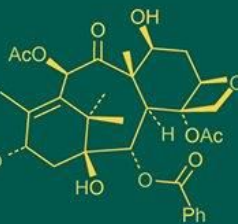
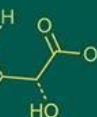
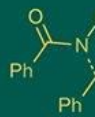


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Evaluation of particle size distribution models across various soil textures in Nashik district

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Abstract

Accurate modeling of particle size distribution (PSD) is essential for understanding soil hydraulic properties and optimizing land management practices. This study evaluates the applicability of four PSD models—Fredlund *et al.* (2000), Skaggs *et al.* (2001), Fooladmand *et al.* (2004), and the Gray model (1,1) (Wu *et al.*, 2009)—to describe PSD in diverse soil textures of Nashik district, Maharashtra, India. A total of 34 soil samples were collected across different soil textures, including clay, clay loam, sandy clay loam, and sandy loam. The PSD data were analyzed using conventional methods and fitted to the selected models. The performance of these models was assessed using statistical indicators such as root mean square error (RMSE), coefficient of determination (R^2), adjusted R^2 (Adj R^2), Akaike's information criterion (AIC), mean absolute error (MAE), mean absolute percentage error (MAPE), and chi-square (χ^2). The results indicated that the Fredlund model consistently outperformed the others, particularly for clay, sandy clay loam, and sandy loam soils, with the lowest RMSE, MAPE, and AIC values. The Gray model (1,1) showed the best performance for clay loam and sandy clay loam soils. The Skaggs and Fooladmand models demonstrated lower accuracy across the soil types tested. These findings highlight the superiority of the Fredlund model for accurate PSD predictions in the region, suggesting its potential for improving soil management strategies in diverse agro-ecological zones.

Keywords: Particle size distribution (PSD), Skaggs, Fooladmand, Fredlund, gray (1,1)

Introduction

Soil particle function serves as the foundation for understanding various soil processes, influencing hydrological, geological, physical, chemical, and biological behaviors [5]. The particle-size distribution (PSD) of soil is one of its fundamental and static physical properties, playing a critical role in determining soil hydraulic characteristics. The PSD of a given soil is shaped by complex interactions of hydrological, geological, geophysical, chemical, and biological processes. Selecting the most appropriate model to represent PSD is crucial for accurately estimating soil hydraulic properties and understanding soil behavior under different condition [1].

Nashik district, located in Maharashtra, India, is characterized by diverse soil textures due to its varied topography and climatic conditions. The major soil textures in Nashik include clayey soils, loamy soils, and sandy soils, which are distributed across its agricultural lands, vineyards, and hilly terrains. Clayey soils dominate the black soil regions of Nashik, offering high water retention but limited permeability. Loamy soils, found in the alluvial plains, provide balanced fertility and drainage, making them ideal for crops like onions and grapes. Sandy soils, present in the riverine areas, have high drainage capacity but low nutrient-holding ability. This variability in soil textures necessitates precise modeling of PSD to better understand and manage the soil's hydraulic properties across the district.

The objective of this study was to evaluate the applicability of four PSD models—Fredlund *et al.* (2000) [5], Skaggs *et al.* (2001) [9], Fooladmand *et al.* (2004) [4], and the Gray model (1,1) (Wu *et al.*, 2009) [11]—to describe the particle-size distribution data in different soil textures of Nashik district, Maharashtra, India. To assess the performance of these models, statistical indicators such as root mean square error (RMSE), coefficient of determination (R^2), adjusted coefficient of determination (Adj- R^2), Akaike's information criterion (AIC), mean absolute error (MAE), mean absolute percentage error (MAPE), and chi-square tests were used [3, 7, 10].

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Materials and Methods

The study was conducted in the geographical region of Nashik district, Maharashtra, India, located between 19.5° N to 20.5° N latitude and 73.5° E to 74.5° E longitude. Nashik is situated in the northwestern part of Maharashtra, bordered by Dhule to the north, Jalgaon to the northeast, Aurangabad to the east, Ahmednagar to the south, and Thane and Palghar to the southwest, with Gujarat forming its western boundary. A total of thirty four surface soil samples, each weighing at least 2.0 kg, were collected to analyze their physical properties, such as soil texture, and chemical properties, including pH, electrical conductivity, organic carbon, and calcium carbonate content [6, 8]. The soil samples were air-dried and sieved through a 2 mm mesh before laboratory analysis.

To determine the particle-size distribution (PSD), conventional methods were employed following a pretreatment with hydrogen peroxide (H₂O₂) to remove

organic matter. The hydrometer method was used to measure fine-sized soil fractions, while sieving was used for coarse-sized fractions. A series of sieves with pore radii of 1, 0.5, 0.25, 0.2, 0.105, and 0.053 mm were utilized for this purpose. Additionally, ten data points were recorded during the hydrometer analysis by measuring the density of the soil suspension at specific time intervals: 1, 2, 4, 8, 15, 60, 120, 240, 360, and 1440 minutes. This process resulted in a total of 16 particle-size limits for each soil sample [6].

