Abstract: Methods to predict soil hydraulic properties frequently require information on the particle size distribution (PSD). The objectives of this study were to investigate various protocols for rapidly measuring PSD using the laser diffraction technique, compare the obtained PSD with those determined using the traditional hydrometer-and-sieves method (HSM), and assess the accuracy of soil hydraulic properties predicted from the measured PSD. Ten soil samples encompassing a wide range of textures were measured using laser diffraction methods (LDM1, LDM2, and LDM3). In LDM1, the soil sample was thoroughly mixed before analysis. In LDM2, the sand fraction was sieved out and analyzed separately from the silt-clay fraction. LDM3 was similar to LDM2 except that the silt-clay fraction was diluted so that a large sample volume could be used while maintaining an acceptable level of obscuration. LDM2 and LDM3 improved the agreement between the PSD with the HSM in comparison to LDM1, without the need of altering the Mie theory parameters or the use of scaling factors. Moreover, a reasonable prediction of measured saturated hydraulic conductivity and water retention curve was achieved when using the PSD from LDM2 and LDM3, in conjunction with bulk density information.

Key words: Particle size distribution, laser diffraction, soil hydraulic properties.

A nalytical and numerical models (Philip, 1969; van Genuchten and Wierenga, 1977; Šimůnek et al., 1999; Bradford et al., 2003) that simulate the transport and fate of water, solutes, organic compounds, and microorganisms in the vadose zone require as input information about soil hydraulic properties. Direct measurement of these properties (Klute, 1986; Klute and Dirksen, 1986) is laborious and expensive, especially when studying environmental processes at the farm, basin, or regional scales where numerous samples are needed (Hopmans et al., 2002; Vereeken et al., 2007).

Measurements of soil bulk density (ρb), particle size distribution (PSD), and soil texture (Blake and Hartage, 1986; Gee and Or, 2002) is usually smaller and less time consuming than direct measurements of water flow and retention. Methodologies have therefore been developed to estimate soil hydraulic properties from this information (Arya and Paris, 1981; Vereeken et al., 1990; Rajkai and Varalayay, 1992). In particular, pedotransfer functions based on large soil databases have been developed to predict soil hydraulic properties from more easily obtained soil physical data (Tietje and Tapkenhenrichs, 1993; Schaap and Leij, 1998; Schaap et al., 2001). Most of the clay, silt, and sand size fraction contained in those databases were obtained using sieving in combination with either the hydrometer or pipette method (e.g., Schaap et al., 2001).

The light scattering method has been used during the last decade to measure the PSD and the surface area of soils (Buurman et al., 1997; Eshel et al., 2004; Sperazza et al., 2004, Arriaga et al., 2006). Modern light scattering methods use polarization intensity differential scattering technology to study patterns of light (tungsten-halogen) and laser (780 nm) scattering in soil particle suspensions, which can be described mathematically by the Mie theory (Eshel et al., 2004; Arriaga et al., 2006; Berger et al., 2008). The advantages and disadvantages of these methods are well documented (Beuselinck et al., 1998; Eshel et al., 2004; Arriaga et al., 2006; Berger et al., 2008). Potential advantages of laser diffraction methods (LDM) include simplicity, small sample size, and rapid analysis and information on the full range of the PSD. Potential disadvantages include the need to make assumptions about particle geometry (sphere) and refractive indexes, overestimation of certain size categories because of competition between two light sources (Berger et al., 2008), a lack of LDM-determined PSD databases that can be used for comparison purposes, and a required initial expensive investment in equipment (Arriaga et al., 2006). To date, few studies have compared PSD information from LDM with PSD information obtained with traditional hydrometer-and-sieves method (HSM) (Konert and Vandenberghe, 1997; Beuselinck et al., 1998; Eshel et al., 2004; Berger et al., 2008).

Our research objectives were: (i) to investigate the agreement between PSD measured with laser diffraction and hydrometer methods, (ii) to predict hydraulic properties from PSD and bulk density measurements, and (iii) to evaluate the accuracy of the hydraulic properties predicted from laser diffraction-based PSD.

MATERIALS AND METHODS

We used eight pairs of undisturbed soil cores sampled from heterogeneous soil profiles in a field located near San Jacinto, CA (33°50'32"N, 117°00'30"W), and two disturbed soil samples from a field located west of Firebaugh, CA (36°50'44"N, 120°33'17"W) (Table 1). The undisturbed cores were obtained by driving brass cylinders measuring 6 cm tall and 5.4 cm in diameter into an exposed soil profile at variable depths. The two disturbed soil samples were air-dried, ground, passed through a 2-mm sieve, and packed in brass cylinders to their original bulk density (1.25 g·cm⁻³). Once core from each undisturbed pair was used to determine the ηb (Blake and Hartage, 1986). The eight remaining undisturbed cores and the two repacked cores were then used for measurement of the primary drainage branch of the water retention curve (WRC) and the saturated hydraulic conductivity (Ks), as later described. The samples were then used for PSD analysis by the HSM and LDM, also later described.

