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Pore Size Distribution in Relation to Bulk Density and Texture of Some Egyptian Alluvial Soils

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MECHANICAL analysis and bulk density measurements of 162 soil samples were done. The samples taken at three depths of 54 profiles from different alluvial soils of Nile Delta and Nile Valley, representing wide variations in soil texture and densities. For the undisturbed soil cores from the same layers, soil moisture content on weight and volume basis were determined at different pressures and the pore size distribution was determined. Regression analyses were utilized to develop equations for predicting soil bulk density from particle size distribution, and for predicting pore size distribution from bulk density and particle size distribution. The correlation coefficients were calculated and the best equations for predicting total porosity (TP), wide or water drainable pores (WP), medium or water holding pores (MP) and fine capillary pores (FP) were developed.

The obtained results showed that soil bulk density (DB) can be predicted using sand (SA), silt (SI) and clay (CL) contents with a standard error (SE) of 0.174 g cm^{-3} ($R^2 = 0.35$):

$$DB = - 115.2259 + 1.1680\ SA + 1.1650\ SI + 1.1606\ CL.$$

Clay content and bulk density predict the total porosity with a SE of 0.406% ($R^2 = 0.9999$). Wide pores (WP) are significantly and positively correlated with sand fraction, and are significantly and negatively correlated with silt and clay fractions. Sand content alone predicts the wide pores with a SE of 4.16%, while bulk density, sand, silt and clay contents predict them with a SE of 3.85%. Medium or water holding pores (MP) are significantly and positively correlated with silt fraction and are significantly and negatively correlated with clay content and bulk density. Fine capillary pores (FP) are significantly and positivelly correlated with clay fraction and are significantly but negatively correlated with bulk density, sand and silt fractions. Clay content and bulk density predict medium and fine pores with standard errors of 3.37% and 4.88%, respectively.

The obtained results showed also that a reasonable estimate of clay content and sand content in the alluvial soils was attained using sample densities. The equations predicting the pore size distribution and having the highest correlation coefficients and the lowest standard error of estimate were calculated. Hence, the utilized data in this study cover a wide range of soil textures and densities, the obtained equations provide reasonable accurate estimates of pore size distribution of the alluvail soils of Egypt.

Keywords: Particle size distribution, Wide pores, Medium pores, Fine pores, Regression analyses, Nile Delta and Nile Valley.

It is commonly most appropriate to express the quantities of soil property values in units of soil volumes, but the volume weights (or bulk densities) are not always known. Therefore, a suitable equation for predicting bulk densities of soils would be very useful for characterizing many soil properties. Measurementts of water retention and pore size distribution for the soil are difficult, expensive, time consuming, and subjected to significant sources of error (Gupta and Larson, 1979 and Wu *et al.,* 1990). It is practical to predict the pore size distribution of the soils from simple estimated soil characteristics such as particle size and soil densities. Therefore, many regression models have been proposed to predict soil water-retention curves from simple and routine experimental data (Gupta and Larson, 1979; Rawls *et al.,* 1982 and Saxton *et al.,* 1986). Prediction from regression models can be improved when more variables are included in the model (Vachaud *et al.,* 1985). The effect of soil structure on pore size distribution can be obtained after Hartge (1969) if beside soil texture the total porosity, expressed numerically by bulk density is considered. Many researchers reported that reasonable estimates of pore size distribution from soil texture data can be obtained if a wide range of soil texture was available.

In the present study regression analyses were utilized to develop equations for predicting soil bulk density from particle size distribution, pore size distribution from both bulk density and particle size distribution, particle size from bulk density. The predictive equations were developed by using data from alluvial soils of Egypt from 54 locations of the Nile Delta and Valley. Several investigators in Egypt (Talha *et al.,* 1978 and 1987; Gamal Abdel-Nasser, 1995) have developed equations to predict the soil moisture characteristics and pore size distribution from soil texture and chemical analyses data, but they did not utilize data of sufficient number of soil samples in their studies, and the ranges of various soil properties were limited. Data used in the present study include 162 soil samples and cover a wide range of soil textures and densities, and are sufficient to be utilized in the regression analyses.

