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TECHNICAL PAPER

Discussion: A Fuzzy Classification Process for Swelling Soils [Transp. Infrastruct. Geotechnol. 10(3), 474–487]

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Abstract

This communication article presents a discussion of various fundamental points pertaining to the Toksöz Hozatlıoğlu and Yılmaz (2023) (the Authors) investigation [published in Transp. Infrastruct. Geotechnol. 10(3), 474–487], specifically scrutinizing the practical ramifications of employing the liquid limit (LL) parameter (by itself) to infer soil expansivity. Based on previous experimental investigations and their own independent analyses presented in this article, the Discussers demonstrate that without proper consideration of soil mineralogical activity, the sole reliance on the LL parameter (as adopted in the Authors' investigation) is often not a reliable basis for performing soil expansivity assessments. Accordingly, the LL-based fuzzy classification approach reported by the Authors, despite addressing potential uncertainties arising from LL determinations by the Casagrande percussion-cup method, would, in itself, not lead to significantly more reliable soil expansivity assessments. As a way forward, a practical and more realistic classification framework for expansive soils based on equilibrium sediment volume measurements is presented and compared to the LL-based scheme adopted in the Authors' investigation. Through this endeavor, it is demonstrated that the sole reliance on the LL parameter generally produces overly conservative soil expansivity rankings.

Keywords Expansive soil · Liquid limit · Plasticity index · Mineralogical activity · Equilibrium sediment volume

Abbreviations

ASTM	American Society for Testing and Materials
BS	British Standard
CE	Clay with extremely high plasticity
CH	Clay with high plasticity
CI	Clay with intermediate plasticity
CL	Clay with low plasticity
CV	Clay with very high plasticity
ESV	Equilibrium sediment volume (of soil)

Extended author information available on the last page of the article

IS	Indian Standard
K	Kaolinite
M	Montmorillonite
ME	Silt with extremely high plasticity
MH	Silt with high plasticity
MI	Silt with intermediate plasticity
ML	Silt with low plasticity
MV	Silt with very high plasticity
NZS	New Zealand Standard
XRD	X-Ray Diffraction

Notations

FSR	Free swell ratio
LL	Liquid limit [%]
N_C	Number of soil-expansivity classification discrepancies
N_S	Number of soil materials (or LL:FSR data pairs) investigated
PI	Plasticity index (= LL − PL) [%]
PL	Plastic limit [%]
SI	Shrinkage index(= LL − SL) [%]
SL	Shrinkage limit [%]
$T_{(-1)}$	Classification percentage underestimated (in relation to FSR) by one expansivity-level class [%]
$T_{(1)}$	Classification percentage overestimated (in relation to FSR) by one expansivity-level class [%]
$T_{(2)}$	Classification percentage overestimated (in relation to FSR) by two expansivity-level classes [%]
$T_{(3)}$	Classification percentage overestimated (in relation to FSR) by three expansivity-level classes [%]
$T_{(4)}$	Classification percentage overestimated (in relation to FSR) by four expansivity-level classes [%]
V_D	ESV of oven-dried soil placed in distilled water [mL]
V_K	ESV of oven-dried soil placed in kerosene [mL]
μ	Arithmetic mean
σ	Standard deviation

1 Introduction

Recently, Toksöz Hozatlıoğlu and Yılmaz (2023) (the Authors) proposed a fuzzy classification approach aimed at minimizing potential uncertainties arising from liquid limit (LL) determinations (obtained by the Casagrande percussion-cup method) in performing soil expansivity assessments. For this purpose, the Authors invoked the Dakshanamurthy and Raman (1973) classification framework, which allocates soil expansivity rankings on the basis of six discrete LL domains (assigned in a Casagrande-style soil plasticity chart). Within this framework, there is a major anomaly in that for a given LL domain, the same soil expansivity ranking arises, regardless of the plasticity index (PI = LL − PL, where

PL denotes the plastic limit) value. For instance, high-PI clay and low-PI silt materials with similar LLs would be assigned the same soil expansivity ranking, which is clearly not correct in practice. This communication article presents a discussion of various fundamental points pertaining to the Authors' investigation, specifically scrutinizing the practical ramifications of employing the LL parameter (by itself) to infer soil expansivity.

