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A simple equation to determine the breakdown of individual aggregate size fractions in the wet-sieving method

T.B.S. Christopher [a,*], A.M. Mokhtaruddin [a], M.H.A. Husni [a], M.Y. Abdullah [b]

[a] Department of Soil Science, Universiti Pertanian Malaysia, 43400 UPM Serdang, Selangor, Malaysia
[b] Department of Mathematics, Universiti Pertanian Malaysia, 43400 UPM Serdang, Selangor, Malaysia

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Abstract

Wet-sieving method using nested sieves is one common method to measure aggregate stability. However, this method cannot be used to measure the stability of individual aggregate size fractions, only of whole soils. Thus, this study was to develop an equation to estimate the aggregate breakdown of individual aggregate size fractions in this particular method. The key to develop the equation was to assume that aggregate breakdown happens sequentially and consistently, and that the aggregate breakdown between any two aggregates in the same aggregate size fractions is equal in percentage. Applying these two assumptions, this equation was developed: $x_i = (W_{ai} \times D_i)/(W_{ai} + D_{i-1})$, where x_i is the weight of aggregate breakdown in aggregate size fraction i, W_{ai} is the weight of the aggregates in aggregate size fraction i before wet-sieving, and D_i and D_{i-1} are the weight of aggregates that have passed through sieve i and $i-1$, respectively. This equation was tested with five soil series. The soils were separated into six aggregate size fractions: 4.76–8.0, 2.83–4.76, 2.0–2.83, 1.0–2.0, 0.5–1.0 and 0.3–0.5 mm. For every soil, each of their aggregate size fraction was separately wet-sieved to determine the actual aggregate breakdown. The separate wet-sievings results were then combined in such a way to simulate the usual wet-sieving method; that is, to construct the data that would have been produced if each of the aggregate size fractions was wet-sieved together in the same nested sieves. Paired sample *t*-test showed that the differences between the actual and estimated aggregate breakdown values were significant at 5%. However, there was very close correlation between the actual and estimated values ($r = 0.974$; $p < 0.001$); thus, the equation was calibrated by simple linear regression. The calibrated equation was: $\hat{y}_i = 100\ \sin^2\alpha_i$, where $\hat{y}_i$ is the calibrated breakdown

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[*] Corresponding author. Tel.: +60-6-03-948 6101; fax: 6-03-943 4419; e-mail: chris@agri.upm.edu.my

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estimate for aggregate size fraction i, and α_i is $0.0166 x_i + 0.1$ in unit radians. This calibrated equation was highly significant at 1% ($F = 766.039$; $p < 0.001$), with the values fitting very tightly along the regression line ($R^2 = 0.961$), and with very small standard error (*std. error* = 0.023). The calibrated equation was validated with three additional soils. Paired sample *t*-test showed there was insignificant differences between the actual and calibrated breakdown estimate values. Moreover, using fewer aggregate size fractions did not affect the accuracy of the calibrated equation, as this equation still predicted the actual values with very small errors.

Keywords: Aggregate breakdown; Wet-sieving; Nested sieves; Aggregate stability

1. Introduction

Soil aggregate stability is the ability of aggregates to resist disruptive forces (Hillel, 1982). One common method to measure aggregate stability is the wet-sieving method using nested sieves (Yoder, 1936; Kemper and Chepil, 1965). This technique breaks down and separates the aggregates into various sizes by sieving them through a nest of sieves under water. A disadvantage of this method is that it is insensitive to changes in individual aggregate sizes; it only considers the weight of all aggregates above a given size. This means one can only measure the stability of whole soil, not the stability of individual aggregate size fractions. It is impossible to determine the stability of individual aggregate size fractions because, in a particular sieve, there is a mixing of aggregates that were originally placed in that sieve (before wet-sieving) with the aggregates that had ruptured and fallen from the above sieves (after wet-sieving).

At times it may be more important to determine the stability of individual aggregate size fractions than of whole soils. This is because the physical and chemical properties of aggregate size fractions are often different from each other. The amount of clay, organic matter and cations, for example, differ from one aggregate size fraction to another (Garey, 1954; Piccolo and Mbagwu, 1990; Cambardella and Elliott, 1993; Cruvinel et al., 1993). To separately wet-sieve individual aggregate size fractions, however, is too tedious and time-consuming.

