid:0000-0001-7177-7851).
† Department of Engineering, University of Cambridge, Cambridge, UK (Orcid:0000-0003-3782-0099).
‡ Department of Civil, Structural and Environmental Engineering, Trinity College Dublin, Dublin, Ireland (Orcid:0000-0002-1343-4428).
§ State Key Laboratory of Geomechanics and Geotechnical Engineering, Institute of Rock and Soil Mechanics, Chinese Academy of Sciences, Wuhan, P. R. China (Orcid:0000-0002-0283-4493).
‖ State Key Laboratory of Geomechanics and Geotechnical Engineering, Institute of Rock and Soil Mechanics, Chinese Academy of Sciences, Wuhan, P. R. China; University of Chinese Academy of Sciences, Beijing, P. R. China (Orcid:0000-0002-8165-2259).
¶ State Key Laboratory of Geomechanics and Geotechnical Engineering, Institute of Rock and Soil Mechanics, Chinese Academy of Sciences, Wuhan, P. R. China.
** State Key Laboratory of Geomechanics and Geotechnical Engineering, Institute of Rock and Soil Mechanics, Chinese Academy of Sciences, Wuhan, P. R. China; University of Chinese Academy of Sciences, Beijing, P. R. China.

Table 2. Soil information

Data sources	Soil description	Particle composition: % Sand	Silt	Clay	w_L: %	I_P: %	Atterberg limits test methods	Soil classification according to CPC	Soil classification according to NPC*
The discussers	Natural DE	2·8–6·6	53–67·3	29·9–40·4	96·6–126	59·58–81	Thread-rolling test	CE	CE
	DKM, 0D:100K	0	35·1	64·9	42	25	and fall-cone test	CI-MI (on A-line)	CI-MI (on corr. A-line)
	DKM, 20D:80K	0·8	39	60·2	49·3	30·77		MI	MI
	DKM, 40D:60K	1·8	43·6	54·6	63	41·9		MH	MH
	DKM, 60D:40K	2·2	46·5	51·3	70	46		MH-MV	MH-MV
	DKM, 80D:20K	3·4	58·3	38·3	128	98		ME	ME
	DKM, 100D:0K	4	70·6	25·4	175	153†		ME	ME
Tanaka & Locat (1999)	DKM, 0D:100K	—	—	64	69	32·92	Thread-rolling test and	MH	MH
	DKM, 25D:75K	—	—	40	83	35·58	Casagrande's cup	MV	MV
	DKM, 50D:50K	—	—	25	101	36·3		ME	ME
	DKM, 75D:25K	—	—	19	112	25·69		ME	ME
Tanaka *et al.* (2012)	DKM, 10D:90K	0·9	10·9	88·2	65	31	Thread-rolling test and	MH	MH
	DKM, 20D:80K	2·9	16·8	80·3	69	30	Casagrande's cup	MH	MH
	DKM, 30D:70K	3·5	21·0	75·5	73	32		MV	MV
	DKM, 40D:60K	3·2	24·6	72·2	83	28		MV	MV
	DKM, 50D:50K	4·9	28·9	66·2	92	30		ME	ME
	DKM, 75D:25K	6·9	36·6	56·5	NP	94		—	—
Diaz-Rodríguez & Moreno-Arriaga (2017)	DKM, 0D:100K	—	—	—	62·4	27·5	Not given in the	MH	MH
	DKM, 5D:95K	—	—	—	62·9	27·2	original paper	MH	MH
	DKM, 10D:90K	—	—	—	63·2	26		MH	MH
	DKM, 15D:85K	—	—	—	63·7	24·9		MH	MH
	DKM, 20D:80K	—	—	—	64·2	25·2		MH	MH
	DKM, 40D:60K	—	—	—	66·8	21·8		MH	MH
	DKM, 60D:40K	—	—	—	69·9	18·2		MH-MV	MH-MV
Wiemer *et al.* (2017)	DKM, 0D:100K	0·1	71·1	34	56·21	18·31	Swedish fall cone method	MH	MH
	DKM, 25D:75K	2·9	69·8	31·1	93·35	34·25	(Sivakumar *et al.*, 2009)	ME	ME
	DKM, 50D:50K	5·1	72·9	27·4	153·12	69·52		ME	ME
	DKM, 75D:25K	6·8	75·8	22·9	198·82	37·32		ME	ME
	DKM, 100D:0K	7·8	81·0	19·6	289·69	84·19		ME	ME
Shiwakoti *et al.* (2002)‡	DKM, 0D:100K	0·1	19·6	80·3	68·8	33·9	Thread-rolling test and	MH	MH
	DKM, 25D:75K	0·2	38	61·8	83·1	35·1	Casagrande's cup	MV	MV
	DKM, 50D:50K	0·5	53·8	45·7	100·5	33		ME	ME
	DKM, 75D:25K	0·6	62·6	36·8	112	23·9		ME	ME
	DKM, 100D:0K	0·9	77·1	22	NP	NP		—	—
Kim (2012)	DKM, 0D:100K	—	—	86·8	53·35	23·95	Not given in the	MH	MH
	DKM, 25D:75K	—	—	74·1	59·31	24·76	original paper	MH	MH
	DKM, 50D:50K	—	—	61·4	70·08	18·77		MH-MV	MH-MV
	DKM, 75D:25K	—	—	48·6	96·05	21·68		ME	ME
	DKM, 100D:0K	—	—	35·9	117·61	15·35		ME	ME