Material and Methods

Disturbed and undisturbed soil samples were taken at the depths of 0-30, 30-60 and 60-90 cm from 54 widely separated locations of Nile Delta and Nile valley, in six governorates (Kafr El-Sheikh, El-Gharbia, Damiette, El-Beheira, El-Fayoum and El-Menia). The investigated soils were chosen to respresent wide variations in texture and density. Most horizons (layers) were sampled in triplicate but mean values were used here. Hundred and sixty two soil samples were used in this study. Mechanical analysis was carried out by sieving and pipette method (Day, 1965) to obtain data on the particle size distribution in size grades based on the classification of the International Soil Science Society (ISSS). The determinations of soil moisture characteristics curves were carried out using pressure cooker and pressure membrane apparatus according to Richards (1949). Soil pores were classified according to De Leenher and De Boodt (1965) as wide or total drainable pores (WP)>10 μ, medium or water holding (MP) 10-0.2 μ and fine capillary pores (FP)<0.2 μ. The undisturbed soil cores were used to determine bulk density according to the method described by Blake (1965).

Single and multiple linear regression analyses were done using computer to calculate predictive equations for bulk density and pore size distribution. The ranges of these data are given in Table 1. The computer program compared all combinations of different sets of independent variables to determine which are most efficient for predicting bulk density and pore size distribution. The best predictive equations based on the smallest standard errors of estimate were developed.

Results and Discussion

Regression analyses showed that bulk density increased with decreasing clay content and with increasing sand content, while it was affected positively but not significantly by silt content. The best equations for predicting bulk densities using sand, silt and clay contents are listed in Table 2. Clay content was the best predictor of bulk density in alluvial soils followed with sand content. Sand content and clay contents predicted bulk density with a SE of 0.1833 and 0.1776 g cm^{-3}, respectively. Sand and silt, sand and clay, and silt and clay predicted

TABLE 1. **A list of variables, symbol and range, mean, standard error (SE) and standard deviation (SD) in the predictive equations.**

Variable	Symbol	Range Min.	Range Max.	Mean	SE	SD
Sand content, %	SA	2.1	81.36	31.095	1.381	17.58
Silt content, %	SI	3.33	61.3	32.076	1.055	13.43
Clay content, %	CL	3.6	81.7	36.827	1.432	18.49
Bulk density, g cm^{-3}	DB	0.851	1.919	1.206	0.017	0.21
Total porosity, %	TP	27.56	68.0	54.515	0.636	8.09
Wide pores, %	WP	1.9	27.6	14.675	0.390	4.96.
Medium pores, %	MP	0.4	27.97	15.424	0.443	5.64
Fine pores, %	FP	7.29	42.6	24.368	0.725	9.23

bulk densities with a SE of 0.1745 g cm^{-3}. SE of 0.1744 g cm^{-3} was obtained when DB is a function of sand, silt, and clay contents. Standard errors of estimate of 0.17-0.18 g cm^{-3} for alluvial soils may seem high, but densities may increase more than these amounts by compaction during cultivation or other soil disturbances. Therefore, soil bulk densities depend on land use, as well as on natural parameters. In this concern, Alexander (1980) showed that coefficients for the particle- size parameters have interpretative significance in equations for predicting bulk densities of alluvial soils in California. He reported also that bulk densities increase with increasing silt content and with increasing sand content up to a maximum at approximately 65%. Bodman and Constantin (1965) found maximum bulk densities, both theoretically and experimentally, in mixtures with slightly more than 75% sand. In this study maximum bulk densities were obtained at 74.2% sand.

TABLE 2. **Predictive equations, correlation coefficients and standard errors for predicting bulk density from texture data.**

Equation*	R	SE
DB = 1.0074 + 0.0064 SA	0.5230	0.1833
DB = 1.4462 - 0.0065 CL	0.5636	0.1776
DB = 0.8295 + 0.0075 SA + 0.0045 SI	0.5877	0.1745
DB = 1.2799 + 0.0029 SA - 0.0045 CL	0.5877	0.1745
DB = 1.5745 - 0.0029 SI - 0.0075 CL	0.5877	0.1745
DB = -115.2259 + 1.1680 SA + 1.1650 SI + 1.1606 CL	0.5917	0.1744

* all correlation equations are significant at 0.1% level.