The objective of this paper was to develop an equation to determine the breakdown of individual aggregate size fractions in the usual wet-sieving method (using nested sieves). By knowing the amount of breakdown in each aggregate size fraction, it would be possible to determine their respective aggregate stabilities.

2. Theory

2.1. Description of the parameters and assumptions of the model

Fig. 1 illustrates the breakdown and movement of aggregates in each sieve during wet-sieving. In Fig. 1(a) and (b), i denotes the sieve number ($i = 1$ to n) so that sieve no. 1 is the sieve with the largest aperture size, followed by sieve no. 2, and so on. Note that the last sieve, sieve n, refers to the container that holds the water and the nest of

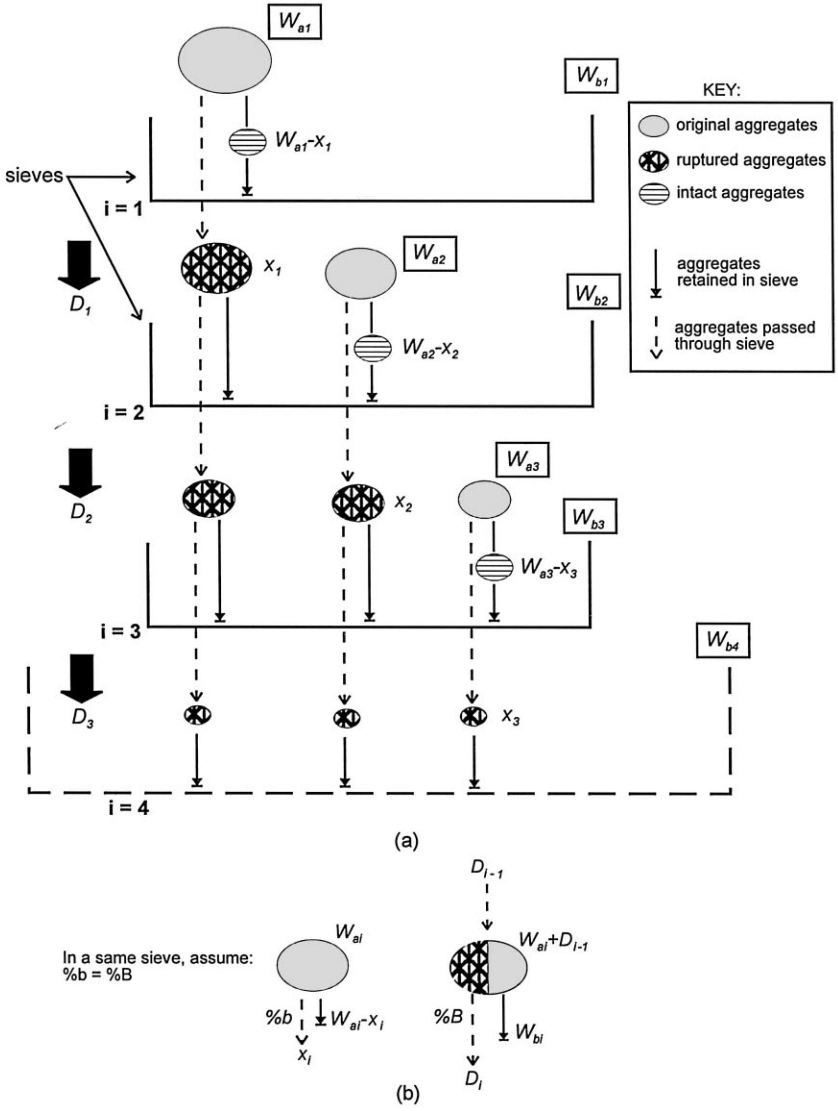

Fig. 1. (a) Simplified illustration of the aggregate breakdown and movement in a nest of sieves during wet-sieving. (b) In the same sieve, the breakdown percentage between the original aggregates and all the aggregates in that sieve is assumed equal.

sieves. Aggregates that are placed in each sieve before wet-sieving are referred as *original aggregates*. The weight of the original aggregates in sieve i is W_{ai}. On the other hand, W_{bi} is the weight of all aggregates in sieve i after wet-sieving.