CPC, Casagrande plasticity chart; NPC, new plasticity chart; NP, non-plastic.
*$w_{L\ FC}$ used for classification has been corrected according to equation (9) when liquid limits were determined using Casagrande's cup.
†Determined through equation (5) as the thread-rolling test is not appropriate for non-plastic diatomite.
‡Particle size in the original paper: sand (>0·075 mm); silt (0·005–0·075 mm); clay (<0·005 mm).

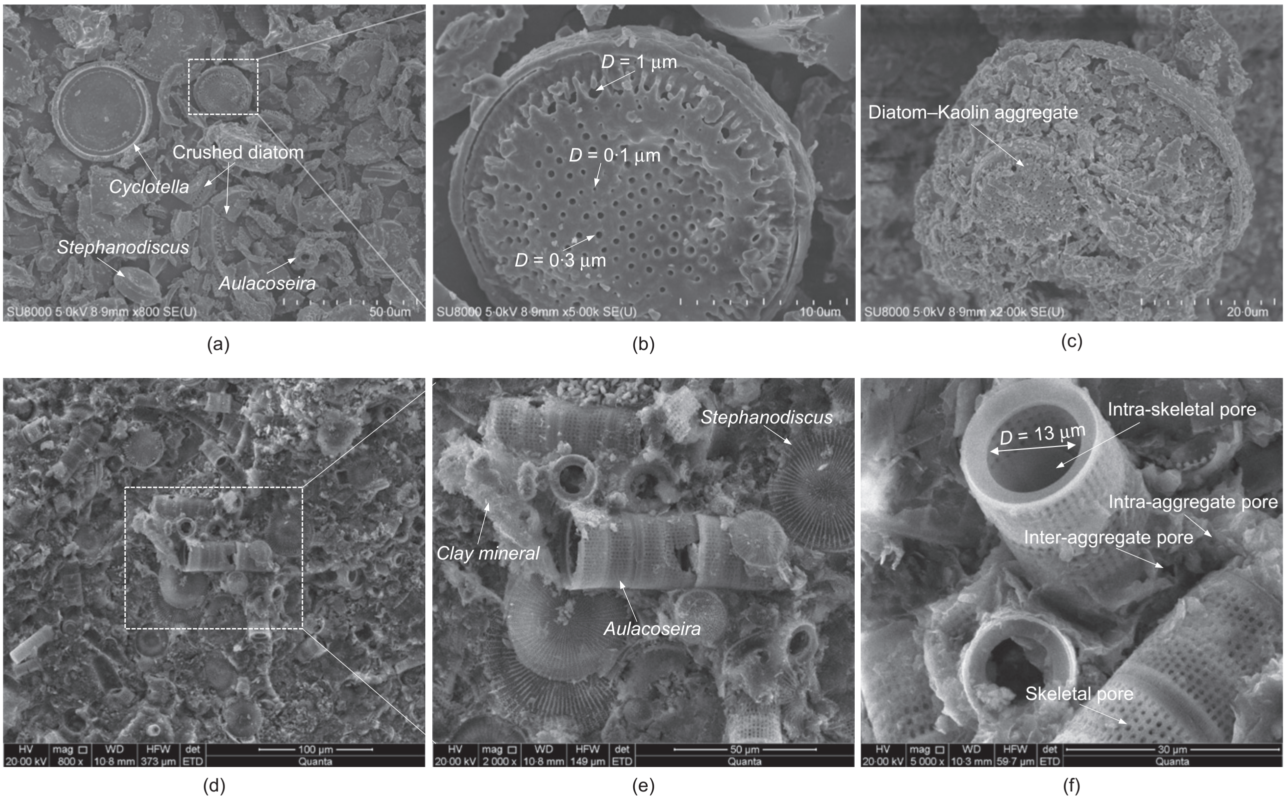

Fig. 7. SEM images of the soils studied: (a) 100D:0K DKM; (b) 100D:0K DKM; (c) 60D:40K DKM; (d), (e) and (f) natural DE