Particle Size Distribution

Sample preparation for both HSM and LDM was similar, except that 40 g of soil was used for the HSM and 4 g for LDM.
Preparation protocols of soil sample before the analysis with the laser method.

**FIG. 1.** Particle size distribution of sandy loam and clay loam soil, as generated by the LDM. LDM1, LDM2, and LDM3 are three preparation protocols of soil sample before the analysis with the laser method.
plate apparatus (Soilmoisture Equip. Corp, Santa Barbara, CA) according to the approach outlined by Richards (1965). The measured WRC was parameterized for subsequent analysis using the model of van Genuchten (1980).

The Arya-Paris model (Arya and Paris, 1981), which assumes the pore size distribution curve mimics the soil WRC, was used to predict the relationship among PSD, ρ₀, and the WRC. The soil coefficient of the Arya-Paris model was taken to be 1.285 for sand, 1.459 for sandy loam, 1.375 for loam, and 1.15 for silt-loam (Arya and Paris, 1981). Because of the discrete form of the PSD data, the predicted WRC from the Arya and Paris model were also discrete. Parameters from the van Genuchten (1980) model were fitted to these retention data sets so that the agreement between measured and predicted data could be better quantified.

Additional predictions of soil hydraulic properties were obtained using the Rosetta pedotransfer function model, which can predict soil hydraulic properties (Kₛ, and the WRC model parameters) from ρ₀ and the percentages of sand, silt, and clay (Schaap et al., 2001).

Statistical analysis was performed on the measured PSD data to assess the agreement of LDM1, LDM2, and LDM3 methods with the conventional HSM method and to quantify the agreement of observed and predicted hydraulic properties (Kₛ, Aₛ, and WRC). Statistical measures of goodness of fit

FIG. 2. Particle size distributions for the 10 soils by the HSM and LDM. LDM1, LDM2, and LDM3 are three preparation protocols of soil sample before the analysis with the laser method.
RESULTS AND DISCUSSION

Particle Size Distribution

Bulk density, texture, and sand, silt, and clay fractions obtained with the HSM are presented in Table 1. The soils encompass a wide range of texture classes, from sand to silty clay. The soil separate percentages ranged from 15% to 93% for sand, 3% to 60% for silt, and 2.5% to 44% for clay. Bulk density ranged from 1.19 to 1.57 g cm⁻³.

Table 1 presents example particle size distributions measured with the LDM. Figure 1 shows the cumulative particle frequency (F) on a volume basis plotted versus particle diameter as measured by the laser method for sandy loam (SaL-1) and clay loam (CL) soils. The dashed and dash-dotted lines are two repetitions of LDM1, in which all the size fractions were simultaneously analyzed. The solid and dotted lines are data from two repetitions of LDM2 or LDM3 (LDM2/3), where the sand fraction was separately analyzed from the silt-clay fraction. The agreement between the dotted and solid lines for both soils demonstrates the good repeatability of LDM2 or LDM3 (P = 0.88 and P = 0.94 for SaL-1 and CL, respectively). In contrast, duplicate samples from LDM1 showed inconsistencies between the repetitions (P = 0.36 and P = 0.00 for SA-L-1 and CL, respectively). One potential explanation for this inaccuracy is caused by competition of the various size categories for the two light sources. This competition is especially likely to influence measurements of the size class having the smallest fractions; for example, clay in the sandy loam and the sand in the clay loam (Table 1).

The cumulative particle frequency (F) by volume versus particle diameter measured by the HSM (triangles), LDM1 (dotted line), and LDM2 (solid line) for all 10 soils is presented in Fig. 2. Also shown are curves generated for the clay loam and silty clay soils using LDM3 (dashed lines), where the silt-clay fraction was diluted with NaHMP (1:10 ratio) before analysis. Overall, good agreement was found between PSD obtained with HSM and LDM2 or LDM3 (LDM2/3) over all textures (r² and RMSE in Table 2). The HSM tended to indicate a higher percentage of clay-sized particles than did LDM2/3, a finding that is possibly explained by the tendency of HSM to overestimate the clay fraction caused by the assumptions of a single spherical shape (Loveland and Whalley, 1991) and a constant particle density. The agreement between the HSM- and LDM1-measured PSD deteriorated as the samples transitioned from coarse- to fine-textured soils (r² and RMSE in Table 2). In the clay loam and silty clay soils, the PSD obtained using LDM3 achieved a superior match to HSM than LDM2 (Fig. 2).