Variable x_i is the weight of the original aggregates in sieve i that had ruptured or broken down. This is the variable of great interest because $(W_{ai} - x_i)$ refers to the weight of the original aggregates in sieve i that had resisted breakdown. Hence, $(W_{ai} - x_i)$ can be aptly referred to as the weight of the *intact aggregates*. If x_i could be determined, then the stability $(\mathrm{AS_i})$ of aggregate size fraction i is just:

$$\mathrm{AS}_i = 100 \times \frac{(W_{ai} - x_i) - s_i}{W_{ai} - s_i} \tag{1}$$

where s_i is the weight of sand particles larger than the aperture size of sieve i. However, except for the uppermost sieve, x_i cannot be determined with absolute certainty because of the intimate mixing between the intact and ruptured aggregates in every sieve (Fig. 1a). x_i, however, can be estimated in two steps.

First, one needs to determine the *total* weight of aggregates that *have* passed through sieve i, or D_i:

$$D_1 = (W_{a1} + D_0) - W_{b1} = (W_{a1} + 0) - W_{b1} = \Delta W_1$$

$$D_2 = (W_{a2} + D_1) - W_{b2} = \Delta W_1 + \Delta W_2$$

$$D_3 = (W_{a3} + D_2) - W_{b3} = \Delta W_1 + \Delta W_2 + \Delta W_3$$

which can be re-expressed as:

$$D_i = \Delta W_1 + \Delta W_2 + \Delta W_3 + \ldots + \Delta W_i = \sum_{k=1}^{i} \Delta W_k \tag{2}$$

For the uppermost sieve, D_1 is just the difference between W_{a1} and W_{b1} because $D_0 = 0$, as there is no addition of ruptured aggregates from above. However, $D_2 \neq W_{a2} - W_{b2}$, and $D_3 \neq W_{a3} - W_{b3}$ because in the lower sieves there is an addition of ruptured aggregates from the upper sieves.

In the second step, one must make two assumptions. The first assumption is that aggregate breakdown happens sequentially and consistently; that is, sequential breakdown begins at the largest aggregate size fraction followed by the breakdown of successively smaller aggregate size fractions; and consistent breakdown means that aggregates would always breakdown into smaller and *equal-sized* aggregates.

The second assumption is that, in a particular sieve, the percentage of aggregate breakdown between the original aggregates and all the aggregates in that sieve is assumed equal (Fig. 1b). This second assumption is reasonable because aggregates of the same size fraction and of the same soil sample can be regarded to breakdown equally in percentage.

2.2. Application of the parameters and assumptions of the model

How to use the various D_i values and the two assumptions can be described in the following manner. As shown in Fig. 1a, the original aggregates in sieve no. 1 is assumed to breakdown first. And their breakdown is consistent so that all of their fragments (ruptured aggregates) will have a size equal to the size of the original aggregates in sieve no. 2. Here, the weight of the ruptured aggregates passing through sieve no. 1 is D_1. These equal-sized ruptured aggregates will fall and settle in sieve no. 2. Hence, the total weight of aggregates in sieve no. 2 is the weight of the original aggregates in sieve no. 2 and the ruptured aggregates, or $(W_{a2} + D_1)$. Together with the ruptured aggregates, the original aggregates in sieve no. 2 will now breakdown. This means that the total weight of aggregates breaking down in sieve no. 2 is D_2. Note that x_2 is a portion or fraction of D_2.

Correspondingly, if $\%b_i$ is the breakdown percentage of the original aggregates, and $\%B_i$ is the breakdown percentage of all aggregates (original and ruptured) in sieve i, then:

$$\%b_i = \frac{x_i}{W_{ai}} \times 100 \ \textit{and} \ \%B_i = \frac{D_i}{W_{ai} + D_{i-1}} \times 100$$

Applying the second assumption, $\%b_i$ is equal to $\%B_i$:

$$\frac{x_i}{W_{ai}} = \frac{D_i}{W_{ai} + D_{i-1}} \quad x_i = \frac{W_{ai} \times D_i}{W_{ai} + D_{i-1}} \tag{3}$$

3. Materials and methods

3.1. Model testing

Five soil series were used to test the model. The soil series were Munchong, Melaka, Bungor, Serdang and Baging. All soil series were taken at soil depth 0–15 cm (topsoil). But in addition to Serdang (topsoil), Serdang series was also sampled at soil depth 15–30 cm (subsoil). All soil samples were taken randomly in the field, mixed, and air-dried for one week. Particle size distribution was determined with the pipette method (Gee and Bauder, 1986). The soil samples were also dry-sieved into six aggregate size fractions: 4.76–8.0, 2.83–4.76, 2.0–2.83, 1.0–2.0, 0.5–1.0 and 0.3–0.5 mm. The characteristics of the soils are shown in Table 1.