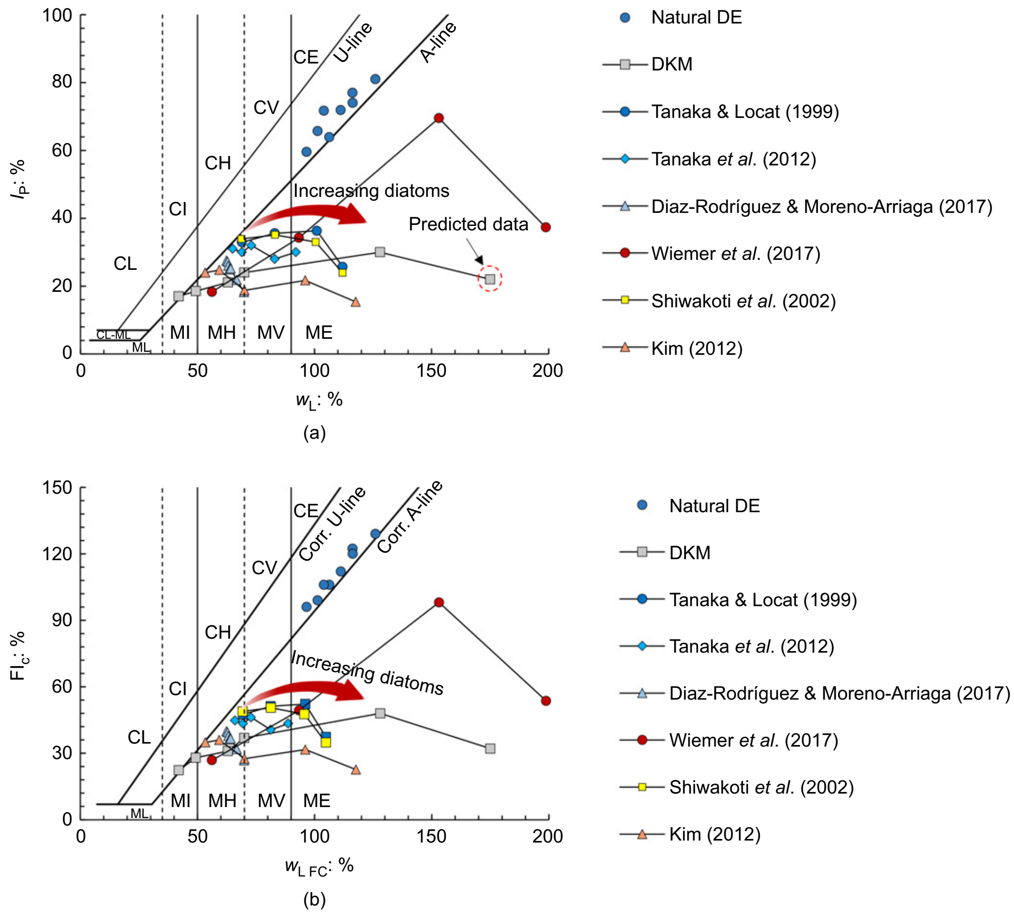

Fig. 8. Positions of the soils in Table 2 on (a) Casagrande plasticity chart and (b) new soil plasticity chart. Note that I_P of 100D:0K DKM was determined using equation (5) because of the inapplicability of the thread-rolling test to non-plastic diatomite

mixtures (Table 2). Note that although the studied soil can be classified as clay with an extremely high liquid limit according to the new plasticity chart, a large amount of water is in the intra-skeletal pore spaces, and thus it barely interacts with soil particles (Bandini & Al Shatnawi, 2017). Consequently, current results show that the consistency limits of diatomaceous soil do not provide information on the soil property as they are conventionally expected to do. Caution should be used when classifying diatomaceous soil according to the Casagrande plasticity chart and the new plasticity chart, as well as deriving the fundamental soil parameters from w_L, w_P and I_P.

