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NOTE

An alternative method for determining particle-size distribution of forest road aggregate and soil with large-sized particles

Hakjun Rhee, Randy B. Foltz, James L. Fridley, Finn Krogstad, and Deborah S. Page-Dumroese

Abstract: Measurement of particle-size distribution (PSD) of soil with large-sized particles (e.g., 25.4 mm diameter) requires a large sample and numerous particle-size analyses (PSAs). A new method is needed that would reduce time, effort, and cost for PSAs of the soil and aggregate material with large-sized particles. We evaluated a nested method for sampling and PSA by comparing it with the methods that follow the American Association of State Highway and Transportation Officials (AASHTO) standard T88-00 and the American Society for Testing and Materials (ASTM) standard D422-63. Using 33 forest road aggregate samples from the Clearwater National Forest in northern Idaho, the nested method required much less laboratory time and effort and resulted in similar PSA values, except for the 0.149 mm (No. 100) sieve, where the smallest particle-size fraction (PSF) values (1.30% and 1.39%) were observed. The nested method shows great potential for determining PSDs of the soil and aggregate material with large-sized particles and should be tested on other forest soils and road aggregates. The nested sampling and analysis method allows for the same number of samples to be collected but requires less laboratory time, making it more efficient and economical for testing the soil and aggregate material with large-sized particles such as forest road aggregate.

Key words: grain-size distribution, gravel road, soil grading, soil sampling, unpaved road.

Résumé : Il faut un vaste échantillonnage et plusieurs analyses granulométriques pour mesurer la distribution granulométrique d'un sol qui contient de grosses particules (p. ex., diamètre de 25,4 mm). Une nouvelle méthode est nécessaire pour réduire le temps, les efforts et les ressources financières nécessaires pour faire l'analyse granulométrique des sols et matériaux granulaires qui contiennent de grosses particules. Nous avons évalué une méthode imbriquée pour l'échantillonnage et l'analyse granulométrique en la comparant aux méthodes prescrites par la norme T88-00 de l'American Association of State Highway and Transportation Officials (AASHTO) et la norme D422-63 de l'American Society for Testing and Materials (ASTM). Avec 33 échantillons de granulat provenant de chemins forestiers dans la forêt nationale de Clearwater dans le nord de l'Idaho, la méthode imbriquée a nécessité beaucoup moins d'efforts et de temps de laboratoire et les valeurs de l'analyse granulométrique étaient similaires à l'exception de la passoire de 0,149 mm (N° 100) où les plus faibles valeurs (1,30 et 1,39 %) de classe granulométrique ont été observées. La méthode imbriquée offre un fort potentiel pour déterminer la distribution granulométrique des sols et matériaux granulaires qui contiennent de grosses particules et elle devrait être testée pour d'autres sols forestiers et granulats utilisés pour les chemins forestiers. La méthode imbriquée d'échantillonnage et d'analyse permet de collecter la même quantité d'échantillons mais exige moins de temps de laboratoire, ce qui en fait une méthode plus efficace et plus économique pour tester les sols et les matériaux granulaires qui contiennent de grosses particules tels que le granulat utilisé pour les chemins forestiers. [Traduit par la Rédaction]

Mots-clés : distribution granulométrique, route de gravier, granulométrie des sols échantillonnage des sols, route non revêtue.

Introduction

Particle-size analysis (PSA) is a method commonly used to determine the particle-size distribution (PSD) of soil and aggregate material. The PSD consists of particle-size fractions (PSFs) of each individual particle size class and is often plotted as a cumulative frequency diagram (i.e., particle size using a logarithmic scale on the *x* axis and percent passing on the *y* axis; Fig. 1). The PSD is one of the most important soil characteristics and is used to understand soil physical properties such as pore distribution, water retention, and conductivity (Arya and Paris 1981; Prosperini and Perugini 2008; Ryżak and Bieganowski 2011). It is also an important criterion used to meet the requirements of engineering material and is used extensively on soil and aggregate material during road construction (Gnanendran and Beaulieu 1999). For example, the USDA Forest Service specifies aggregate and soil grading requirements for various road courses and treatments (e.g., Fig. 1; Turner and Hutchinson 1996), which are verified by road engineers using PSA. Researchers and scientists use PSD to characterize soil (Zhao et al. 2010), road surface, and eroded sediment (MacDonald et al. 2001).

