DISCUSSION

Proposal for a new plasticity chart

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Geotechnical engineers are normally not very well trained in the application of statistics in soil mechanics. Spurious observations or incorrect conclusions are therefore often made from graphical plots of soil data owing to inappropriate choice of variables in correlating different soil properties (Li & White, 1993). The plasticity chart proposed by A. Casagrande, which has been used for decades as a tool for classification of soils, is a case in point.

In the plasticity chart, the plasticity index I_p is plotted against the liquid limit w_L . Different types of clayey or silty soils tend to take up different zones in the plasticity chart. As pointed out by Li & White (1993), the plasticity index is functionally related to the liquid limit by the equation $I_p = w_L - w_p$, where w_p is the plastic limit. Therefore a strong statistical correlation between I_p and w_L can be derived even if there is no strong statistical correlation between w_L and w_p . By performing a simulation in which random numbers are generated for w_L and w_p , Li & White (1993) were able to obtain a statistically significant linear relationship between I_p and w_L , as shown in Fig. 9, with a coefficient of correlation of 0.962, yet this correlation has no meaning as w_L and w_p are unrelated.

Seed *et al.* (1964a) observed that w_L and w_p of organic clays with different activities follow different linear relationships in the plasticity chart, as shown in Fig. 10. As I_p and w_L are functionally related to each other, these linear relationships are very close to each other and occur within a narrow band close to the A-line. They can easily be masked by the innate variability and measurement errors of w_L and w_p . It is therefore not entirely appropriate for Casagrande to choose to define the plasticity chart in terms of w_p and w_L . A better way to discern the correlation of index properties is to use w_p and w_L directly as the variables for constructing the plasticity chart, hereafter called the P-L chart, as distinct from the conventional plasticity chart.

Figure 11 shows the data from Skempton (1953) and Seed *et al.* (1964a) plotted in a P-L chart. A comparison of Figs

Fig. 9. Relationship between I_p and w_L based on randomly generated w_p and w_L

Fig. 10. Relationship between I_p and w_L for different activities of clay. ACT, activity of clay

Fig. 11. P-L chart of clays: (a) data from Skempton (1953); (b) data from Seed *et al.* (1964a)

10 and 11 indicates that clays with different activities exhibit more distinct linear relationships in a P-L chart than in a conventional plasticity chart. This implies that different types of soil will tend to demarcate more distinctly in a P-L

chart. For this reason, the P-L chart is considered to be a more powerful tool for soil classification. The author has given new insights into soil classification based on the conventional plasticity chart. It is therefore of interest to know whether an improved soil classification can also be developed using the suggested P-L chart.

Author's reply

The author thanks the discussor, although he believes the discussion does not specifically address the contents of this paper. In fact, the difference between the two I_p - w_L plasticity charts (that of Casagrande and the author's) seems of lesser importance than the w_p - w_L parameters with which the plasticity could be represented according to Li.

Disregarding some inaccuracies (as in the graphs of Figs 10 and 11) which are not determinant, the fundamental issues in the author's view are as follows.

If it is true that 'a strong statistical correlation between I_p and w_L can be derived even if there is no strong statistical correlation between w_L and w_p ', it is not possible for the data (Skempton, 1953; Seed *et al.*, 1964a) to show a more distinct linear relationship in the P-L chart (Fig. 11) than in the I_p - w_L plasticity chart (Fig. 10). Independent of this consideration, on the basis of Fig. 2, plotting these data on the proposed plasticity chart one can observe—for example the data in fig. 5 of the study in discussion, indicated here as Fig. 12, and in the w_p - w_L chart in Fig. 13—that both charts give equivalent information regarding the classification of the soils tested as well as their clay content (the

Fig. 12. Fig. 5 of the paper under discussion. The dashed lines represent the clay fraction (CF) at 10% intervals

Fig. 13. Plastic limit, w_p , against liquid limit, w_L , of soils plotted in Fig. 12

proposed chart is better suited also for appraising the activity). It is clear that in the w_p - w_L chart the silt and clay zones are reversed when compared with the I_p - w_L plasticity chart.

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The author is to be complimented for creating a platform for a useful discussion on the issue of soil classification.