Table 1
Characteristics of the soils used to test the model

Soil series	Taxonomy	Particle size distribution (%)		
		Clay	Silt	Sand
Munchong	Typic Hapludox	72.65	9.37	17.98
Melaka	Xanthic Hapludox	52.80	26.57	20.63
Bungor	Typic Paleudult	26.14	16.22	57.65
Serdang (topsoil)	Typic Paleudult	30.22	24.39	45.39
Serdang (subsoil)	Typic Paleudult	36.23	25.56	38.21
Baging	Typic Quartzipsamment	1.22	0.92	97.86

To determine the actual breakdown of individual aggregate size fractions, a specific weight of each aggregate size fraction was separately wet-sieved using the nested sieves. After wet-sieving, aggregates retained in the original sieve were the intact aggregates, and the aggregates retained in the subsequent lower sieves were the distribution of the ruptured aggregates. For soil series Munchong, Melaka, Bungor, Serdang (topsoil) and Serdang (subsoil), 20 g of each aggregate size fraction was separately wet-sieved. To increase the variation of the data set, 27 g of each aggregate size fraction for Munchong series, and 10 g of each aggregate size fraction for Baging series were also separately wet-sieved.

Before wet-sieving, all aggregate size fractions were pre-wetted by incubation under room temperature and at approximately 98% relative humidity for 24 h. Each aggregate size fraction was wet-sieved separately using the nested sieves for 30 min, at 40 rpm, and through a vertical distance of 4.0 cm. After wet-sieving, aggregates retained in each sieve were separately collected, oven-dried, then weighed.

For each soil sample, the results of the separate wet-sievings must somehow be combined to simulate the usual wet-sieving method; that is, to construct the data that would have been produced if each of the aggregate size fractions was wet-sieved together in the same nested sieves. How this was done is better explained by showing Table 2 which was the data collected for Melaka series. Of the 20 g of original aggregates sized 4.76–8.0 mm, only 10.99 g remained as intact aggregates. The values directly below 10.99 g are the distribution of the ruptured aggregates. For example, 1.79 g of the original aggregates had ruptured and settled in the sieve 2.83–4.76 mm. Each bolded value is the weight of intact aggregates for each aggregate size fraction.

Because the specific weight for each aggregate size fraction was fixed at 20 g for Melaka series, then all W_{ai} were 20 g. The actual aggregate breakdown was determined by subtracting the weight of the intact aggregates from W_{ai}. W_{bi} was obtained by adding the weight of aggregates in sieve i across several separate wet-sievings. For example, 11.55 g of aggregates in sieve 2.0–2.83 mm was obtained by adding 1.08 to 0.89 and to 9.58. Lastly, Eq. (2) was used to determine D_i, and Eq. (3) for x_i. The above method was repeated for the other soil samples.

Table 2
Wet-sieving results for Melaka soil series

Sieve size (mm)	i							W_{ai} (g)	W_{bi} (g)	D_i (g)	Estimated breakdown x_i (g)	Actual breakdown y_i (g)
		4.76–8.0	2.83–4.76	2.0–2.83	1.0–2.0	0.5–1.0	0.3–0.5					
4.76–8.0	1	**10.99**						20.00	10.99	9.01	9.01 [a]	9.01
2.83–4.76	2	1.79	**9.16**					20.00	10.95	18.06	12.45	10.84
2.0–2.83	3	1.08	0.89	**9.58**				20.00	11.55	26.51	13.93	10.42
1.0–2.0	4	1.49	1.59	2.19	**12.37**			20.00	17.64	28.87	12.41	7.63
0.5–1.0	5	1.43	2.16	1.76	2.64	**15.10**		20.00	23.09	25.78	10.55	4.90
0.3–0.5	6	1.07	2.10	1.96	1.18	1.84	**11.51**	20.00	19.66	26.12	11.41	8.49
< 0.3	7	2.15	4.10	4.51	3.81	3.06	8.49		26.12			

[a] Aggregate breakdown for the uppermost sieve need not be estimated as $D_0 = 0$.