As context, the basis for the Dakshanamurthy and Raman (1973) classification framework is first critically scrutinized. Subsequently, supported by previous investigations and their own independent analyses presented in later sections of the present article, it is the Discussers' viewpoint that without proper consideration of soil mineralogical activity, the sole reliance on the LL parameter (as employed in the Dakshanamurthy and Raman (1973) classification scheme) is often not a reliable basis for performing soil expansivity assessments. As such, the fuzzy approach reported by the Authors, despite addressing potential classification uncertainties arising from LL determinations, would, in itself, not lead to significantly more reliable soil expansivity assessments.

As a way forward, a practical and more realistic classification framework for expansive soils based on equilibrium sediment volume (ESV) measurements (Sridharan and Prakash 2000a; Prakash and Sridharan 2004) is presented and compared to the LL-based scheme adopted in the Authors' investigation. The ESV-based approach has the advantage of requiring straightforward sediment volume measurements compared to the more sophisticated and/or time-consuming testing needed for clay content and activity (Seed et al. 1962), clay content and PI (Van der Merwe 1964), or suction–water content (McKeen 1992) measurements used in other expansive soil classification schemes described in the Authors' paper.

2 The Dakshanamurthy and Raman (1973) Classification Framework for Expansive Soils

The Dakshanamurthy and Raman (1973) classification framework is seemingly a modified version of the IS 1498 (1970) classification scheme for expansive soils, allocating soil expansivity rankings on the basis of six discrete LL domains, with its upper-five classification domains identical to the LL-determined soil plasticity class levels (domains) presented in the BS 5930 (2015) version of the Casagrande-style soil plasticity chart (see Table 1). From Atterberg limits results for 50 *clay* soils (i.e., CL, CI, CH, and CE) investigated by them, along with 34 *silt* soils (i.e., MH, MV, and ME) reported elsewhere in the existing literature, Dakshanamurthy and Raman (1973) considered these data in plots of PI and shrinkage index (i.e., SI = LL − SL, where SL denotes the shrinkage limit) against the LL. With the PI:LL data providing a plasticity rating, Dakshanamurthy and Raman (1973) considered/assumed that the SI:LL data provided a swelling rating, and reported that as plasticity (i.e., PI) increased (from non-plastic to very high plasticity), the swelling rating (i.e., SI) also increased in the same range of plasticity. Although not explicitly stated in their paper, it would seem that with the SI as their measure of soil expansivity and based on the data for the 50 *clay* soils, Dakshanamurthy and Raman (1973) took a one-to-one correspondence between the SI and PI parameters, and assumed the latter increased proportionately with increasing LL, thereby reducing their proposed soil expansivity

Table 1 Classification procedures for fine-grained soils based on the LL parameter

Dakshanamurthy and Raman (1973)		IS 1498 (1970)		BS 5930 (2015)	
Expansivity level	LL (%)	Expansivity level	LL (%)	Plasticity level	LL (%)
Non-swelling	≤ 20%	—	—	—	—
Low	20–35	Non-critical	20–35	Low (CL, ML, OL)	≤ 35%
Medium	35–50	Marginal	35–50	Intermediate (CI, MI, OI)	35–50
High	50–70	Critical	50–70	High (CH, MH, OH)	50–70
Very high	70–90	Severe	70–90	Very high (CV, MV, OV)	70–90
Extra high	> 90	—	—	Extremely high (CE, ME, OE)	> 90