As the author had made clear, the paper was a result of the need to answer the following questions:

- Why do inorganic soils represented on Casagrande's plasticity chart, with clay fractions (CF) $< 2 \mu\text{m}$ that are smaller than their silt and/or sand fractions ($2-425 \mu\text{m}$), lie above the A-line in the clay zone?
- Conversely, why does pure kaolinite lie below the A-line in the silt zone?

The classification of fine-grained soils has three stages:

- grain size analysis, which determines sand fraction, silt fraction and clay fraction
- positioning of the fine-grained soil in the plasticity chart so as to judge whether the soil is inorganic clay, inorganic silt or organic soil
- depending upon the liquid limit of the soil, deciding whether the soil has low, medium or high plasticity.

The first two stages should not be interlinked. Whereas the first stage considers only soil grain size, the classification of soil into silt or clay through a plasticity chart is based purely on plasticity: the liquid limit and plasticity index are the two parameters required to do so. In other words, the term 'silt size fraction' is different from the term 'silt', and the term 'clay size fraction' is different from the term 'clay'.

It is well established that clay minerals such as montmorillonite and kaolinite are responsible for soil plasticity. The type and quantity of clay minerals with their associated exchangeable cations present in a fine-grained soil control the extent of soil plasticity and volume change behaviour rather than the CF. For the same bentonite clay, depending upon the exchangeable cation, the liquid limit can vary several fold, whereas marginal variations are seen in the plastic limit (e.g. Sridharan *et al.*, 1986a). The author recognises the importance of clay mineralogy. Fig. 14 shows that w_L and CF are not interrelated. Two types of engineering behaviour of soils—silty behaviour and clayey behaviour—are recognised. If the montmorillonitic clay mineral content in the CF is more, then the soil exhibits clayey behaviour and high plasticity (i.e. relatively high w_L and low w_p). If the kaolinitic clay mineral content is more, then the soil exhibits silty behaviour and low plasticity (i.e. relatively low w_L and high w_p). A given soil may have a CF less than 50%, but if the quantity of montmorillonitic clay minerals within that dominates, then that soil lies above the A-line. On the other hand, a given soil may have a silt fraction less than 50%, and if the quantity of kaolinitic clay minerals within that is dominant and the CF contains relatively inert particles, then the soil lies below the A-line. Hence Casagrande's plasticity chart classifies the given soil into silt or clay based on a behavioural standpoint rather than on the soil content based on particle size only. This is the answer to the first question posed by the author.

Even though kaolinite is a clay mineral, as it is coarser in size it is normally of silt size. Kaolinite clay mineral contributes to the silty type of soil behaviour. It has a higher plastic limit and hence less plasticity. Hence it is unsurprising to see pure kaolinite lying below the A-line in the silt zone. This is the answer to the authors' second question.

Fig. 14. Relationship between percent clay fraction content and liquid limit (Sridharan & Prakash, 2000)

The discussers wish to present some more illustrations to highlight the limitations of the proposed plasticity chart (Fig. 15 & Table 6). Fig. 15 shows the author's new plasticity chart along with the A-line of Casagrande's chart. The soils that fall in zone p are really silts from their behavioural viewpoint, but are classified as clays in the new plasticity chart. The inorganic clays that lie in zone q will be treated by the new chart as organic soils! The soils that locate themselves between the 0.5 C-line and U-line, particularly at high liquid limits, are classified by the new plasticity chart as silts. It should be noted that high plastic clays which can be regarded as expansive soils have high liquid limits and high plasticity indices. It is not correct to classify them as silts.

Soils 1–5 in Table 6 have a CF content more than 50%. They are classified by both British and ASTM standards as inorganic clays, whereas the proposed new plasticity chart treats them as silts. It can be noted that soils 1–3 are expansive soils. Soil 6 is classified as silt of high plasticity by both British and ASTM standards even though its CF

Fig. 15. New plasticity chart proposed by the author along with A-line

content is more than 50%. This is because of its silty behaviour due to the presence of kaolinite as its primary clay mineral.

Soils 7–18 in Table 6 have a silt fraction more than 50%. They are regarded as inorganic silts, true to their clay mineral composition, by the British and ASTM standards, whereas the proposed new plasticity chart of the author classifies them as either organic soils or clays. Soil 19, even though it has a silt fraction more than 50%, is classified as clay of high plasticity by the British and ASTM standards. This could be due to the influence of dominant clay mineral content in the CF.