In addition to DE, the new plasticity chart appears also to be inapplicable to peat with a porous and compressible nature due to the open cellular structure of the organic solids. Previous studies have confirmed the inappropriateness of Atterberg limits to peat (O'Kelly, 2015; O'Kelly *et al.*, 2018) and their adoption could be misleading. The ΔI_P–ΔI_{Pc} plots in Fig. 4 quantify the deviations of data points from the A-line. Interestingly, the discussers found that the data points with the most significant deviations from the A-line are those representing peat from the southwest of England (Vardanega *et al.* (2019) data in Table 1). Consequently, it is reasonable to expect that a minor modification of equation (5) with the data of peat excluded will lead to more accurate predictions, considering the notional nature of Atterberg limits for peat.

The discussers kindly welcome ongoing comments and discussions from the authors.

Authors' reply

The authors welcome the discussion on their paper proposing a new classification chart for plastic soils. The authors appreciate the opportunity in this reply to respond to and clarify some of the points raised by the discussers.

Use and evolution of soil classification frameworks

The need to update the Casagrande plasticity chart due to the preference in various codes employing the cone penetrometer device over the Casagrande cup device for liquid limit (w_L) determination (as suggested in Dragoni *et al.*, 2008), or to change the function of the A-line (e.g. Reznik, 2017), or to develop new soil classification methods (e.g. Polidori, 2003, 2004, 2007; Jang & Santamarina, 2016; Moreno-Maroto & Alonso-Azcárate, 2018) has been the subject of considerable research efforts. The original paper (Vardanega *et al.*, 2021) sought to do two things: (*a*) remove the need for the thread-rolling test for the plastic limit (w_P) from the classification system by using the fall-cone flow index (FI_c) from Sridharan *et al.* (1999), and (*b*) adjust the A-line and U-line equations (equations (1) and (2)) (based on the work of Casagrande (1947), as given in Howard (1984)) using equation (5) and the equations developed in the paper by O'Kelly *et al.* (2018) for linking the fall-cone liquid limit with the Casagrande cup liquid limit. The authors acknowledge that any deficiencies in the original Casagrande classification methodology will not be overcome by the achievement of aims (*a*) and (*b*).

The discussers introduce the idea that both the traditional Casagrande approach for soil classification, incorporating the thread-rolling test for the plastic limit, and the updated version based on flow index do not correctly classify two soil types: DE and peat soils. As demonstrated by the discussers for DE soils (but also for peat soils, cf. Skempton & Petley (1970)), consistency limits can be determined in the laboratory for these soils, but the Casagrande classification system (traditional or revised) alone does not give sufficient insight into the behaviour of these materials in the field (O'Kelly, 2015, 2016). While noting this, the authors would also contend that the Casagrande system for classification has this drawback to some extent for all natural materials, as it is based on remoulded soil parameters (w_L and w_P), testing only the fraction of the disaggregated material that passes the 425 μm sieve size. It is acknowledged that this drawback is considerably more marked for the DE and peat soil types referred to in the discussion. In the case of peats, more useful tests for soil classification purposes may be organic content, fibre content, natural water content and degree of humification (decomposition), as elaborated in the papers by Edil & Wang (2000) and O'Kelly (2015, 2016). Users of any soil classification framework should be aware of its inherent limitations and potential drawbacks in indicating relevant soil field behaviour. The authors' response to the discussers' specific comments is given in the following sections.

Diatomaceous earth soils

The discussers note that for DE soils, a group of soils that was not included in the original database, the soil classifications derived using both the Casagrande plasticity chart and that described by Vardanega *et al.* (2021) are identical in all cases. It is pleasing to see that the new classification scheme agrees with the Casagrande chart. The discussers further note, however, that the natural DE soils they investigated are misclassified by both charts, with these soils (comprising a majority of silt-sized particles) plotting above the A-line and hence being classified as clays. (Note, solely based on their w_L and I_P values listed in Table 2, all six DKM soils investigated by the discussers also plot above the A-line. On this basis, these soils would also be classified as clay – hence, it would seem their listed I_P values are incorrect.) It should be remembered that there is no

Table 3. Listing of peat or soils of very high organic content excluded from the database (see Table 1 in the original paper for a complete listing of all the database soils) to generate the new regression shown in Fig. 9

Database	Source publications	*n*	Data excluded to generate Fig. 9
TCD database	O'Kelly (2005)*	2	Peats, Ireland
	O'Kelly (2006)*	1	Fine fibrous peat, Ireland
	O'Kelly (2008)*	1	Residue from Ballymore Eustace water treatment plant (WTP), Ireland
	O'Kelly & Quille (2010)*	2	Residue from Leixlip and Clareville WTPs, Ireland
	O'Kelly (2013)*	1	Biosolids from Tullamore waste-water treatment plant, Ireland
	O'Kelly (2014a)	1	Residue from Ballymore Eustace WTP, Ireland
	O'Kelly (2014b)*	1	Residue from Ballymore Eustace WTP, Ireland
	O'Kelly & Sivakumar (2014)*	2	Clara and Derrybrien bog peats, Ireland
Other publication	Vardanega *et al.* (2019)	16	Soils derived by removing fibres from peat materials sourced from southwest of England

*$w_{L\ FC}$ values and other geotechnical properties reported in original papers, but not the raw $w_{L\ FC}$ test data.