classification scheme to simply rely on the six discrete LL domains specified. Note that the Discussers' independent analysis of these separate datasets confirmed that the SI did increase overall for increasing PI, and in approximately the same range as PI for the 50 *clay* soils (with PI = 11–70% and SI = 8–88%), but the latter was not the case for the 34 *silt* soils (with PI = 16–50% and SI = 35–77%). Of course, this outcome is expected since the purpose of the soil plasticity chart is to distinguish between *clay* and *silt* soils (in this chart plotting above and below the A-Line demarcation boundary, respectively). That is, while the *clay* and *silt* SI:LL datasets plot approximately along the same correlation line, when considered separately the PI:LL correlation line for the 34 *silt* soils plots significantly below that of the 50 *clay* soils investigated. It should also be considered that the SI and PI parameters are not independent of the LL (i.e., both are computed using the LL), more so for SI, with the mean and standard deviation of the SI-to-LL ratio being $\mu = 0.68$ and $\sigma = 0.17$, respectively, compared to $\mu = 0.58$ and $\sigma = 0.09$ for the PI-to-LL ratio, considering the 50 *clay* soils. The corresponding values for the 34 *silt* soils are $\mu = 0.81$ and $\sigma = 0.07$ for the SI-to-LL ratio, and $\mu = 0.41$ and $\sigma = 0.09$ for the PI-to-LL ratio. This would suggest that in terms of these two parameters with LL, the PI may be a better option than SI for soil expansivity assessments. Considering soil shrinkage as a 'particle-packing' phenomenon, as postulated by Sridharan and Prakash (1998, 2000b), the SL-state water content (and hence by association the SI parameter) would be governed by the relative particle-size distribution and internal shear resistance of fine-grained soils, such that, irrespective of their inherent swelling potential (Asuri and Keshavamurthy 2016), soils with more uniform gradations and/or higher shear resistance at the particle level would mobilize higher SLs (Sridharan and Prakash 1998, 2000b).

3 Liquid Limit and Soil Expansivity

The soil clay fraction and its associated mineralogical activity are the primary drivers of swelling potential, such that soils containing greater clay content of higher mineralogical activity (e.g., greater montmorillonite content) exhibit higher degrees of expansivity (Nelson and Miller 1992; Mitchell and Soga 2005). In terms of soil physicochemical attributes, in this case, the LL and swelling potential, fine-grained soils can be broadly classified into (and hence investigated as) two groups, namely *montmorillonitic* and *kaolinitic* soils (Sridharan 1991, 2014), the former having a notable fraction of expanding lattice-type clay minerals that trigger moisture-induced swelling due to double-layer repulsion (Mitchell and Soga 2005; Estabragh et al. 2020).

Like the swelling phenomenon, the LL (here specifically referring to the percussion-cup derived LL) of montmorillonitic soils is mainly governed by the double-layer thickness (Sridharan et al. 1986a), whereas particle arrangements and inter-particle attractive forces are the primary factors controlling the LL of kaolinitic soils (Sridharan et al. 1988). Accordingly, one can expect the LL parameter to be a reasonable indicator of swelling capability in montmorillonitic soils, as both the LL and swelling potential of these soils are to a large extent governed by the double-layer thickness. The same, however, need not be true for kaolinitic soils, such that a high LL value would not necessarily indicate high mineralogical activity (and hence by association high expansivity) in these soils (Sridharan and Prakash 2000a). This viewpoint is supported in Fig. 1, which illustrates 69 different fine-grained soil materials (with known mineralogical composition determined by X-Ray Diffraction (XRD) analysis) compiled from Prakash and Sridharan (2004) and plotted on the Casagrande-style soil expansivity chart proposed by Dakshanamurthy and Raman (1973). It should be mentioned that the LL and PL of these 69 soil materials were determined by the BS 1377–2 (1990) percussion-cup and thread-rolling methods, respectively. Employing the LL-based classification scheme proposed by Dakshanamurthy and Raman (1973) (see Table 1) for the kaolinitic soils shown in Fig. 1, which, true to their mineralogical activity are expected to be associated with 'negligible to low' expansivity,