Highly significant relationships were found between sample density and both of clay and sand content:

$CL = 95.4648 - 48.6338\ DB$ ($R = 0.5636^{***}$, $SE = 15.33\%$),

$SA = 20.6266 + 42.8977\ DB$ ($R = 0.5230^{***}$, $SE = 15.03\%$)

and such estimate of clay and sand content from bulk density is a reliable and an inexpensive method of soil texture estimation. The use of this quick and simple procedure is suited for interpretation of soil analytical data for irrigation and fertilization purposes. Similar results were reported by Johnston *et al.* (1987).

Soil total porosity increased with increasing clay content and with decreasing sand content, and not affected significantly by silt content. The regression statistics of the correlation between total porosity and ten sets of independent variables are listed in Table 3. Bulk density and clay content were found to be the best predictors of total porosity. The following equation was attained as the best estimation for total porosity of alluvial soils with sand, silt and clay as independent variables:

$TP = 4459.361 - 44.1886\ SA - 44.0762\ SI - 43.9082\ CL$ ($R^2 = 0.3507$, $SE = 6.588$)

and by adding bulk density as the fourth variable, large reductions in the standard errors of estimate were attained. And the following regression equations were found to be a good estimate of TP:

1) $TP = 100.0365 + 0.0004\ CL - 37.7665\ DB$, ($R^2 = 0.9999$, $SE = 0.0407$)

2) $TP = 107.3751 - 0.0733\ SA - 0.0735\ SI - 0.0729\ CL - 37.7692\ DB$, ($R^2 = 0.9999$, $SE = 0.0408$)

3) $TP = 100.0713 - 37.7843\ DB$ ($R^2 = 0.9999$, $SE = 0.0409$)

Simple linear regression showed that total porosity and fine pores are significantly correlated positively with clay and negatively with each of sand and bulk density. Wide pores are significantly correlated positively with sand and negatively with the each of clay and silt. The medium pores are significantly positively correlated with the content of silt and significantly negatively correlated with clay and bulk density. The correlation coefficients obtained for the relationships between particle size, bulk density and pore size are given in Table 4. It is clear that clay has a highly significat effect on all pore groups. MP and FP were strongly affected by soil bulk density. It is feasible, within a limited range, to control the pore size distribution parameters by using field techniques to achieve optimum bulk density for particular soils. Such conclusion was stated by many workers (Archer and Smith, 1972; Reeve *et al.*, 1973 and Alexander, 1980).

TABLE 3. Constant, R^2, standard error (SE) and F-value of variables in equations for predicting total porosity.

Variable	Constant	R^2	SE	F
SA	62.0092	0.2737	6.9241	60.293^{***}
SI	56.2998	0.0085	8.0900	$1.374^{n.s}$
CL	45.4170	0.3183	6.7082	74.705^{***}
DB	100.0713	0.9999	0.0409	6309748^{***}
SA+SI	68.7475	0.3459	6.5912	42.053^{***}
SA+CL	51.6839	0.3459	6.5914	42.046^{***}
SI+CL	40.5827	0.3459	6.5916	42.042^{***}
CL+DB	100.0365	0.9999	0.0407	3194826^{***}
SA+SI+CL	4459.361	0.3507	6.5881	28.446^{***}
SA+SI+CL+DB	107.3751	0.9999	0.0408	1584978^{***}

n.s Non-significant *** Significant at 0.1% level.