Paired sample *t*-test was used to test the significance of differences between the estimated and actual aggregate breakdown values. The mean square error of estimation (MSE) was calculated as:

$$\mathrm{MSE} = \frac{\sum_{i=1}^{n} (y_i - x_i)^2}{n}$$

where n is the number of observations, and y_i and x_i are the actual and estimated aggregate breakdown for the ith observation, respectively.

3.2. Model calibration

Paired sample *t*-test had showed that the differences between the estimated and actual aggregate breakdown values were significant at 5%. Eq. (3) was calibrated using simple linear regression. The stability of the calibrated equation's estimation power was tested using PRESS (prediction error sum of squares) statistic (Allen, 1971; Allen, 1974; Montgomery and Peck, 1982). PRESS statistic is a form of data splitting that determines the predictive stability of a regression model. To calculate PRESS, an observation was selected, for example y_i, and the regression model was re-fitted to the remaining $n-1$ observations to predict the withheld observation y_i. Denoting the predicted value as $\hat{y}_{(i)}$, the prediction error for point i is: $e_{(i)} = y_i - \hat{y}_{(i)}$. This procedure was then repeated for each observation $i = 1, 2, \dots, n$ to produce a set of $e_{(i)}$. PRESS is defined as:

$$\mathrm{PRESS} = \sum_{i=1}^{n} e_{(i)}^2 = \sum_{i=1}^{n} \left[y_i - \hat{y}_{(i)} \right]^2$$

The lower the difference between the PRESS value and the regression's SSE (sum square of error) value, the more stable the model's predictive power.

3.3. Model validation

The calibrated model was validated by using three additional soil samples. These three soils had very different soil texture from each other (clay, sandy clay, and sandy clay loam soil), and were from different agricultural use. These three soils were sampled and treated in the same way as the previous soil samples, and also dry-sieved into the same six aggregate size fractions.

3.4. Further tests

The calibrated model was also tested if it would estimate accurately when fewer number of aggregate size fractions were used. This is in view that sometimes fewer number of aggregate size fractions are used in research. In this study, it was possible to construct the data that would have been produced if fewer number aggregate size fractions were wet-sieved together in the same nested sieves. How this was done is as previously described (Table 2) except now the wet-sieving results of the unused aggregate size fractions were disregarded. For example, if considering only five aggregate size fractions (2.83–4.76, 2.0–2.83, 1.0–2.0, 0.5–1.0 and 0.3–0.5 mm), the wet-sieving results of the aggregate size fraction 4.76–8.0 mm were disregarded in the construction of data.

The calibrated model was tested with five aggregate size fractions (2.83–4.76, 2.0–2.83, 1.0–2.0, 0.5–1.0 and 0.3–0.5 mm), four aggregate size fractions (2.0–2.83, 1.0–2.0, 0.5–1.0 and 0.3–0.5 mm), and three aggregate size fractions (1.0–2.0, 0.5–1.0 and 0.3–0.5 mm).

Note that all weights of the aggregate breakdown for the largest aggregate size fraction (4.76–8.0 mm) were not used in the model calibration, model validation, or in the comparison between the actual and estimated breakdown values. This is because aggregate breakdown for the largest aggregate breakdown could always be determined directly (without estimation) simply by $(W_{a1} - W_{b1})$.

4. Results and discussion

Paired sample *t*-test revealed that the differences between the actual and estimated breakdown values were significant at 5% ($t = 7.35$; $p < 0.001$). This can also be seen in Fig. 2a, where Eq. (3) was accurate only when the actual aggregate breakdown was lesser than 4 g and greater than 18 g. Overall, Eq. (3) tend to overestimate the actual aggregate breakdown. The MSE value using Eq. (3) was 8.220—an unacceptable level of error.