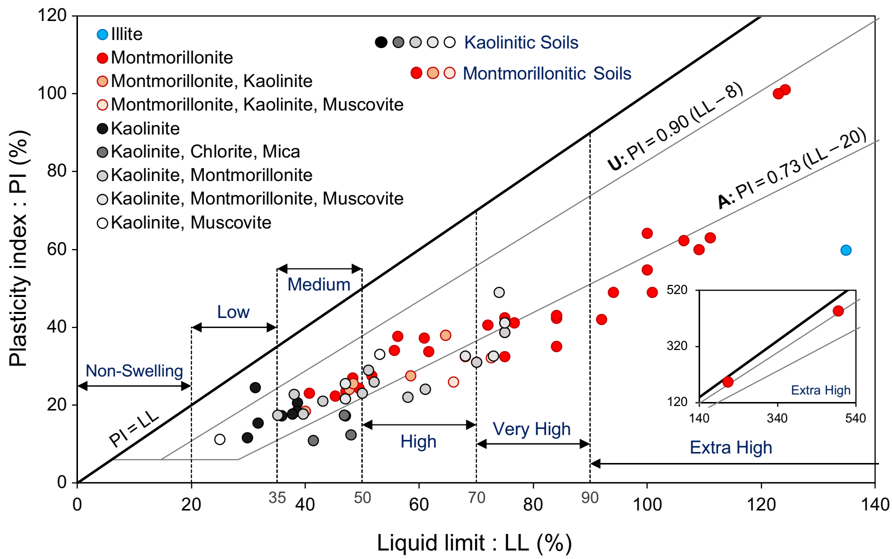

Fig. 1 Soil expansivity rankings, based on the Dakshanamurthy and Raman (1973) LL-based classification framework, for *montmorillonitic* and *kaolinitic* soils (data sourced from Prakash and Sridharan (2004))

incorrectly assigns ‘low to very high’ expansivity rankings to these soils. Considering the above, it is the Discussers’ viewpoint, also supported by previous investigations that have cross-checked plasticity-based classification approaches against oedometer swell test results (e.g., Holtz and Gibbs 1956; Chen 1975; Sridharan et al. 1986b; Sridharan and Rao 1988; Sridharan et al. 1990; Sridharan and Prakash 2000a), that the LL alone, without proper consideration of soil mineralogical activity, is often not a reliable basis for performing soil expansivity assessments. As such, the fuzzy approach reported by the Authors, despite addressing potential classification uncertainties arising from LL determinations, would still have limited practical significance.

Another limitation associated with LL-based classification schemes could arise when dealing with chemically stabilized clay–water systems. The stabilization of montmorillonitic and kaolinitic soils with certain chemical agents that induce clay particle flocculation, such as polymers (e.g., Kim and Palomino 2009; Torfi et al. 2021; Soltani et al. 2022), increases the LL while generally suppressing the swelling potential of montmorillonitic soils. If the LL is employed for conducting preliminary evaluations of such chemical agents, one would erroneously predict an increase in the expansivity level of the stabilized soil, and from this viewpoint one would judge the stabilization method under investigation as ineffective.

4 Sediment Volume Tests for Soil Expansivity Assessments

Among the multitude of inferential testing methods proposed for assessing soil expansivity, as reviewed in the paper by Asuri and Keshavamurthy (2016), soil sedimentation tests that work on the basis of ESV measurements appear to be the most practical and hence warrant further attention. For a complete review of ESV-based methods, the reader is referred to the paper by Prakash and Sridharan (2010). The most recently proposed ESV-based classification scheme for expansive soils, by Sridharan and Prakash (2000a) and Prakash and Sridharan (2004), employs the free swell ratio (FSR) parameter (given by Eq. 1), allocating soil expansivity rankings based on five FSR domains (established based on corresponding oedometer swell tests), as outlined in Table 2.