From the calculated correlation coefficients (Table 4) it is obvious that soil texture and bulk density have a significant effect on pore size distribution. Therefore, the following variables were selected: SA, SI, CL and DB, and after choosing the most appropriate functions of all independent variables, they were placed in nine sets: 1) SA, 2) CL, 3) DB, 4) SA+SI, 5) SA+CL, 6) SI+CL, 7) CL+DB, 8) SA+SI+CL, and 9) SA+SI+CL+DB. The simple and multiple linear regression programs were utilized to compare different combinations of these variables to determine the most efficient ones for predicting the pore size distribution. To determine the equation that best predicts the pore size distribution, the standard error of estimate (SE), R^2 and F-values were calculated for the regression equations. The best predictive equations for each pores group were obtained, firstly without the bulk density and secondly by adding it as independent variable (sets No.3, 7 and 9).

TABLE 4. Correlation coefficients between texture, density and pore size distribution.

Variable	Pore-size distribution			
	TP	WP	MP	FP
SA	-0.5232^{***}	0.550^{***}	$-0.0227^{n.s}$	-0.7358^{***}
SI	$-0.0923^{n.s}$	-0.1914^{*}	0.3646^{***}	-0.1963^{*}
CL	0.5642^{***}	-0.3839^{***}	-0.2431^{**}	0.8419^{***}
DB	-0.9999^{***}	$0.0136^{n.s}$	-0.496^{***}	-0.5766^{***}

n.s non-significant * Significant at 5% level
** Significant at 1% level *** Significant at 0.1% level.

The statistics of the best equations for predicting the wide pores, with one to nine sets of these independent variables, are listed in Table 5. The obtained results showed that, sand was the best predictor of wide pores:

$WP = 9.8443 + 0.1554\ SA \qquad (R^2 = 0.3025, SE = 4.160).$

And the other independent variables of soil texture gave only small increases in the standard errors of estimate as following:

$WP = 25.507 - 0.1615\ SI - 0.1534\ CL \qquad (R^2 = 0.303,\ SE = 4.1717),$

$WP = 10.1649 + 0.1534\ SA - 0.0081\ SI \qquad (R^2 = 0.3029,\ SE = 4.1719),$

$WP = 9.3539 + 0.1615\ SA + 0.0081\ CL \qquad (R^2 = 0.3029,\ SE = 4.1719).$

TABLE 5. Constant and coefficients of variables in equations used for predicting wide pores (WP) of alluvial soils. Each column 1 through 9 respresents the best equation for the specified number of independent variable sets.

Variable	Tested sets								
	1	2	3	4	5	6	7	8	9
Constant	9.844	18.471	14.295	10.165	9.354	25.507	28.426	1881.9	792.63
SA	0.155			0.1534	0.1615			-18.565	-7.523
SI				-.0081		-0.1615		-18.725	-7.712
CL		-0.1031			0.0081	-0.153	-0.148	-18.718	-7.747
DB			0.3154				-6.883		-9.454
R^2	0.303	0.1474	0.0002	0.3029	0.3029	0.303	0.2076	0.3052	0.4134
SE	4.160	4.599	4.9808	4.1719	4.1719	4.1717	4.448	4.1781	3.8512
F	*** 69.39	*** 27.654	n.s 0.029	*** 34.552	*** 34.552	*** 34.559	*** 20.829	*** 23.139	*** 27.667

n.s Non-significant *** Significant at 0.1% level.

Renger (1971) observed that the agreement between measured and calculated values of > 10 μ pores is only satisfactory when man take into consideration the soil structure. Bulk density is considered a good index for soil structure. The best equation for predicting wide pores, which has the smallest standard error of estimate and the highest correlation coefficient, was obtained by adding bulk density as independent variable to texture data in the regression analyses:

$$WP = 792.6286 - 7.5225\ SA - 7.7116\ SI - 7.7466\ CL - 9.4536\ DB$$
$$(R^2 = 0.4134, SE = 3.8512)$$

Medium pores were examined using the same tested sets. The obtained results (Table 6) indicated that all tested sets (with the exception of sand, set No. 1) were highly significant. It was found that sand and clay, silt and clay, and sand, silt, clay and bulk density (sets No. 5, 6 and 9) are a good estimate of medium pores. The following regression equations were found to be a good estimate of MP:

$MP = 25.711 - 0.1339\ SA - 0.1663\ CL \qquad (R^2 = 0.1421,\ SE = 5.2526),$

$$MP = 12.319 + 0.1339\ SI - 0.0323\ CL \qquad (R^2 = 0.1421,\ SE = 5.2527),$$

$$MP = 699.428 - 6.5018\ SA - 6.4367\ SI - 6.7091\ CL - 23.4609\ DB \qquad (R^2 = 0.6653,\ SE = 3.302)$$

TABLE 6. Constant and coefficients of variables in equations used for predicting medium pores (MP) of alluvial soils. Each column 1 through 9 represents the best equation for the specified number of independent variable sets.

Variable	Tested sets								
	1	2	3	4	5	6	7	8	9
Constant	15.650	18.152	31.149	9.088	25.711	12.319	53.433	3402.7	699.4
SA	-0.0073			0.0323	-0.1339			-33.905	-6.502
SI				0.1662		0.1339		-33.769	-6.437
CL		0.074			0.1663	-0.0323	-0.2334	-33.938	-6.709
DB			-13.043				-24.395		-23.46
R^2	0.0005	0.059	0.2461	0.1421	0.1421	0.1421	0.6465	0.1479	0.665
SE	5.6519	5.4837	4.9087	5.2528	5.2526	5.2527	3.3716	5.2514	3.302
F	n.s 0.083	** 10.052	*** 52.229	*** 13.168	*** 13.175	*** 13.169	*** 145.43	*** 9.145	*** 78.04

n.s Non-significant, ** Significat at 1% level, *** Significant at 0.1% level.

Fine pores (FP) were also examined using the same tested sets. The obtained results are illustrated in Table 7. The obtained results showed that also the sets No. 5, 6 and 9 (SA+CL, SI+CL and SA+SI+CL+DB) gave the best prediction of fine pores of the alluvial soils. The following equations were found to be the best estimate of fine pores (FP):

$$FP = 16.752 - 0.1394\ SA + 0.3245\ CL \qquad (R^2 = 0.7423,\ SE = 4.7188)$$

$$FP = 2.813 + 0.1394\ SI + 0.4639\ CL \qquad (R^2 = 0.7423,\ SE = 4.7188)$$

$$FP = -1271.875 + 12.823\ SA + 12.947\ SI + 13.251\ CL - 4.7926\ DB \qquad (R^2 = 0.7504,\ SE = 4.6732)$$

TABLE 7. Constant and coefficients of variables in equations used for predicting fine pores (FP) of alluvial soils. Each column 1 through 9 represents the best equations for the specified number of independent variable sets.

Variable	Tested sets								
	1	2	3	4	5	6	7	8	9
Constant	36.389	8.885	54.324	49.199	16.752	2.813	18.207	-719.64	-1271.9
SA	-0.3866			-0.4639	-0.1394			7.2247	12.823
SI				-0.3245		0.1394		7.3638	12.947
CL		0.4204			0.3245	0.4639	0.3783	7.6888	13.251
DB			-24.845				-6.446		-4.7926
R^2	0.5414	0.7088	0.3324	0.7423	0.7423	0.7423	0.7240	0.7424	0.7504
SE	6.2748	5.00	7.5707	4.7189	4.7188	4.7188	4.8828	4.7328	4.6732
F***	188.88	389.4	79.67	228.94	228.95	228.95	208.58	151.76	118.0

All correlation equations are significant at 0.1% levels.

The obtained results emphasized that sand, in addition to clay, is a very important predictor of bulk density and pore size distribution in the soils. In spite of that the previous studies did not take and into consideration and used more clay and silt content (Renger, 1971; Talha *et al.*, 1978 and 1987). The obtained equations in this study provide excellent computational efficiency and they provide reasonable accurate estimates of bulk density and pore-size distribution parameters in alluvial soils of Egypt. Several investigators stated that, grouping soils into subsets in order to reduce the variability of soil properties other than those of the independent variables may reduce the standard errors of estimate for the soils in each subset (Alexander, 1980; Vachaud *et al.*, 1985; Johnston *et al.*, 1987). But then it is less likely that the equations will be suitable predictors for large groups of soils. Therefore, in the present study alluvial soils of Egypt with widely ranging properties and with more independent variables were utilized in developing predictive equations for bulk density and pore size distribution. Therefore the obtained equations have undoubtedly a wide application and can be applied in different locations with similar conditions.