### Table 2. Statistical Comparison of PSD Obtained With the HSM Versus Distributions Obtained With the LDM Using Different Preparation Protocols LDM1 and LDM2/3

<table>
<thead>
<tr>
<th>Soil ID</th>
<th>r²</th>
<th>RMSE</th>
<th>p*</th>
<th>r²</th>
<th>RMSE</th>
<th>p*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sa</td>
<td>1.00</td>
<td>0.02</td>
<td>0.93</td>
<td>0.99</td>
<td>0.02</td>
<td>0.73</td>
</tr>
<tr>
<td>LSa</td>
<td>0.97</td>
<td>0.02</td>
<td>0.48</td>
<td>0.96</td>
<td>0.03</td>
<td>0.45</td>
</tr>
<tr>
<td>SaL-1</td>
<td>0.97</td>
<td>0.05</td>
<td>0.79</td>
<td>0.99</td>
<td>0.01</td>
<td>0.99</td>
</tr>
<tr>
<td>SaL-2</td>
<td>0.94</td>
<td>0.08</td>
<td>0.58</td>
<td>0.99</td>
<td>0.01</td>
<td>0.83</td>
</tr>
<tr>
<td>L-1</td>
<td>0.99</td>
<td>0.03</td>
<td>0.69</td>
<td>0.99</td>
<td>0.01</td>
<td>0.93</td>
</tr>
<tr>
<td>L-2</td>
<td>0.97</td>
<td>0.04</td>
<td>0.69</td>
<td>0.99</td>
<td>0.01</td>
<td>0.93</td>
</tr>
<tr>
<td>SiL-1</td>
<td>0.82</td>
<td>0.14</td>
<td>0.10</td>
<td>0.97</td>
<td>0.02</td>
<td>0.68</td>
</tr>
<tr>
<td>SiL-2</td>
<td>0.87</td>
<td>0.12</td>
<td>0.42</td>
<td>0.99</td>
<td>0.03</td>
<td>0.17</td>
</tr>
<tr>
<td>CL</td>
<td>0.64</td>
<td>0.07</td>
<td>0.08</td>
<td>0.95</td>
<td>0.03</td>
<td>0.31</td>
</tr>
<tr>
<td>SiC</td>
<td>0.80</td>
<td>0.03</td>
<td>0.04</td>
<td>0.96</td>
<td>0.02</td>
<td>0.83</td>
</tr>
<tr>
<td>Overall</td>
<td>0.86</td>
<td>0.06</td>
<td>N/A</td>
<td>0.97</td>
<td>0.02</td>
<td>N/A</td>
</tr>
</tbody>
</table>

*p* test conducted on the PSD (unequal variances) written in terms of the probability density function.

P: probability associated with the Student t test that the sample means are equal; r²: coefficient of linear correlation.

### Table 3. Measured and Predicted Ks for the 10 Soils

<table>
<thead>
<tr>
<th>Soil ID</th>
<th>Measured</th>
<th>Rosetta</th>
<th>HSM</th>
<th>LDM2/3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sa</td>
<td>32.34</td>
<td>31.04</td>
<td>63.22</td>
<td>20.50</td>
</tr>
<tr>
<td>LSa</td>
<td>1.73</td>
<td>2.75</td>
<td>4.63</td>
<td>1.96</td>
</tr>
<tr>
<td>SaL-1</td>
<td>2.34</td>
<td>1.78</td>
<td>5.33</td>
<td>1.62</td>
</tr>
<tr>
<td>SaL-2</td>
<td>1.28</td>
<td>2.25</td>
<td>8.65</td>
<td>2.00</td>
</tr>
<tr>
<td>L-1</td>
<td>0.50</td>
<td>2.23</td>
<td>7.43</td>
<td>1.97</td>
</tr>
<tr>
<td>L-2</td>
<td>0.61</td>
<td>1.75</td>
<td>8.70</td>
<td>1.72</td>
</tr>
<tr>
<td>SiL-1</td>
<td>2.07</td>
<td>3.50</td>
<td>14.01</td>
<td>2.61</td>
</tr>
<tr>
<td>SiL-2</td>
<td>0.51</td>
<td>1.23</td>
<td>3.35</td>
<td>0.89</td>
</tr>
<tr>
<td>CL</td>
<td>0.30</td>
<td>0.98</td>
<td>0.57</td>
<td>0.16</td>
</tr>
<tr>
<td>SiC</td>
<td>0.06</td>
<td>0.92</td>
<td>0.73</td>
<td>0.08</td>
</tr>
<tr>
<td>Overall</td>
<td>1.00</td>
<td>0.82</td>
<td>0.78</td>
<td>0.85</td>
</tr>
<tr>
<td>Overall RMSE</td>
<td>0.00</td>
<td>2.50</td>
<td>36.99</td>
<td>1.18</td>
</tr>
</tbody>
</table>