Nevertheless, the actual breakdown values correlated very strongly with the estimated values ($r = 0.974$; $p < 0.001$). This means the error of estimation was constant, and

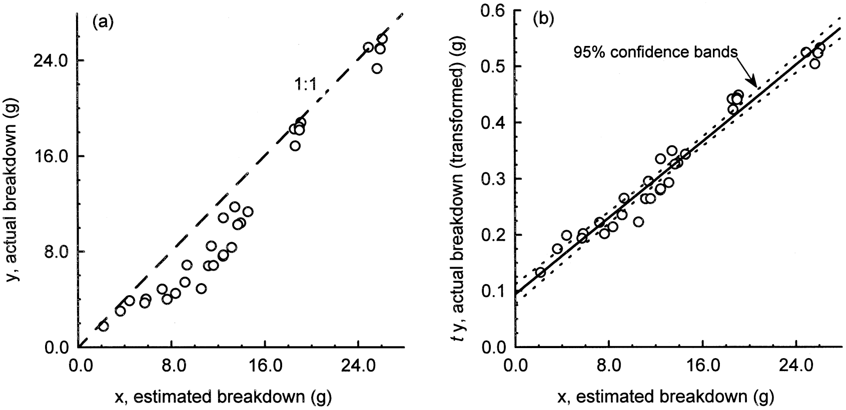

Fig. 2. (a) Actual vs. estimated aggregate breakdown. (b) Calibration by simple linear regression between the actual (transformed) and estimated breakdown variables.

therefore could be calibrated by linear regression. Simple linear regression between the actual and estimated variable had violated two assumptions of regression: the assumption of normality and homogeneity of variance. To correct for these violations, the actual breakdown variable was transformed by $ty = \sin^{-1}[\surd(y/100)]$. Many types of transformation were tried, but it was the $\sin^{-1}[\surd(y/100)]$ transformation that gave the best correction and tightest fit in the regression model.

The regression model was highly significant at 1% ($F = 766.039$; $p < 0.001$), with the values fitting very tightly along the regression line, and with a very narrow 95% confidence band (Fig. 2b). The calibrated equation was as follows (std. error of the regression coefficient and constant are shown in brackets):

$$\begin{array}{lr} \mathrm{ty} = 0.0166x + 0.1000 & \mathrm{R}^2 = 0.961 \\ \quad (0.0006)\ (0.0092) & \mathrm{std.\ error} = 0.023 \\ & \mathrm{c.v.} = 0.205\% \end{array}$$

which can be re-expressed as:

$$\hat{y} = 100\sin^2\alpha_i \qquad (4)$$

where $\hat{y}_i$ is the calibrated breakdown estimate for aggregate size fraction i, α_i is $(0.0166x_i + 0.1)$ in unit radians, and x_i is taken from Eq. (3). The MSE value using Eq. (4) was 1.646. This is a five times increase in accuracy compared to using Eq. (3).

SSE and PRESS value for Eq. (4) were 0.0163 and 0.0183, respectively. This is an increase in error of only 1.12 times. This small increase in prediction error means the predictive power of Eq. (4) was very stable, and would not degrade much in predicting future observations.

Eq. (4) was validated by testing it with three additional soils (clay, sandy clay and sandy clay loam soil), and the results are shown in Fig. 3. The outliers in Fig. 3a, Fig. 3b, Fig. 3c, Fig. 3d all belong to the same 0.3–0.5 mm aggregate size fraction of the clayey soil. Only the aggregate breakdown of this size fraction could not be estimated accurately by Eq. (4). These outliers were most probably caused by a large error occurring during wet-sieving, or mishandling of the 0.3–0.5 mm aggregate size fraction of the clayey soil. This error may have caused the loss of aggregates or excessive aggregate breakdown. Thus, in subsequent analysis, these outliers were disregarded because to include them would inflate the MSE values and obscure the true accuracy of Eq. (4).

For the full six aggregate size fractions, paired sample *t*-test showed that differences between the values of the actual and calibrated breakdown estimate were not significant at 5% ($t = 0.580$; $p < 0.571$). And as shown in Fig. 3a, all points (except one outlier) were along the 1:1 line, denoting good accuracy in estimation. This was also true for the results of other numbers of aggregate size fractions (Fig. 3b, Fig. 3c, Fig. 3d). The MSE values for the six, five, four and three aggregate size fractions were 0.972, 1.151, 1.092 and 0.700, respectively (note: for the calculation of MSE values, all points were used except the one outlier). This showed that the accuracy of Eq. (4) was stable and would not be affected by the number of aggregate size fractions used.