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التوزيع الحجمى للمسام وعلاقته بالكثافة والقوام لبعض الاراضى المصرية الرسوبية

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تم فى هذه الدراسة تقدير التحليل الميكانيكى والكثافة الظاهرية لعدد ١٦٢ عينة تربة مأخوذة من ثلاث طبقات من ٥٤ قطاعا من الأراضى الرسوبية فى الدلتا ووادى النيل، ولقد تم أخذ اسطوانات تربة من الطبقات المذكورة لتقدير المحتوى الرطوبى بالوزن وبالحجم عند ضغوط مختلفة ومن ذلك تم تقدير التوزيع الحجمى للمسام، وتم استخدام تحليلات الارتباط الإحصائى للحصول على معادلات للتنبؤ بالكثافة الظاهرية من نتائج التحليل الميكانيكى وللتنبؤ بالتوزيع الحجمى للمسام من نتائج الكثافة الظاهرية والتوزيع الحجمى للحبيبات. ولقد تم حساب معاملات الارتباط واختيار أفضل المعادلات المناسبة لحساب كل من المسامية الكلية (TP) ونسبة المسام الواسعة (WP) ونسبة المسام المتوسطة (MP) ونسبة المسام الضيقة (FP) .

ولقد أوضحت النتائج أن الكثافة الظاهرية (DB) يمكن التنبؤ بها من محتوى الأرض من الرمل (SA) والسلت (SI) والطين (CL) من المعادلة :

$$DB = 115.226 + 1.168\ SA + 1.165\ SI + 1.161\ CL$$

ويمكن التنبؤ بدقة بالمسامية الكلية باستعمال الكثافة الظاهرية ومحتوى الأرض من الطين. وترتبط المسام الواسعة

معنوياً بمحتوى الأرض من الرمل ارتباطا موجبا ومع الطين والسلت ارتباطا سالبا. ويمكن التنبؤ بنسبة المسام الواسعة من محتوى الأرض من الرمل بخطأ قياسى قدره ٤,٦٥ ٪ بينما يمكن التنبؤ بها بمعلومية الكثافة الظاهرية والرمل والسلت والطين بخطأ قياسى قدره ٣,٨٥ ٪ والمسام المتوسطة ترتبط ارتباط معنويا موجبا بمحتوى الارض من السلت و ارتباطاً معنوياً سالباً بالكثافة الظاهرية ومحتوى الارض من الطين. وترتبط المسام الضيقة معنوياً ارتباطا موجبا بالطين وارتباطا سالبا بالكثافة والرمل والسلت. ويمكن استعمال محتوى الارض من الطين والكثافة الظاهرية للتنبؤ بالمسام المتوسطة والمسام الضيقة بخطأ قياسى قدره ٣,٣٧٪ ، ٤,٨٨٪ على التوالى .

ولقد أوضحت النتائج أيضاً أنه يمكن تقدير محتوى الاراضى الرسوبية من الطين والرمل بمعلومية الكثافة الظاهرية للأرض . وفى هذه الدراسة تم تقدير أفضل المعادلات التى يمكن استعمالها فى التنبؤ بالتوزيع الحجمى للمسام وهى المعادلات التى لها أعلى معامل ارتباط وأقل خطأ قياسى كما هو موضح فى البحث . وحيث أن البيانات المستعملة فى هذه الدراسة تغطى مدى واسعا من القوام والكثافة فإن المعادلات المتحصل عليها تعطى توقعات مناسبة للتوزيع الحجمى للمسام للأرض الرسوبية المصرية . وهذه المعادلات تعتبر بديل مناسب لتقديرات التوزيع الحجمى للمسام ، والتى تحتاج لكثير من الجهد والوقت .