The procedures of PSA of soil and aggregate typically follow the American Association of State Highway and Transportation Officials (AASHTO) and American Society for Testing and Materials

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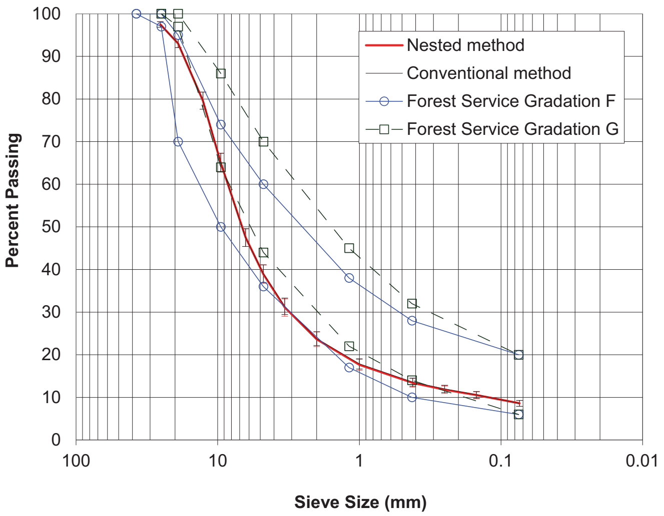
Fig. 1. The average PSDs of the aggregate samples using the nested and conventional methods, and the USDA Forest Service grading designations F and G for surface course aggregate (Turner and Hutchinson 1996). The bars in the PSD curves indicate 95% confidence intervals. The average PSDs are within the range of the gradation F.



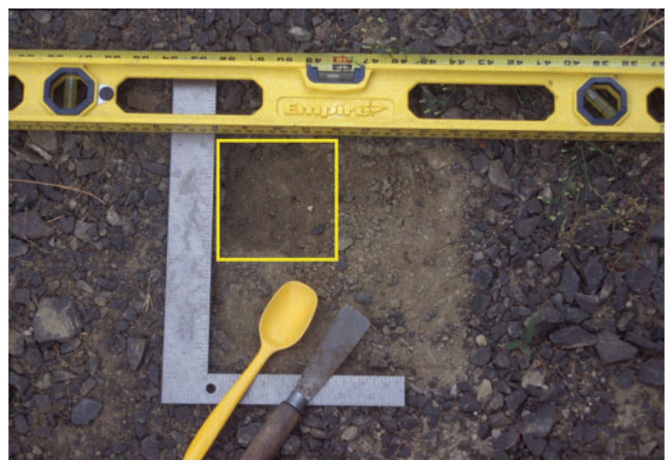
(ASTM) standards. Forest soils often contain coarse fragments such as large rocks (Lutz and Chandler 1946; Comerford 2002). Road aggregate materials consist of large-sized particles as large as, e.g., 25.4 mm (1 inch) in diameter (Turner and Hutchinson 1996). To conduct PSA for the soil and aggregate material with large-sized particles, the AASHTO T88-00 standard (AASHTO 2004) and the ASTM D422-63(2002) standard (ASTM 2002) suggest a dry mass of samples: approximately 2.0 kg to analyze the soil–aggregate material with the largest particle size of 25.4 mm in diameter; 0.5 kg for 9.51 mm (3/8 inch) in diameter; and less than 0.5 kg for 6.35 mm (1/4 inch) in diameter. Larger particle sizes can be under-represented in a small sample, resulting in unacceptably large errors for the large PSF. The AASHTO and ASTM procedures reduce this potential error by requiring a larger mass for 25.4 mm diameter material. USDA Forest Service specifications for surface course aggregate require less than 3% in the 25.4 mm size class (Turner and Hutchinson 1996), likely making it the largest particle size. When analyzed following the AASHTO and ASTM procedures (AASHTO T88-00 standard (AASHTO 2004) and ASTM D422-63(2002) standard (ASTM 2002)), the 2.0 kg dry mass is often subdivided in the laboratory into three or four subsamples for ease in handling because the usual mass collected and used for PSA is 0.5 kg (AASHTO T146-96 standard (AASHTO 2000)). The resulting PSAs from these subsamples are mathematically combined to make a single representative PSD. The large mass and division into subsamples results in a time-consuming, labor-intensive, and expensive process.