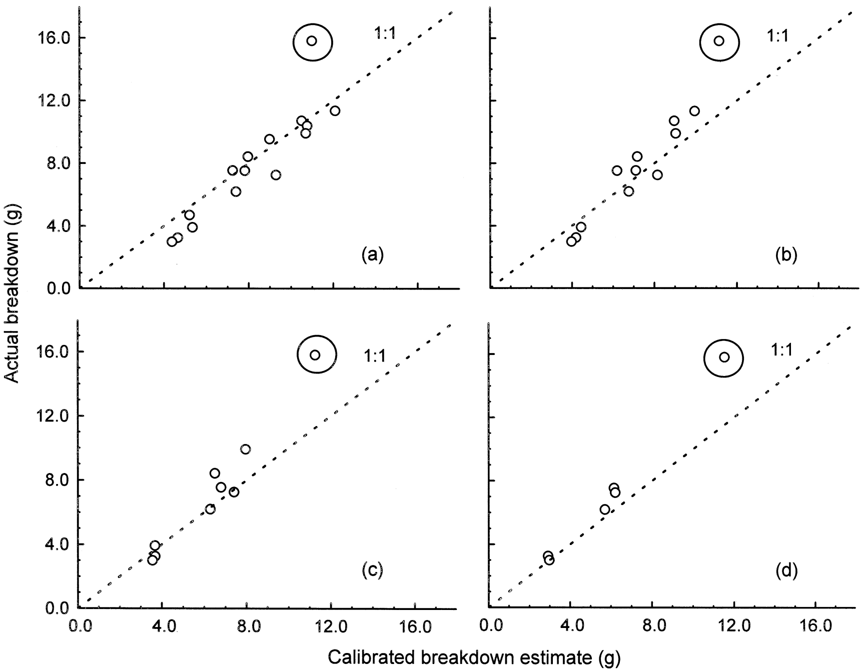

Fig. 3. Model validation. Actual breakdown vs. calibrated breakdown estimate for different number of aggregate size fractions used (the outlier is circled): (a) Six aggregate size fractions. (b) Five aggregate size fractions. (c) Four aggregate size fractions. (d) Three aggregate size fractions.

Eq. (4) saves an enormous amount of work and time because one need not separately wet-sieve each aggregate size fraction to determine their individual breakdown. The stability of individual aggregate size fractions can then be determined by using Eq. (1).

The accuracy of Eq. (4) would not be effected by: 1) the duration and speed of wet-sieving, 2) amount of water used, 3) pre-wetting treatment of aggregates, and 4) type of soil. This is because what matters ultimately for Eq. (4) are the weight of aggregates in each sieve before and after wet-sieving. The need for calibration, however, showed that the first assumption was too simplistic; it is unlikely that aggregates would breakdown sequentially and consistently. Different sizes of aggregates would breakdown simultaneously and into various sizes at once. Nevertheless, the strong correlation between the actual and estimated values showed that the error of estimation was constant.

Eq. (4) however, would be affected by the range of the aggregate size fractions used. The second assumption is that all aggregates in an aggregate size fraction would breakdown equally in percentage. Nevertheless, the larger the range of an aggregate size fraction, the larger the variability of aggregate sizes. For example, aggregate size fraction of 1–8 mm would have more aggregates of various sizes than aggregates from a size fraction of 4–8 mm. Thus, assuming equal breakdown between any two aggregates in the former aggregate size fraction would be more unreasonable than in the latter size fraction. Therefore, it is important to keep the range of all aggregate size fractions as narrow as practically possible.

5. Conclusion

Aggregate breakdown of each aggregate size fraction was successfully estimated using a very simple equation, Eq. (4). This equation was very efficient as it estimated the actual aggregate breakdown very well, and it had a very strong and stable predictive power. Eq. (4) saves an enormous amount of work and time because one need not separately wet-sieve each aggregate size fraction to determine their breakdown. The stability of individual aggregate size fractions can then be determined by using Eq. (1).

The accuracy of Eq. (4) would not be affected by the duration and speed of wet-sieving, amount of water used, pre-wetting treatment of aggregates, type of soil, and the number of aggregate size fractions used. It would, however, be affected by the ranges of the aggregate size fractions. Hence, it is important to keep the range of all aggregate size fractions used as narrow as practically possible.

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