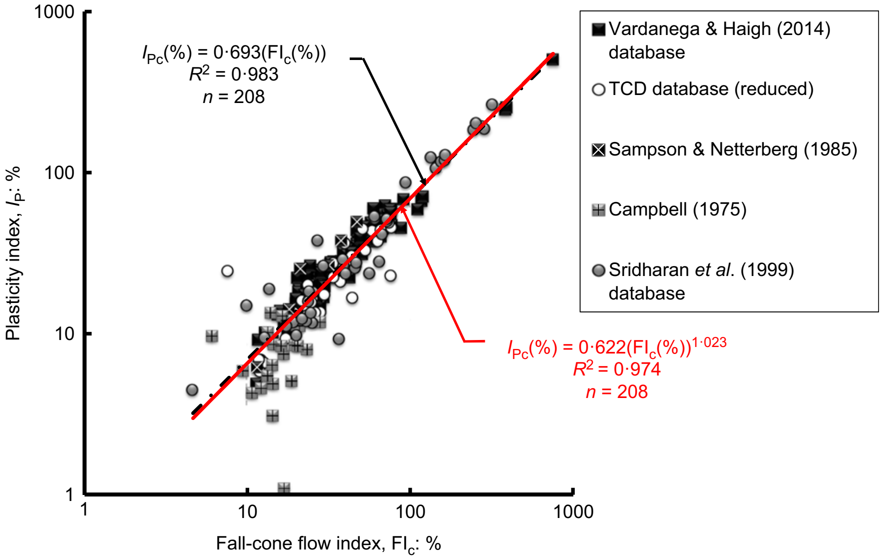

Fig. 9. Correlation of the fall-cone flow index of Sridharan *et al.* (1999) and plasticity index for the database used in the original paper (Vardanega *et al.*, 2021), with the peat materials of the TCD database and Vardanega *et al.* (2019) dataset removed (see Table 3 for full listing of these materials)

Table 4. Comparison of computed $FI_c(\%)$ values for the revised A-line and U-line formulations given in the original paper (equations (10) and (11)) and in this reply (equations (14) and (15))

$w_{L\ FC}$: %	A-line			U-line		
	Equation (10)	Equation (14)	ΔFI_c	Equation (11)	Equation (15)	ΔFI_c
30	6·4	6·0	−0·4	23·5	23·0	−0·5
50	28·7	28·3	−0·4	50·4	50·5	0·1
80	64·1	64·7	0·6	93·4	95·4	2
120	114	117	3	154	160	6
250	290	307	17	370	394	24
450	586	634	48	732	797	65
600	821	897	76	1020	1122	102

theoretical basis for the original formula for the A-line given in Casagrande (1947). More recent experience has shown that, in general, this line divides clays and silts well, the position of soils on the Casagrande chart has become the de facto classification tool for fine-grained soils, with their classification by measurement of particle-size composition rarely carried out. The fact that both charts misclassify the natural DE soils is hence interesting, but not necessarily surprising. As already pointed out, because the proposed new classification chart is derived from the Casagrande chart, any misclassification will naturally persist with use of the new chart.

The discussers also rightly point out that for some DE soils, such as pure crushed DE consisting of whole and broken frustules (i.e. DKM, 100D:0K), which are clearly identified as non-plastic, the new plasticity chart (and the Casagrande chart) would still classify said materials as plastic silts. Although both classification charts should only be used having established the plasticity credentials of the fine-grained test materials, the authors accept that this should be clarified for the new chart, as with the lack of need for a thread-rolling test, this point may be missed. It should, however, be pointed out that the plasticity, or otherwise, of fine-grained soil can generally be judged by touch rather than requiring a plastic limit test. As also pointed out in the original paper (Vardanega *et al.*, 2021), for fine-grained soil identified as being non-plastic, equation (5) in that paper should not be applied to compute a 'plasticity index' (plastic range), or from that, a 'plastic limit'.