$$\mathrm{FSR} = \frac{V_{\mathrm{D}}}{V_{\mathrm{K}}} \tag{1}$$

Referring to Eq. 1; the FSR parameter is defined as the ratio of the ESV of a 10 g oven-dried soil sample, passing the 425-μm sieve, when placed in distilled water (i.e., V_{D}) (the *polar* liquid where active clay minerals expand) to that of an identical dry sample when placed in kerosene or carbon tetrachloride (i.e., V_{K}) (the *non-polar* liquid where active clay minerals do not expand). Accordingly, unlike the LL-state water content, the FSR parameter can be viewed as a ‘direct’ inferential measure of soil expansivity. Moreover, the FSR can be considered an indirect, but quantitative, measure of clay mineralogy in fine-grained soils. In their study, Prakash and Sridharan (2004) proposed and validated (based on XRD analysis results) a simple classification framework capable of linking the FSR value to the type of dominant clay mineral present in fine-grained soils (see Table 2).

Table 2 Classification procedures for fine-grained soils based on the FSR parameter (after Sridharan and Prakash (2000a) and Prakash and Sridharan (2004))

FSR = V_D/V_K	Probable swelling potential (%) [A]	Expansivity level	Dominant clay mineral
≤ 1.0	≤ 1.0	Negligible	Kaolinite (K)
1.0–1.5	1–5	Low	Kaolinite + Montmorillonite (K, M)
1.5–2.0	5–15	Moderate	Montmorillonite (M)
2.0–4.0	15–25	High	Montmorillonite (M)
> 4	> 25	Very high	Montmorillonite (M)

[A] % vertical swelling strain of an air-dried standard Proctor-compacted sample under an applied surcharge of 7 kPa

It should be mentioned that the various pros and cons of the FSR parameter were discussed in the papers by Prakash and Sridharan (2021) and Moreno-Maroto et al. (2021). In terms of practicality, the FSR test can be executed within 24 h (if not shorter) for most soils and without the need for any major testing equipment. For some highly expansive soils that may require more time to settle, a 0.025% sodium chloride (NaCl) solution can be employed in lieu of distilled water, which significantly reduces the settling time without altering the deduced V_D and hence FSR values (Sridharan et al. 1990). Note that unlike the LL, the FSR parameter is able to correctly assess the expansivity of both montmorillonitic and kaolinitic soils treated with flocculant agents (e.g., Soltani et al. 2019; Torfi et al. 2021; Soltani et al. 2022).

Herein, an attempt is made to examine the level of agreement between the soil expansivity rankings deduced by the LL (Dakshanamurthy and Raman 1973) and FSR (Sridharan and Prakash 2000a; Prakash and Sridharan 2004) parameters. For this purpose, a large and diverse database of LL:FSR measurements pertaining to 122 different fine-grained soil materials, as summarized in Table 3, was gathered from eleven sources (i.e., Prakash and Sridharan 2004; Rao et al. 2004; Prakash and Sridharan 2010; Horpibulsuk et al. 2011; Rao et al. 2011; Estabragh et al. 2013; Phanikumar and Nagaraju 2018; Elsaidy et al. 2019; Elsaidy 2021; Torfi et al. 2021; Prakash and Sridharan 2022). It should be mentioned that in compiling this database, only data sources having LL magnitudes obtained based on the percussion-cup method were considered. This was to eliminate systematic variations in the LL parameter arising from differences between the mechanics of the percussion-cup and fall-cone devices employed for LL determination (O'Kelly et al. 2018; O'Kelly 2021; O'Kelly and Soltani 2022). For the compiled database, Figs. 2a and 2b illustrate the variations of FSR against the LL and PI respectively. As is evident from these figures, the FSR is poorly correlated with the LL and PI parameters (especially the LL); a similar observation was reported in Elsaidy et al. (2020). For instance, 41 of the database soils had LL values in the range of 50–70% (i.e., signifying High expansivity according to the Dakshanamurthy and Raman (1973) classification), with 4, 20, 7, 7 and 3 of these soils plotting in the regions of Negligible, Low, Moderate, High and Very High expansivity, respectively, according to the FSR classification system after Sridharan and Prakash (2000a) and Prakash and Sridharan (2004). Moreover, no visually detectable boundaries could be identified to establish new LL or PI classification domains based on