Soils 20–22 in Table 6 have both CF and silt fractions less than 50%. Soils 21 and 22 in particular are highly expansive inorganic clays, owing to the presence of dominant expansive clay mineral in the CF, but the proposed new plasticity chart identifies them as silts!

In addition to the above, Table 1 assumes a linear variation of w_L and w_p with the CF content. Figs 16 and 17 show a variation of w_L and w_p with the CF content that is non-linear. Many similar examples could be cited.

Finally, the discussers wish to conclude by stating that the classification of soils into clays and silts through a plasticity chart is nothing to do with the clay size fraction or silt size fraction, but it is from their plasticity behaviour. As the soil plasticity does not depend upon the content of clay-size and silt-size particles, the author's suggestion that the classification of silt or clay should be in agreement with the main component (silt size or clay size fraction) defined by the nomenclature for the grain size distribution of the soil fraction seems untenable.

Author's reply

The author wishes to thank Professor Prakash and Professor Sridharan for their discussion of the author's paper.

It should be noted that considerations regarding inorganic soils with platey clay minerals are not valid for residual inorganic soils containing non-platey clay minerals (allophane, halloysite, attapulgite) because their characteristics (high plastic limit, low plasticity index, high residual strength; Kenney, 1967; Lupini *et al.*, 1981; Wesley, 1992; Mitchell, 1993) are very different from those of platey clay minerals for which the plasticity chart was developed. Hence these soils may lie below or above the C-line according to their particular characteristics.

Figure 18 shows all the soil values (25 in number) reported in Wasti & Bezirci (1986). The clay fraction of these soils ranges from 13% to 88%. All the soils lie above Casagrande's A-line and between the C-line and the U-line. The same is true of the soils plotted in Fig. 19.

According to the author, the classification of inorganic soils as silts or clays from a behavioural standpoint must be pursued exclusively in the zone between the U-line and the C-line in which the soils lie (see Fig. 18).

The classification of the soils (with CF < 50%) that lie between the 0.5C-line and the U-line in the silt zone (such as soils no. 1, 19, 20, 21 and 22 in Table 6) should be different from the classification proposed by Casagrande. But some soils, including many of those chosen by the discussers and reported in Table 6, lie in a zone that does not correspond to their clay fractions. The values of the Atterberg limits of these soils, if compared among themselves or with other data reported in the literature, may be difficult to understand, particularly W_p . For example, soils no. 8 and no. 19 (Table 6) have the same w_L value and an almost equal percentage of clay. The respective values of the plastic limit are $w_p = 51.9\%$ and $w_p = 25\%$. What accounts for this difference of more than 100%? Why is the difference among the w_p values greater than the difference among

Table 6. Details of some typical soils

No.	Soil	w_L : %	I_p : %	Grain size distribution			Classification			Reference
				Clay size: %	Silt size: %	Sand size: %	BS	ASTM	Proposed modified chart	
1	Bentonite–sand mixture	198	172.6	60	—	40	CE	CH	MH	Sivapullaiah & Sridharan (1985)
2	Sample no. 17	362	333	84	?	?	CE	CH	MH	Wasti & Bezirci (1986)
3	Sample no. 16	526	488	88	?	?	CE	CH	MH	Wasti & Bezirci (1986)
4	Sample no. 06	52	30	59	?	?	CH	CH	MH	Wasti & Bezirci (1986)
5	Red earth-2	51.5	30.3	62	38	00	CH	CH	MH	Sridharan & Prakash (1998)
6	Bangalore soil	70	31	66	28	06	MH-MV	MH	CH	Sridharan <i>et al.</i> (1990)
7	Korapet soil	66	26	30	58	12	MH	MH	OH	Sridharan <i>et al.</i> (1990)
8	Illitic soil	73.4	21.5	27.5	71.6	0.9	MV	MH	OH	Sridharan & Nagaraj (2000)
9	Cochin soil	56.4	18.3	17.5	64.5	18	MH	MH	CH	Sridharan & Nagaraj (2000)
10	Kaolinite-3	58.7	13.5	11.5	88.5	00	MH	MH	OH	Sridharan & Nagaraj (2000)
11	Peenya soil-7	72.2	25	15.7	80	4.3	MV	MH	OH	Sridharan & Prakash (1998)
12	Hemavathi Project soil	58.5	27.5	20.8	51.2	28	MH	MH	CH	Sridharan & Prakash (1998)
13	Kaolinite-1	48	12.4	10	77.5	12.5	MI	ML	OL	Sridharan & Prakash (1998)
14	Kaolinite-2	46.8	17.4	36	63.6	0.4	MI	ML	CL	Sridharan & Prakash (1998)
15	Silty soil	41.4	10.9	11.5	59.7	28.8	MI	ML	CL-OL	Sridharan & Prakash (1998)
16	Bentonite–kaolinite mixture	75	38.6	21	79	00	MV	MH	CH	Satyanarayana Murthy (1986)
17	Na–kaolinite	52	13	11.1	81.3	7.6	MH	MH	OH	Sivapullaiah <i>et al.</i> (1996)
18	Mangalore soil	73	32.6	21	66	13	MV	MH	OH	Sridharan <i>et al.</i> (1988)
19	CPRI soil	74	39	30	58	12	CV	CH	MH	Sridharan <i>et al.</i> (1988)
20	Maddur soil	60.8	37.2	36	38.7	25.3	CH	CH	MH	Present study
21	Gumballi soil	214.5	193.6	42	25.5	32.5	CE	CH	MH	Present study
22	Chittoor soil	123	100	39	28	33	CE	CH	MH	Sridharan <i>et al.</i> (1990)