The HSM and laser (LDM2 and LDM3) predictions were based on the geometric surface area calculation, whereas the Rosetta prediction was obtained by the pedotransfer function. The overall coefficient of linear correlation (r²) and RMSE are also provided.

### Table 4. Geometric Surface Area Per Particle Volume (Aₐ) for the 10 Soils

<table>
<thead>
<tr>
<th>Soil ID</th>
<th>Kozeny-Carman</th>
<th>HSM</th>
<th>LDM2/3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sa</td>
<td>815</td>
<td>584</td>
<td>1026</td>
</tr>
<tr>
<td>LSa</td>
<td>2813</td>
<td>1724</td>
<td>2646</td>
</tr>
<tr>
<td>SaL-1</td>
<td>3700</td>
<td>2455</td>
<td>4454</td>
</tr>
<tr>
<td>SaL-2</td>
<td>4992</td>
<td>1926</td>
<td>4009</td>
</tr>
<tr>
<td>L-1</td>
<td>9659</td>
<td>2509</td>
<td>4867</td>
</tr>
<tr>
<td>L-2</td>
<td>7079</td>
<td>1885</td>
<td>4239</td>
</tr>
<tr>
<td>SiL-1</td>
<td>5292</td>
<td>2044</td>
<td>4734</td>
</tr>
<tr>
<td>SiL-2</td>
<td>8859</td>
<td>3466</td>
<td>6711</td>
</tr>
<tr>
<td>CL</td>
<td>12,486</td>
<td>8042</td>
<td>17,053</td>
</tr>
<tr>
<td>SiC</td>
<td>27,781</td>
<td>9071</td>
<td>23,210</td>
</tr>
<tr>
<td>Overall</td>
<td>1.00</td>
<td>0.79</td>
<td>0.87</td>
</tr>
<tr>
<td>Overall RMSE</td>
<td>0.00</td>
<td>3135</td>
<td>693</td>
</tr>
</tbody>
</table>

The first column of Aₐ values were calculated from the measured values of Ks (Table 3) using the Kozeny-Carman equation, whereas the second and third columns were determined from PSD information obtained with the HSM and laser (LDM2 and LDM3) methods, respectively. The overall coefficient of linear correlation (r²) and RMSE are also provided.
might be caused by the high optical density associated with high silt-clay fractions and the fact that less than 0.1 mL of sample was needed to obtain the correct level of obscuration when using LDM2. This diminutive volume may not be a representative sample and can induce variations. The dilution (LDM3) allows analyzing a larger volume of silt-clay suspension while maintaining an acceptable level of obscuration.

Soil Hydraulic Properties

This section compares measured and predicted soil hydraulic and physical properties (\(K_e\), \(A_e\), and WRC) for the 10 soils. Predictions were obtained using PSD information from HSM and LDM2/3 methods and/or the Rosetta pedotransfer function.

Information on the PSD from LDM1 was not considered in this analysis because of the limitations previously noted.

Measured and predicted \(K_e\) values for the soils are presented in Table 3. The measured \(K_e\) values ranged over three orders of magnitude. All three methods (HSM, LDM2/3, and Rosetta) provided a relatively good estimation of \(K_e\), with values of \(r^2\) on log(\(K_e\)) values ranging from 0.78 to 0.85. However, the overall prediction by LDM2/3 was found to be better than others (smallest RMSE and the highest \(r^2\) in Table 3).