Table 3 Summary of the compiled database of 122 LL:PL:FSR test results

Source	N_S	LL (%) [A]	Standard designation	PL (%) [B]	Standard designation	FSR
Prakash and Sridharan (2004)	69	25.0–495.0	BS 1377–2 (1990)	6.7–75.0	BS 1377–2 (1990)	0.5–13.4
Rao et al. (2004)	10	60.5–148.0	ASTM D4318 (2000)	17.0–26.0	ASTM D4318 (2000)	2.1–3.5
Prakash and Sridharan (2010)	14	31.2–88.7	IS 2720–5 (1985)	15.5–37.4	IS 2720–5 (1985)	0.4–2.0
Horpibulsuk et al. (2011)	3	46.0–211.0	ASTM D4318 [C]	24.0–36.0	ASTM D4318 [C]	0.7–12.0
Rao et al. (2011)	14	47.0–69.0	ASTM D4318 (1993)	18.0–28.0	ASTM D4318 (1993)	1.1–5.0
Estabragh et al. (2013)	1	88.0	ASTM D4318 [C]	31.0	ASTM D4318 [C]	2.37
Phanikumar and Nagaraju (2018)	1	83.0	ASTM D4318 (2000)	29.0	ASTM D4318 (2000)	2.45
Elsaidy et al. (2019)	4	50.0–128.0	NZS 4402.2.2 (1986)	25.0–72.0	NZS 4402.2.2 (1986)	1.1–1.4
Elsaidy (2021)	1	90.5	NZS 4402.2.2 (1986)	41.0	NZS 4402.2.2 (1986)	1.26
Torfi et al. (2021)	1	69.0	ASTM D4318 [C]	28.0	ASTM D4318 [C]	1.44
Prakash and Sridharan (2022)	4	52.4–402.0	BS 1377–2 (1990)	31.6–50.1	BS 1377–2 (1990)	0.6–20.7