Fig. 16. Variation of liquid limit with clay fraction of the soil

Fig. 17. Variation of plastic limit with clay fraction of the soil

the w_L values in soils no. 10 and no. 14? Why do soils no. 3 (with $w_L = 526\%$), no. 6 (with $w_L = 70\%$) and no. 17 (with $w_L = 52\%$) have a nearly equal w_p value (38–39%)? Finally, why does the lowest plastic limit value (20.9%)

Fig. 18. Location on proposed plasticity chart of all soils (Wasti & Bezirci, 1986). Casagrande's A-line is also shown

Fig. 19. Location on Polidori's plasticity chart of soils reported on discussor's Figs 16 and 17. Casagrande's A-line is also shown

belong to soil no. 21 with $w_L = 214$, 5% and $CF = 42\%$? Table 7 shows several soils composed of only one clay mineral (from Table 6 and the literature). In particular, the plastic limit of the clay minerals kaolinite and montmorillo-

Table 7. Index properties of kaolinite and bentonite soils

Sample no.	Soil/mineralogy	w_L : %	I_p : %	w_p : %	CF: %	A	Reference
10	Kaolinite-3	58.7	13.5	45.2	11.5	1.17	Table 6
13	Kaolinite-1	48	12.4	35.6	9.5	1.3	Table 6
14	Kaolinite-2	46.8	17.4	29.4	36	0.48	Table 6
	Kaolinite-quartz	38	22.7	15.3	27	0.84	Sridharan <i>et al.</i> (1988)
	Kaolinite-quartz	55	23.6	31.4	32	0.74	Sridharan & Nagaraj (2000)
	Kaolinite-quartz	31.5	15	16.5			Sridharan <i>et al.</i> (2000)
	Kaolinite-quartz	37	19	18			Sridharan <i>et al.</i> (2000)
	Kaolinite-quartz	44	26	18			Sridharan <i>et al.</i> (2000)
	Kaolinite-quartz	48	26.7	21.3			Sridharan <i>et al.</i> (2000)
1	Bentonite-sand mixture	198	172.6	25.4	40	4.31	Table 6
3	Bentonite	526	488	38	88	5.54	Table 6
	Bentonite	536	486.3	49.7			Figs 16, 17
	Bentonite-sand mixture	396	356.7	39.3	80		Figs 16, 17
	Montmorillonite-quartz	84	42	42	37	1.13	Sridharan <i>et al.</i> (1986b)
	Montmorillonite: round particles	75	32.5	42.5	50	0.65	Sridharan <i>et al.</i> (1986b)
	Montmorillonite: round particles	100	54.8	45.2	31	1.77	Sridharan <i>et al.</i> (1986b)
	Montmorillonite-quartz	73.5	37.9	35.6	51	0.74	Sridharan <i>et al.</i> (2000)
	Montmorillonite-quartz	98	49.3	48.7			Sridharan <i>et al.</i> (2000)
	Montmorillonite-quartz	44	19.4	24.6			Sridharan <i>et al.</i> (2000)