The measured PSD data were then fitted into four different mathematical models to derive continuous PSD curves. The models used in this study included the Skaggs model (Skaggs *et al.*, 2001), the Fooladmand model (Fooladmand and Sepaskhah, 2006), the Gray model GM (1,1) (Wu *et al.*, 2009), and the unimodal Fredlund equation (Fredlund *et al.*, 2000). Soil texture fractions were classified according to the United States Department of Agriculture (USDA) classification scheme [2].

Table 1: Particle size distribution models tested in this study

Name	Model	Parameter
Skaggs	$P(r) = \frac{1}{1 + (C_1^{-1} - 1) \exp \{-\mu(R - 1)^c\}}$	μ , c are coefficients
Fooladmand	$P(r) = \frac{1}{1 + (C_1^{-1} - 1) \exp \{-\mu(R - 1)^c\}}$	μ , c are coefficients
Gray	$\widehat{P}^{(0)}(r_{k+1}) = \left[P^{(0)}(r_1) - \frac{b}{a} \right] [1 - \exp(a)] \exp(-ak)$	a , b are coefficients
Fredlund (F _{4p})	$P_p(d) = \frac{1}{\left\{ \ln \left[\exp(1) + \left(\frac{a_{gr}}{b} \right)^{n_{gr}} \right] \right\}^{m_{gr}}} \left\{ 1 - \frac{\left[\ln \left(1 + \frac{d_{rgr}}{d} \right) \right]^7}{\left[\ln \left(1 + \frac{d_{rgr}}{d_m} \right) \right]^7} \right\}$	a_{gr} , n_{gr} , m_{gr} and d_{rgr} are parameter showing inflection point, steepest slope, shape of the curve and amount of fines in a soil respectively.

Fitting procedure and Evaluation criteria

An iterative nonlinear optimization procedure was applied to fit the parametric functions to the observed cumulative PSD data. The SAS routine operator within Microsoft Excel software was used for this purpose. The adequacy of the fitted models was assessed using various statistical criteria, including root mean square error (RMSE), coefficient of determination (R²), adjusted coefficient of determination (Adj-R²), and Akaike's information criterion (AIC). These criteria ensured that the models were robust and accurately represented the observed PSD data.

Results and Discussion

The particle size distribution of soil samples from Nashik district showed sand (7.8–65.3%, mean 36.6%), silt (8.5–58.2%, mean 33.4%), and clay (6.3–56.6%, mean 20.6%) with diverse textures, predominantly clay and clay loam [6].

The pH of soils in Nashik district ranged from 6.40 to 8.23 (mean 7.32), with 17.65% acidic, 67.65% neutral, and 14.71% alkaline soils. Electrical conductivity (0.05–0.58 dS m⁻¹, mean 0.32 dS m⁻¹), organic carbon (0.20–1.35%, mean 0.78%), and calcium carbonate content (0.13–11.96%, mean 6.05%) also varied across the district [2].

Comparison of Evaluation Criteria for PSD Models Across Soil Textures in Nashik District

The performance of four particle size distribution (PSD) models—Skaggs, Fooladmand, Fredlund, and Gray (1,1)—was evaluated for clay, clay loam, sandy clay loam, and sandy loam soils in Nashik district, based on various statistical evaluation criteria. The models were assessed using root mean square error (RMSE), coefficient of

determination (R²), adjusted R² (Adj R²), Akaike's Information Criterion (AIC), mean absolute error (MAE), mean absolute percentage error (MAPE), and chi-square (χ²) [9, 10].

Clay-Textured Soils

For clay-textured soils, the Fredlund model exhibited the best fit with the lowest RMSE (0.026), highest R² (0.987), Adj R² (0.983), and lowest MAPE (0.04%), making it the most accurate model. The Gray (1,1) model performed well, with a relatively low AIC (-115.33) and good fit indicators, but it was slightly outperformed by Fredlund. In contrast, the Skaggs and Fooladmand models showed higher RMSE and MAPE, and their AIC values were not as favorable, indicating a poorer fit for clay-textured soils.

Clay Loam-Textured Soils

For clay loam soils, the Gray (1,1) model demonstrated the best performance with the lowest RMSE (0.019), R² (0.992), and Adj R² (0.991), as well as the lowest chi-square value (0.009). The Fredlund model followed closely, with an excellent fit (RMSE = 0.026, MAE = 0.002), and showed the lowest MAPE (0.04%). The Skaggs and Fooladmand models showed higher AIC values, and their MAPE and chi-square values were comparatively higher, indicating they were less suitable for clay loam soils.