Peat soils

The discussers also suggest that the framework should exclude peat soils. The authors note that organic soils were included in the soils studied by Casagrande when developing the soil classification framework (Casagrande, 1947), so it was deemed valid to include such material types in the determination of equations (5) and (6) in the original paper, as the test data is experimentally valid for the database of fine-grained materials studied (notwithstanding the earlier comments about the link or lack thereof to field performance of the obtained data). The authors would like to clarify (as stated in the original paper) that the peat soil data from Vardanega *et al.* (2019) were determined for soil samples with the peat fibres removed. The authors do agree that the consistency limits are not sufficient alone for classification of natural peat soils for the reasons already mentioned in this reply.

However, as suggested by the discussers, the authors have re-run the correlation analysis presented in the original paper (Vardanega *et al.*, 2021), excluding the peat and high organic content soil data from the TCD database (see Table 3) and the peat soil data from Vardanega *et al.* (2019) (see Table 1 for the full listing of the source publications for the original analysis). This reduces the number of data points for the correlation from 235 to 208 – that is, the 27 points removed comprise approximately 11·5% of the data points. Fig. 9 shows the updated correlations for the reduced database, which are given as equations (12) and (13) in this reply

$$I_{Pc}(\%) = 0{\cdot}693\,(\mathrm{FI_c}(\%)) \quad (R^2 = 0{\cdot}983;\ n = 208) \tag{12}$$

$$I_{Pc}(\%) = 0{\cdot}622(\mathrm{FI_c}(\%))^{1{\cdot}023} \quad (R^2 = 0{\cdot}974;\ n = 208) \tag{13}$$

Interestingly, the simple linear form of the correlation (equation (12)) has a slightly higher coefficient of determination (R^2) than equation (13). Therefore, using the procedure outlined in the original paper (Vardanega *et al.*, 2021), equation (12) is used to update the A-line and U-line, given as equations (14) and (15) in this reply.

Revised A-line

$$\mathrm{FI_c}(\%) = \frac{0{\cdot}73}{0{\cdot}693}\left[\left(\frac{w_{\mathrm{L\,FC}}}{1{\cdot}90}\right)^{(1/0{\cdot}85)} - 20\right] \approx 0{\cdot}495(w_{\mathrm{L\,FC}})^{1{\cdot}176} - 21{\cdot}07 \tag{14}$$

Revised U-line

$$\mathrm{FI_c}(\%) = \frac{0{\cdot}9}{0{\cdot}693}\left[\left(\frac{w_{\mathrm{L\,FC}}}{1{\cdot}90}\right)^{(1/0{\cdot}85)} - 8\right] \approx 0{\cdot}610\,(w_{\mathrm{L\,FC}})^{1{\cdot}176} - 10{\cdot}39 \tag{15}$$

Table 4 shows a numerical comparison between equations (10) and (14), and equations (11) and (15). For both sets of equations, the difference of $\mathrm{FI_c}(\%)$ ranges from around −0·5 to 6 over the w_L range of up to 120%, and from around −0·5 to 102 for the extended plasticity chart with w_L up to 600%. The authors consider that this will not result in a significant change to the classification system presented in the original paper (especially as the current BS 5930 (BSI, 2018) standard only presents the plasticity chart up to w_L of 100%, with very high plasticity being when $w_L > 70\%$). However, a classification chart could be produced using equations (14) and (15), if the user of the revised framework should wish to do so.

ACKNOWLEDGEMENT

The contribution part of this discussion is financially supported by the National Natural Science Foundation of China (nos. 41972285, 41672293, 41972293).

REFERENCES

ASTM (2017). D4318-17e1: Standard test methods for liquid limit, plastic limit, and plasticity index of soils. West Conshohocken, PA, USA: ASTM International.

ASTM (2021). D7928-21: Standard test method for particle-size distribution (gradation) of fine-grained soils using the sedimentation (hydrometer) analysis. West Conshohocken, PA, USA: ASTM International.

Bandini, P. & Al Shatnawi, H. H. (2017). Discussion of 'Fines classification based on sensitivity to pore-fluid chemistry' by Junbong Jang and J. Carlos Santamarina. *J. Geotech. Geoenviron.* **143**, No. 7, 07017011, https://doi.org/10.1061/(ASCE)GT.1943-5606.0001691.

BSI (1990). BS 1377-2: Methods of test for soils for civil engineering purposes (classification tests). London, UK: BSI.

BSI (2018). ISO 14688-2:2017: Geotechnical investigation and testing – identification and classification of soil. Part 2: Principles for a classification. London, UK: BSI.