To reduce time, effort, and cost for PSAs of forest road aggregate, a new PSA method was developed that used a nested sampling that requires excavating and collecting two separate sample portions from the same sampling hole: (1) a small (0.5 kg dry mass) portion and (2) a large (1.5 kg dry mass) portion (Rhee 2006). The small portion of the aggregate samples was collected from a nested location within the large portion (Figs. 2 and 3). Therefore, the new method is called the "nested" method hereafter, and the PSA method that analyzes the 2.0 kg dry mass sample following the AASHTO or ASTM standard will be called the "conventional" method.

The AASHTO and ASTM standards suggest a 0.5 kg dry mass sample for the smallest particles (<6.35 mm diameter) and a 2.0 kg sample for the largest ones (25.4 mm diameter). The nested method approximates PSFs of small sieve sizes (<6.35 mm) using

Fig. 2. Completed excavation of 0.1 m × 0.1 m hole for the small portion of a nested aggregate sample.

Fig. 3. Excavation of 0.2 m × 0.2 m hole for the large portion of a nested aggregate sample. The square indicates the 0.1 m × 0.1 m hole for the small portion referred to in Fig. 2.



the PSA results from the small portion samples (0.5 kg dry mass) and large sieve sizes (≥6.35 mm) using the combined portions (small + large portion; 2.0 kg dry mass). The PSFs of small sieve sizes are weighted using the dry mass ratio of particles less than 6.35 mm diameter ($M_{6.35\text{mm}-}$) to all particle sizes (M_{all}) as follows:

$$(1)\qquad \text{PSF}_x = \frac{M_x}{M_{\text{all}}} = \frac{M_x}{M_{6.36\text{mm}-}} \times \frac{M_{6.35\text{mm}-}}{M_{\text{all}}} = \frac{M_{x(\text{small})}}{M_{6.35\text{mm}-(\text{small})}} \times \frac{M_{6.35\text{mm}-}}{M_{\text{all}}}$$

assuming

$$\frac{M_x}{M_{6.35\text{mm}-}} = \frac{M_{x(\text{small})}}{M_{6.35\text{mm}-(\text{small})}}$$

where subscript x indicates sieve size x, the "(small)" indicates that only the small portion of aggregate samples is used, and the absence of "(small)" indicates use of the combined sample (small + large portions). The left-hand side of the assumption in eq. 1 represents the conventional method, and the right-hand side represents the nested method.

Table 1. Example of how the nested and conventional particle-size analysis (PSA) methods determined particle-size fractions (PSFs) that comprise particle-size distribution (PSD) using the same aggregate sample.