Sandy Clay Loam-Textured Soils

For sandy clay loam soils, the Gray (1,1) model again emerged as the best model, with the lowest RMSE (0.021), highest R² (0.993), and lowest chi-square (0.013). The Fredlund model also performed very well, with an RMSE of

0.025 and an exceptionally low MAPE (0.3%). The Skaggs model had slightly higher AIC and MAPE values, but it still showed good fitting characteristics ($R^2 = 0.981$). The Fooladmand model performed the worst, with higher RMSE (0.026), MAPE (5.23%), and chi-square (0.035).

Sandy Loam-Textured Soils

For sandy loam soils, the Fredlund model showed the best fit with the lowest RMSE (0.028), MAE (0.001), and MAPE (0.5%), as well as a relatively low AIC (-111.72) and chi-square (0.016). The Gray (1,1) model also performed well, with similar values but a higher chi-square (0.035) and slightly higher MAPE (3%). The Skaggs model performed well, with the lowest RMSE (0.016) but a higher MAPE (6.15%) and chi-square (0.028). The Fooladmand model

showed the poorest performance with higher AIC (-108.87) and MAPE (7.06%).

Overall Comparison and Ranking

Across all soil types, the Fredlund model consistently outperformed the other models, particularly in terms of RMSE, MAE, MAPE, and AIC. It showed the best fit for clay, sandy clay loam, and sandy loam soils. The Gray (1,1) model performed very well for clay loam and sandy clay loam soils, exhibiting the highest R^2 and Adj R^2 values. The Skaggs model was more suitable for sandy loam and sandy clay loam soils but showed lower performance for clay and clay loam soils. The Fooladmand model showed the poorest performance across most soils, with higher MAPE and AIC values.

Table 2: Comparison of Evaluation Criteria for PSD Models on Clay-Textured Soils in Nashik District

Models	Evaluation criteria							Rank sum
	RMSE	R^2	Adj R^2	AIC	MAE	MAPE (%)	Chi-Sq	
Skaggs model	0.031	0.964	0.961	-91.25	0.012	2.00	0.007	24
Fooladmand model	0.032	0.968	0.966	-110.60	0.014	2.08	0.006	21
Fredlund model	0.026	0.987	0.983	-114.45	0.002	0.04	0.012	11
Gray (1,1) model	0.028	0.978	0.977	-115.33	0.001	0.6	0.018	14

Table 3: Comparison of Evaluation Criteria for PSD Models on Clay Loam-Textured Soils in Nashik District

Models	Evaluation criteria							Rank sum
	RMSE	R^2	Adj R^2	AIC	MAE	MAPE (%)	Chi-Sq	
Skaggs model	0.032	0.958	0.954	-90.16	0.015	3.11	0.012	24
Fooladmand model	0.034	0.975	0.973	-102.57	0.021	3.54	0.021	25
Fredlund model	0.026	0.987	0.984	-114.44	0.002	0.04	0.012	13
Gray (1,1) model	0.019	0.992	0.991	-128.24	0.0001	0.2	0.009	8

Table 4: Comparison of Evaluation Criteria for PSD Models on Sandy Clay Loam-Textured Soils in Nashik District

Models	Evaluation criteria							Rank sum
	RMSE	R^2	Adj R^2	AIC	MAE	MAPE (%)	Chi-Sq	
Skaggs model	0.022	0.981	0.980	-100.58	0.016	4.71	0.021	23
Fooladmand model	0.026	0.989	0.988	-117.84	0.024	5.23	0.035	24
Fredlund model	0.025	0.992	0.990	-115.81	0.002	0.3	0.014	15
Gray (1,1) model	0.021	0.993	0.993	-126.06	0.001	1.1	0.013	8

Table 5: Comparison of Evaluation Criteria for PSD Models on Sandy Loam-Textured Soils in Nashik District

Models	Evaluation criteria							Rank sum
	RMSE	R^2	Adj R^2	AIC	MAE	MAPE (%)	Chi-Sq	
Skaggs model	0.016	0.991	0.990	-110.34	0.017	6.15	0.028	15
Fooladmand model	0.028	0.989	0.989	-108.87	0.029	7.06	0.061	25
Fredlund model	0.028	0.991	0.989	-111.72	0.001	0.5	0.016	11
Gray (1,1) model	0.028	0.989	0.989	-115.79	0.003	3	0.035	17

Conclusion

The Fredlund model is the most accurate and reliable for modeling PSD across various soil textures in Nashik district, followed closely by the Gray (1,1) model. Both models exhibit excellent fit criteria, but Fredlund stands out for its low MAPE and chi-square values. These findings suggest that Fredlund is the best choice for accurate PSD predictions in the region, especially for clay, sandy clay loam, and sandy loam soils. The Skaggs and Fooladmand models are less suitable due to their higher error margins and poorer overall performance.

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