Campbell, D. J. (1975). Liquid limit determination of arable topsoil using a drop-cone penetrometer. *J. Soil Sci.* **26**, No. 3, 234–240, https://doi.org/10.1111/j.1365-2389.1975.tb01946.x.

Casagrande, A. (1947). Classification and identification of soils. *Proc. Am. Soc. Civ. Engrs* **73**, No. 6, 783–810.

Díaz-Rodríguez, J. A. & Moreno-Arriaga, A. (2017). Contributions of diatom microfossils to soil compressibility. In *Proceedings of the 19th international conference on soil mechanics and geotechnical engineering* (eds W. Lee, J. S. Lee, H. K. Kim and D. S. Kim), pp. 349–352. Seoul, Korea: Korean Geotechnical Society.

Dragoni, W., Prosperini, N. & Vinti, G. (2008). Some observations on the procedures for the determination of the liquid limit: an application on Plio-Pleistocenic clayey soils from Umbria region (Italy). *Ital. J. Engng Geol. Environ.* **2008**, Special Issue, No. 1, 185–198, https://doi.org/10.4408/IJEGE.2008-01.S-12.

Edil, T. B. & Wang, X. (2000). Shear strength and K_0 of peats and organic soils. In *Geotechnics of high water content materials* (eds T. B. Edil and P. J. Fox), STP 1374, pp. 209–225, https://doi.org/10.1520/STP14369S. West Conshohocken, PA, USA: ASTM International.

Howard, A. K. (1984). The revised ASTM standard on the unified classification system. *Geotech. Test. J.* **7**, No. 4, 216–222, https://doi.org/10.1520/GTJ10505J.

Jang, J. & Santamarina, J. C. (2016). Fines classification based on sensitivity to pore-fluid chemistry. *J. Geotech. Geoenviron. Engng* **142**, No. 4, 06015018, https://doi.org/10.1061/(ASCE)GT.1943-5606.0001420.

Kim, K. S. (2012). Engineering characteristics of diatom modified soil mixture. *J. Korean Geotech. Soc.* **28**, No. 5, 77–84, https://doi.org/10.7843/kgs.2012.28.5.77.

Moreno-Maroto, J. M. & Alonso-Azcárate, J. (2018). What is clay? A new definition of 'clay' based on plasticity and its impact on the most widespread soil classification systems. *Appl. Clay Sci.* **161**, 57–63, https://doi.org/10.1016/j.clay.2018.04.011.

O'Kelly, B. C. (2005). Method to compare water content values determined on the basis of different oven-drying temperatures. *Géotechnique* **55**, No. 4, 329–332, https://doi.org/10.1680/geot.2005.55.4.329.

O'Kelly, B. C. (2006). Compression and consolidation anisotropy of some soft soils. *Geotech. Geol. Engng* **24**, No. 6, 1715–1728, https://doi.org/10.1007/s10706-005-5760-0.

O'Kelly, B. C. (2008). Geotechnical properties of a municipal water treatment sludge incorporating a coagulant. *Can. Geotech. J.* **45**, No. 5, 715–725, https://doi.org/10.1139/T07-109.

O'Kelly, B. C. (2013). Undrained shear strength–water content relationship for sewage sludge. *Proc. Instn Civ. Engrs – Geotech. Engng* **166**, No. 6, 576–588, https://doi.org/10.1680/geng.11.00016.

O'Kelly, B. C. (2014a). Characterisation and undrained strength of amorphous clay. *Proc. Instn Civ. Engrs – Geotech. Engng* **167**, No. 3, 311–320, https://doi.org/10.1680/geng.11.00025.

O'Kelly, B. C. (2014b). Drying temperature and water content–strength correlations. *Environ. Geotech.* **1**, No. 2, 81–95, https://doi.org/10.1680/envgeo.13.00016.

O'Kelly, B. C. (2015). Atterberg limits are not appropriate for peat soils. *Geotech. Res.* **2**, No. 3, 123–134, https://doi.org/10.1680/jgere.15.00007.

O'Kelly, B. C. (2016). Briefing: Atterberg limits and peat. *Environ. Geotech.* **3**, No. 6, 359–363, https://doi.org/10.1680/envgeo.15.00003.

O'Kelly, B. C. & Quille, M. E. (2010). Shear strength properties of water treatment residues. *Proc. Instn Civ. Engrs – Geotech. Engng* **163**, No. 1, 23–35, https://doi.org/10.1680/geng.2010.163.1.23.

O'Kelly, B. C. & Sivakumar, V. (2014). Water content determinations for peat and other organic soils using the oven-drying method.