Sieve		Dry mass			PSF	
Designation	Opening (mm)	Small portion (g)	Large portion (g)	Total (g)	Nested PSA (%)	Conventional PSA (%)
1 inch	25.4	24.6	19.7	44.3	2.3	2.3
¾ inch	19.0	14.7	69.8	84.5	4.3	4.3
½ inch	12.7	99.8	139.2	239.0	12.2	12.2
⅜ inch	9.51	109.3	212.5	321.8	16.4	16.4
¼ inch	6.35	126.7	255.4	382.1	19.5	19.5
No. 4	4.76	61.1	133.5	194.6	9.3[a]	9.9[b]
No. 6	3.36	57.0	89.9	146.9	8.7	7.5
No. 10	2.00	49.2	103.9	153.1	7.5	7.8
No. 18	1.00	29.5	59.3	88.8	4.5	4.5
No. 40	0.420	24.2	49.2	73.4	3.7	3.7
No. 60	0.250	10.7	18.3	28.9	1.6	1.5
No. 100	0.149	7.4	16.7	24.1	1.1	1.2
No. 200	0.074	10.2	26.7	36.9	1.6	1.9
Finer than No. 200	<0.074	48.8	96.4	145.2	7.4	7.4
<6.35 mm sieves		298.0	593.9	891.9	45.4	45.4
All sieves		673.0	1290.6	1963.6	100	100

Note: This is the analysis for one arbitrarily chosen sample. The PSFs of sieves ≥ 6.35 mm are the same for both the nested and conventional methods.

[a]For the nested method, the small portion dry mass of individual small sieve ($M_{x(\mathrm{small})}$) is divided by the small portion total dry mass of sieves < 6.35 mm ($M_{6.35\mathrm{mm}-(\mathrm{small})}$), which is then multiplied by the total dry mass of sieves < 6.35 mm ($M_{6.35\mathrm{mm}-}$) and divided by the total dry mass of all sieves (M_{all}), e.g., 61.1/298.0 × 891.9/1963.6 = 9.3%.

[b]For the conventional method, the total dry mass of individual sieve (M_x) is divided by the total dry mass of all sieves (M_{all}), e.g., 194.6/1963.6 = 9.9%.

The objective of this study was to test the differences between the two methods and determine their suitability for routine PSAs on the soil and aggregate material with large-sized particles such as forest road aggregate.

Methods

Study sites

The aggregate samplings were conducted on three roads in the USDA Forest Service Clearwater National Forest, about 39–43 km northeast of Moscow, Idaho, USA (47°03′12″N, 116°40′47″W; 47°04′07″N, 116°40′33″W; 47°02′57″N, 116°43′58″W). Each road was 5 m wide and had basalt aggregate applied 0.1 m deep on a fine subgrade of mineral soil.

Assumption

The nested method used the assumption that the dry mass ratios of PSFs of small sieve sizes to particles less than 6.35 mm diameter for the small portion ($M_{6.35\mathrm{mm}-(\mathrm{small})}$) and the combined portion ($M_{6.35\mathrm{mm}-}$) of aggregate samples are the same (eq. 1). Before comparing the two methods, we compared these dry mass ratios to find out whether or not this assumption was correct.

Comparison of two methods

The same aggregate samples should be used to compare both the nested and conventional methods and to avoid variations from sampling locations. When the two separate aggregate samples collected from the nested sampling protocol are combined (small + large portions), the total amount of the combined samples is the same as the one collected from the conventional method (2.0 kg dry mass). Therefore, we collected two separate aggregate samples (small and large portions) using the nested sampling protocol. We conducted one PSA for the small portion (about 0.5 kg dry mass) and two to three PSAs for the large portion (about 1.5 kg) using the conventional method. The dry masses from the PSAs for the small and large portions were arithmetically combined for individual sieve size to construct one PSD for the conventional method (Table 1). For the nested method, we used the PSA results of all sieve sizes from the small portion to calculate the PSFs for less than 6.35 mm and the sieve size equal to or greater than 6.35 mm from the both small and large portions to calculate the PSFs for equal to or greater than 6.35 mm. The PSFs of sieve sizes equal to or greater than 6.35 mm are the same for both the nested and conventional methods, because the both methods use the same PSA results (eq. 1). Therefore, comparisons of the two methods were made for the PSFs of the sieve size less than 6.35 mm. Table 1 shows an example of how the two PSA methods determined the PSD using the same aggregate sample.