The geometric surface area per particle volume (\(A_e\)) for the various soils was determined from the PSD of HSM and LDM2/3 analysis methods, and this information is presented in Table 4. For comparison purposes, \(A_e\) was also calculated from

![Diagram of measured and predicted WRC of the 10 soils. Here, water pressure head (h) is plotted as a function of the effective water saturation (S_e). Predicted WRC used PSD obtained from the HSM, LDM (LDM2 or LDM3), and the Rosetta pedotransfer function.](image)
TABLE 5. Statistical Comparison of the Measured and Predicted WRC

<table>
<thead>
<tr>
<th>Soil ID</th>
<th>Rosetta r²</th>
<th>RMSE</th>
<th>HSM r²</th>
<th>RMSE</th>
<th>LDM2/3 r²</th>
<th>RMSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sa</td>
<td>0.95</td>
<td>0.03</td>
<td>0.98</td>
<td>0.04</td>
<td>0.96</td>
<td>0.59</td>
</tr>
<tr>
<td>LSa</td>
<td>0.98</td>
<td>0.31</td>
<td>0.92</td>
<td>0.33</td>
<td>0.93</td>
<td>0.94</td>
</tr>
<tr>
<td>SAl-1</td>
<td>0.97</td>
<td>0.01</td>
<td>0.97</td>
<td>0.01</td>
<td>0.97</td>
<td>0.01</td>
</tr>
<tr>
<td>SAl-2</td>
<td>0.97</td>
<td>0.04</td>
<td>0.93</td>
<td>0.03</td>
<td>0.93</td>
<td>0.03</td>
</tr>
<tr>
<td>L-1</td>
<td>0.92</td>
<td>0.02</td>
<td>0.90</td>
<td>0.03</td>
<td>0.92</td>
<td>0.02</td>
</tr>
<tr>
<td>L-2</td>
<td>0.98</td>
<td>0.15</td>
<td>0.99</td>
<td>0.07</td>
<td>0.99</td>
<td>0.05</td>
</tr>
<tr>
<td>SAl-1</td>
<td>0.94</td>
<td>0.10</td>
<td>0.91</td>
<td>0.09</td>
<td>0.88</td>
<td>0.07</td>
</tr>
<tr>
<td>SAl-2</td>
<td>0.94</td>
<td>0.04</td>
<td>0.97</td>
<td>0.01</td>
<td>0.94</td>
<td>0.04</td>
</tr>
<tr>
<td>CL</td>
<td>0.97</td>
<td>0.17</td>
<td>0.96</td>
<td>0.81</td>
<td>0.98</td>
<td>0.04</td>
</tr>
<tr>
<td>SiC</td>
<td>0.97</td>
<td>0.08</td>
<td>0.99</td>
<td>0.01</td>
<td>0.79</td>
<td>0.19</td>
</tr>
<tr>
<td>Overall</td>
<td>0.80</td>
<td>0.09</td>
<td>0.84</td>
<td>0.14</td>
<td>0.77</td>
<td>0.06</td>
</tr>
</tbody>
</table>

Predictions were based on PSD from the HSM and the laser method with different preparation protocols (LDM2/3) and the Rosetta pedotransfer function.

r²: coefficient of linear correlation.

The measured values of $K_s$ (Table 3) using the Kozeny-Carmen equation. The PSD determined using HSM yielded lower values of $A_s$ relative to the LDM2/3 because of the capability of the LDM to detect smaller particles than the HSM. The $A_s$ values from LDM2/3 were closer to the calculated values that were determined from measured values of $K_s$, having an overall r² of 0.87 and a lower RMSE (Table 4).

Measured and predicted WRC for the soils are presented in Fig. 3, with the water pressure head (h) plotted as a function of the effective saturation, $S_e = (O - O_i) / (O_s - O_i)^{-1}$, where $O_i$ is the water content, and $O_s$ and $O_i$ are the saturated and residual water contents. The value of $O_s$ was determined by optimization of the van Genuchten (1980) model to measured and predicted WRC data. In general, all of the prediction methods provided a reasonable description of the WRC when written in terms of $S_e$ ($r^2$ and RMSE, Table 5). No single method (Rosetta, HSM, and LDM2/3) was found to have a consistent advantage for all the soils (Table 5). When the WRC data is plotted in terms of saturation (O/O_s), then the agreement between the measured and predicted WRC is much lower (data not shown), and this indicates sensitivity to the selected value of $O_s$. Hence, the accuracy of the WRC prediction methods is likely to be dependent on differences in the optimized value of $O_s$. Additional research is warranted on this topic.

SUMMARY AND CONCLUSIONS

The particle size distribution (PSD) of 10 soils representing a wide textural range of soils when using PSD from HSM and LDM2/3 methods, provided the data were plotted in terms of effective saturation. Moreover, prediction accuracy was found to be equivalent to alternative tools, such as pedotransfer functions. The integrated benefits of the separated protocols and the laser diffraction technique will facilitate its use in studies requiring analysis of PSD on numerous soils sample (i.e., large areas).

ABBREVIATIONS

PSD: particle size distribution;
HSM: hydrometer and sieves method;
LDM: laser diffraction method;
WRC: water retention curve.

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