N_S number of soil materials investigated

[A] Percussion-cup liquid limit

[B] Thread-rolling plastic limit

[C] Issue date

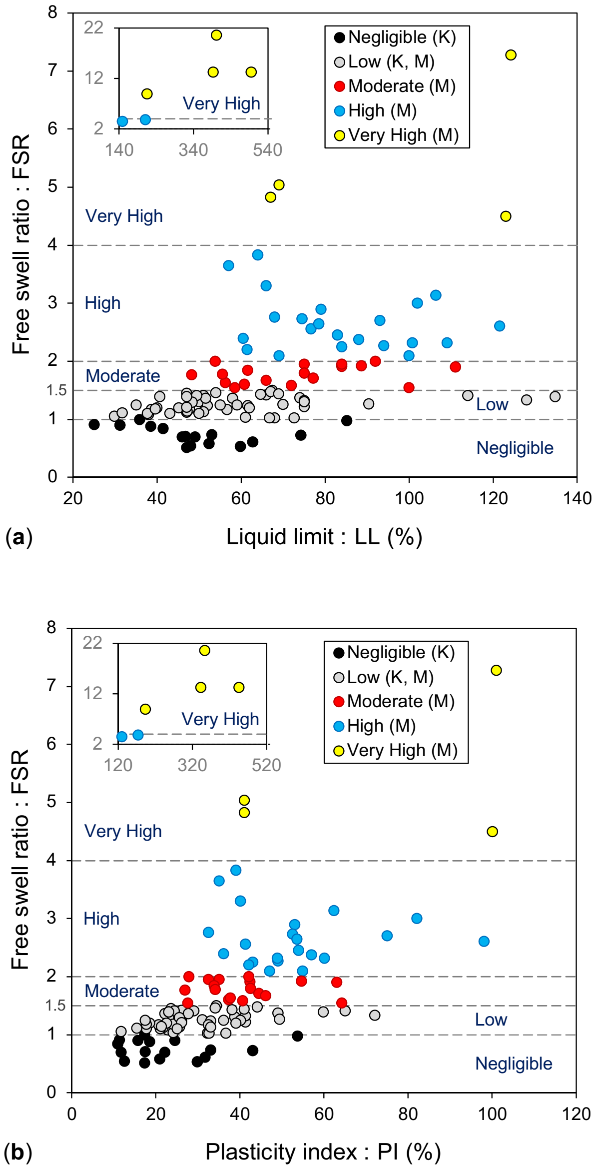

Fig. 2 Variations of FSR against (**a**) LL and (**b**) PI for the compiled database of 122 LL:PL:FSR test results

the distribution of the FSR data. Considering the FSR as a 'direct' inferential measure of soil expansivity, these observations further support the Discussers' viewpoint that soil plasticity, without proper consideration of soil mineralogical activity, is not a reliable/consistent basis to assess swelling potential when considering a variety of fine-grained soils.

To compare the soil expansivity rankings deduced by the LL and FSR parameters, the upper-two expansivity classes of the Dakshanamurthy and Raman (1973) classification approach, namely Very High and Extra High (see Table 1), were merged, thereby

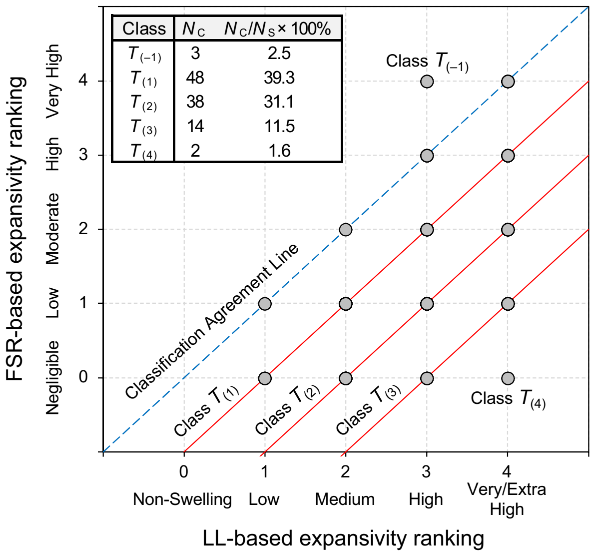

Fig. 3 Level of agreement between the soil expansivity rankings deduced by the FSR (Sridharan and Prakash 2000a; Prakash and Sridharan 2004) and LL (Dakshanamurthy and Raman 1973) parameters

producing a revised five-domain classification scheme comparable to the FSR ranking system (see Table 2). Following the revised LL-based classification framework, a total of $N_C = 105$ cases (out of $N_S = 122$ examined) were found to produce dissimilar soil expansivity rankings when compared to those deduced by the FSR parameter. This implies an overall agreement level of $(1 - N_C/N_S) \times 100 = 13.9\%$. Furthermore, out of the 105 dissimilar rankings, 102 cases plot below the classification agreement line, as demonstrated in Fig. 3, indicating that 83.6% of the LL-based rankings overestimate those deduced by the FSR parameter. The percentage of cases overestimated by one, two, three, and four expansivity-level classes (e.g., Extra/Very High instead of High, Moderate, Low, and Negligible, respectively) were found to be $T_{(1)} = 39.3\%$, $T_{(2)} = 31.1\%$, $T_{(3)} = 11.5\%$, and $T_{(4)} = 1.6\%$ (see the table provided in Fig. 3). In view of these results, one can postulate that the LL parameter invariably produces overly conservative soil expansivity rankings.

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Data Availability All data generated or analyzed during this study are included in this published article.

Declarations

Conflict of Interest The authors declare no competing interests.

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