Aggregate sampling

Aggregate samples were collected from the three roads. We chose an aggregate sampling depth of 33.3 mm to include the largest aggregate particle (25.4 mm) observed in the study plots. A total of 33 aggregate samples were collected and analyzed. A field visit and preliminary data analysis showed that a dry mass of 2.0 kg required a volume of 0.2 m length × 0.2 m width × 33.3 mm depth. Following the nested sampling protocol (Rhee 2006), the small portion of aggregate samples was collected from an area of 0.01 m² (0.1 m × 0.1 m) to have approximately 0.5 kg dry mass of road aggregate (Fig. 2). The large portion was collected from the area of 0.03 m² (the 0.2 m × 0.2 m area excluding the 0.1 m × 0.1 m nested area) to have approximately 1.5 kg dry mass (Fig. 3).

Particle-size analysis method

We used 13 sieves for the PSAs (Table 1): 25.4 mm (1 inch), 19.0 mm (3/4 inch), 12.7 mm (1/2 inch), 9.51 mm (3/8 inch), 6.35 mm (1/4 inch), 4.76 mm (No. 4), 3.36 mm (No. 6), 2.00 mm (No. 10), 1.00 mm (No. 18), 0.420 mm (No. 40), 0.250 mm (No. 60), 0.149 mm (No. 100), and 0.074 mm (No. 200). The PSAs of the samples followed the ASTM D2217-85 and D422-63(2002) standards (ASTM 1998, 2002).

Statistical analysis

Statistical analyses were conducted to compare the new aggregate sampling and PSA method with the conventional method for determining PSD of forest road aggregate. The PSD consists of PSFs of each individual sieves. Therefore, we conducted a paired *t* test (Zar 1996) with a significance level of $\alpha = 0.05$ on the PSFs of individual sieves separately.

Table 2. Comparison of the average dry mass ratios of particle-size fractions (PSFs) of small sieve sizes to particles less than 6.35 mm diameter for the small ($M_{6.35mm\text{–}(small)}$) and combined ($M_{6.35mm\text{–}}$) portions of aggregate samples (n = 33).

Sieve		Dry mass ratios				
		Small portion		Combined portion		
Designation	Opening (mm)	Mean (%)	SD (%)	Mean (%)	SD (%)	p value
No. 4	4.76	18.32	3.72	18.07	2.88	0.422
No. 6	3.36	16.61	3.07	16.23	1.79	0.241
No. 10	2.00	15.66	1.92	15.93	1.46	0.411
No. 18	1.00	12.44	1.94	12.31	1.61	0.453
No. 40	0.420	8.83	1.72	8.95	1.31	0.515
No. 60	0.250	3.30	1.11	3.29	0.69	0.856
No. 100	0.149	2.74	0.56	2.93	0.49	0.015*
No. 200	0.074	4.04	0.93	4.22	0.77	0.107
Finer than No. 200	<0.074	18.06	3.22	18.09	3.25	0.873

Note: A paired t test was used to compare the dry mass ratios. SD, standard deviation. *, degree of significance $p < 0.05$.

Table 3. Comparison of average particle-size fractions (PSFs) for the nested and conventional particle-size analysis (PSA) methods (n = 33).

Sieve		PSF				
		Nested PSA		Conventional PSA		
Designation	Opening (mm)	Mean (%)	SD (%)	Mean (%)	SD (%)	p value
1 inch	25.4	2.50	1.94	2.50	1.94	—
¾ inch	19.0	4.48	2.06	4.48	2.06	—
½ inch	12.7	13.42	3.90	13.42	3.90	—
⅜ inch	9.51	14.54	2.38	14.54	2.38	—
¼ inch	6.35	17.58	2.41	17.58	2.41	—
No. 4	4.76	8.56	1.38	8.47	1.05	0.498
No. 6	3.36	7.83	1.46	7.66	0.94	0.265
No. 10	2.00	7.45	1.40	7.58	1.24	0.404
No. 18	1.00	5.98	1.54	5.91	1.42	0.452
No. 40	0.420	4.25	1.23	4.29	1.03	0.627
No. 60	0.250	1.59	0.66	1.58	0.49	0.846
No. 100	0.149	1.30	0.33	1.39	0.31	0.015*
No. 200	0.074	1.92	0.52	2.00	0.41	0.165
Finer than No. 200	<0.074	8.60	2.04	8.61	2.02	0.950

Note: A paired t test was used to compare the nested and conventional PSA methods. SD, standard deviation. *, degree of significance $p < 0.05$.