Drying Technol. **32**, No. 6, 631–643, https://doi.org/10.1080/07373937.2013.849728.

O'Kelly, B. C., Vardanega, P. J. & Haigh, S. K. (2018). Use of fall cones to determine Atterberg limits: a review. *Géotechnique* **68**, No. 10, 843–856, https://doi.org/10.1680/jgeot.17.r.039 (Corrigendum, 68, No. 10, 935, https://doi.org/10.1680/jgeot.2018.68.10.935).

Polidori, E. (2003). Proposal for a new plasticity chart. *Géotechnique* **53**, No. 4, 397–406, https://doi.org/10.1680/geot.2003.53.4.397.

Polidori, E. (2004). Discussion: Proposal for a new plasticity chart. *Géotechnique* **54**, No. 8, 555–560, https://doi.org/10.1680/geot.2004.54.8.555.

Polidori, E. (2007). Relationships between the Atterberg limits and clay content. *Soils Found.* **47**, No. 5, 887–896. https://doi.org/10.3208/sandf.47.887.

Reznik, Y. M. (2017). A brief note on nonlinear relationship between liquid limits and plasticity indices of soils. *Geotech. Geol. Engng* **35**, No. 6, 3035–3038, https://doi.org/10.1007/s10706-017-0293-x.

Sampson, L. R. & Netterberg, F. (1985). The cone penetration index: a simple new soil index test to replace the plasticity index. In *Proceedings of the 11th international conference on soil mechanics and foundation engineering* (ed. Publications Committee of XI ICSMFE), vol. 2, pp. 1041–1048. Rotterdam, the Netherlands: Balkema. See https://www.issmge.org/uploads/publications/1/34/1985_02_0141.pdf (accessed 11/11/2021).

Shiwakoti, D. R., Tanaka, H., Tanaka, M. & Locat, J. (2002). Influences of diatom microfossils on engineering properties of soils. *Soils Found.* **42**, No. 3, 1–17, https://doi.org/10.3208/sandf.42.3_1.

Sivakumar, V., Glynn, D., Cairns, P. & Black, J. (2009). A new method of measuring plastic limit of fine materials. *Géotechnique* **59**, No. 10, 813–823. https://doi.org/10.1680/geot.2009.59.10.813.

Skempton, A. W. & Petley, D. J. (1970). Ignition loss and other properties of peats and clays from Avonmouth, King's Lynn and Cranberry Moss. *Géotechnique* **20**, No. 4, 343–356, https://doi.org/10.1680/geot.1970.20.4.343.

Sridharan, A., Nagaraj, H. B. & Prakash, K. (1999). Determination of the plasticity index from flow index. *Geotech. Test. J.* **22**, No. 2, 175–181, https://doi.org/10.1520/GTJ11276J.

Tanaka, H. & Locat, J. (1999). A microstructural investigation of Osaka Bay clay: the impact of microfossils on its mechanical behaviour. *Can. Geotech. J.* **36**, No. 3, 493–508, https://doi.org/10.1139/cgj-36-3-493.

Tanaka, M., Watabe, Y., Tomita, R. & Kamei, T. (2012). Effects of diatom microfossils content on physical properties of clays. In *Proceedings of the 22nd international offshore and polar engineering conference (ISOPE)* (eds J. S. Chung, I. Langen, S. Y. Hong and S. J. Prinsenberg), vol. 2, pp. 593–597. Danvers, MA, USA: International Society of Offshore and Polar Engineers (ISOPE).

Vardanega, P. J. & Haigh, S. K. (2014). The undrained strength–liquidity index relationship. *Can. Geotech. J.* **51**, No. 9, 1073–1086, https://doi.org/10.1139/cgj-2013-0169.

Vardanega, P. J., Hickey, C. L., Lau, K., Sarzier, H. D. L., Couturier, C. M. & Martin, G. (2019). Investigation of the Atterberg limits and undrained fall-cone shear strength variation with water content of some peat soils. *Int. J. Pavement Res. Technol.* **12**, No. 2, 131–138, https://doi.org/10.1007/s42947-019-0017-0.

Vardanega, P. J., Haigh, S. K. & O'Kelly, B. C. (2021). Use of fall-cone flow index for soil classification: a new plasticity chart. *Géotechnique*, https://doi.org/10.1680/jgeot.20.P.132.

Wiemer, G., Dziadek, R. & Kopf, A. (2017). The enigmatic consolidation of diatomaceous sediment. *Mar. Geol.* **385**, 173–184, https://doi.org/10.1016/j.margeo.2017.01.006.