Results

The comparison results for testing the assumption in eq. 1 show that there were no significant differences between the dry mass ratios of PSFs of small sieve sizes to particles less than 6.35 mm diameter for the small portion ($M_{6.35mm\text{–}(small)}$) and the combined portion ($M_{6.35mm\text{–}}$) of aggregate samples, except the 0.149 mm sieve (Table 2), which had the smallest PSF values among the all sieve sizes. When the PSF value was small (e.g., less than 3%), the assumption for the nested method might not work.

Little differences were found between the PSDs using the nested and conventional PSA methods (Fig. 1). There were no significant differences between the nested and conventional PSA methods for the PSFs of the sieve size less than 6.35 mm, except the 0.149 mm sieve (Table 3), which is the same as the comparison results for testing the assumption. The 0.149 mm sieve had the smallest PSF values (1.30% for the nested method and 1.39% for the conventional method) among all sieve sizes, but the difference (0.09%) was significant.

Discussion

We found the only difference between the nested and conventional methods in the 0.149 mm sieve, where the smallest PSF values were observed. Considering that these PSF values (1.30% and 1.39%) were very small, the significant difference (0.09%) might be merely a statistical quirk. The nested method should be further tested on other forest soils and aggregate material with large-sized particles.

The PSAs using large sieve sizes (e.g., sieves ≥ 6.35 mm) take less time and effort than the method that uses small sieve sizes. The conventional PSA method would have needed three to four PSAs for all sieves to determine the whole PSD of forest road aggregate. With the nested method, only two PSAs (one PSA for all sieves and the other PSA for sieves ≥ 6.35 mm) were needed. The PSA time is subject to the analyzing individual's skill and the number of sieves used for the analysis. Assuming 8 working hours per day, it took one day or more for our laboratory technician to determine the PSD of one aggregate sample (except drying the sieved samples) using the conventional PSA method, whereas it took a half day (about 4 h) using the nested PSA method. We estimated that the nested PSA method reduced the aggregate analysis time and effort by more than half.

We intended to collect aggregate samples of 0.5 kg dry mass for the small portion and 1.5 kg dry mass for the large portion, for a total aggregate sample size of 2.0 kg dry mass. We actually collected an average of 0.698 kg dry mass (standard deviation of 0.126 kg) of small portion samples and a total of 2.052 kg dry mass (standard deviation of 0.439 kg). We collected more than the target amount of aggregate samples for the small portion, because the side walls of the small sampling holes tended to collapse so we expanded the holes to include the collapsed material with larger aggregate particles that were stuck in the side walls. However, we collected approximately the target total amount of aggregate samples, which suggests that an aggregate sample volume of approximately 0.0013 m^3 should be collected to have a 2.0 kg dry mass sample. A volume of 0.00033 m^3 of the 0.0013 m^3 should be separately collected to have a 0.5 kg dry mass sample for the nested small portion.

Conclusions

We conclude that the nested method can be used for determining PSD of the soil and aggregate material with large-sized particles, e.g., 25.4 mm diameter particles. However, when PSF values are too small, there might be a difference between the two methods. An aggregate sample volume of approximately 0.0003 m^3 should be collected to have a 0.5 kg dry mass sample for the small portion that is nested within the large portion for which an aggregate sample volume of 0.001 m^3 needs to be collected to have a 1.5 kg dry mass sample. The nested method could find applications not only in forest road engineering, but also in forest ecosystem studies where soils with coarse fragments are common and require a large mass of samples for PSA.

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