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A Simple Relationship to Estimate Parameters of the Optimum Compaction Point

Abdelkabir Maqsoud

RIME, Research Institute on Mines and the Environment, Université du Québec en Abitibi-Témiscamingue, 675, 1re Avenue, Val-d'Or, QC J9P 1Y3, Canada; abdelkabir.maqsoud@uqat.ca

Abstract: Compacted clay covers have been the most commonly used materials for hydraulic barrier layers. During their construction, the control of some parameters such as compactive effort and molding water content is required. These last parameters affect the hydraulic conductivity, which is considered as one of the important key parameters for cover design. To reach the target in terms of hydraulic conductivity, the cover must be compacted to a pre-determined dry unit weight that usually corresponds to a certain percentage of the maximum dry unit weight (γ_{dmax}). During the prefeasibility stage of a project (before conducting the required tests), γ_{dmax} and the optimum water content (w_{Opt}) can be estimated to obtain an early overview of the conditions that can be anticipated. In this regard, a new approach was proposed to estimate these parameters using the liquid limit (w_L) and the plastic limit (w_P). The proposed equations were developed using data from 56 compacted clay liners and validated using 44 others taken from published data. Results presented in this paper indicate how the proposed equations can successfully estimate parameters of the optimum compacted point.

Keywords: maximum dry unit weight; optimum water content; liquid limit; plastic limit

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1. Introduction

Mine site reclamation can be considered as very recent compared to the history of mine activities and to waste landfill management. Despite this discrepancy, mining regulations in developed countries (such as Canada) require the establishment of a plan of mine site reclamation and financial guarantees for the final reclamation of the mine site must be given before mine site development [1]. Thus, different scenarios of mine site reclamation were proposed [2], such as oxygen and hydraulic barriers.

Different materials can be used for hydraulic layer barriers, among which one can find: (1) natural or treated clay, (2) geosynthetic clay liner (GCL), and (3) geomembranes (GM). Natural clayey (NC) or compacted material (compacted clay linear CCLs) layer covers consist of materials with stable mineralogy that are well known by geologists and engineers. Historically, clay covers have been the most commonly used material for hydraulic layer barriers [3]. During the construction of the hydraulic barrier, the control of some parameters such as compactive effort and molding water content is required. These last parameters affect the hydraulic conductivity [4–6], which is considered as one of the important key parameters for cover design. The required hydraulic conductivity for clay liners ranges from 1×10^{-8} to 1×10^{-10} m/s, respectively, for Japan and Denmark [7].

To reach the target in terms of hydraulic conductivity, the cover must be compacted to a pre-determined dry unit weight that corresponds usually to a certain percentage of the maximum dry unit weight (γ_{dmax}). The last parameter that corresponds to the peak point of the compaction curve and having a water content corresponding to the optimum water content (w_{Opt}) can be evaluated using laboratory tests (Standard or Modified Proctor [8,9]).

In some situations, for example, at the prefeasibility stage of a project (before conducting the required tests), it may be useful to estimate γ_{dmax} and w_{Opt} to obtain an early overview of the conditions that can be anticipated. In this regard, various predictive models have been developed to estimate γ_{dmax} using routinely available data such as the liquid limit (w_L) and the plastic limit (w_P), the pasticity index (I_p), gravel content, sand content, and fine-grained content [10–18]. The proposed equations were based on multilinear regression or linear regression and their results were validated using literature data.

In this study, a new approach was used with the objective to estimate the optimum compaction point parameters with limited parameters and with higher regression coefficients.

2. Materials and Methods

2.1. Used Data

Data obtained from literature and published by [19] were used in the establishment of different correlations (56 soils). The used data correspond to materials where the fine-grained content is between 48% and 99%, w_L is between 21% and 101%, w_P is between 28% and 172% and I_P ranged between 7% and 71% (see Table 1). The γ_{dmax} and w_{Opt} parameters were evaluated using the standard proctor test [9]. The obtained values are between 9.9% and 31.6% and between 13.4 and 20.4 kN/m^3, respectively, for w_{Opt} and γ_{dmax}.

Table 1. Statistical parameters of used soils.

	w_L (%)	w_P (%)	I_P (%)	w_{Opt} (%)	γ_{dmax} (kN/m^3)
Minimum	21	28	7	9.9	13.4
Maximum	101	172	71	31.6	20.4
Mean value	44.9	71.0	26.4	18.5	16.9

2.2. Method Used

The approach used is described in Figure 1. The first step, to establish the equations for the estimation of the maximum dry unit weight and the optimum water content, was to evaluate the correlation between the different used parameters. In this evaluation, w_L, w_P, I_P, γ_{dmax}, w_{Opt} and fine-grained content were selected. The XLSTAT [20] was used to establish a matrix correlation between the different selected parameters. The used formula for the correlation calculation is presented in Equation (1):

$$r = \frac{\sum_{i=1}^{n}(xi - xm)^2(yi - ym)^2}{\left(\sum_{i=1}^{n}(xi - xm)^2\right)^{\frac{1}{2}}\left(\sum_{i=1}^{n}(yi - ym)^{2)/2}\right)^{1/2}} \quad (1)$$

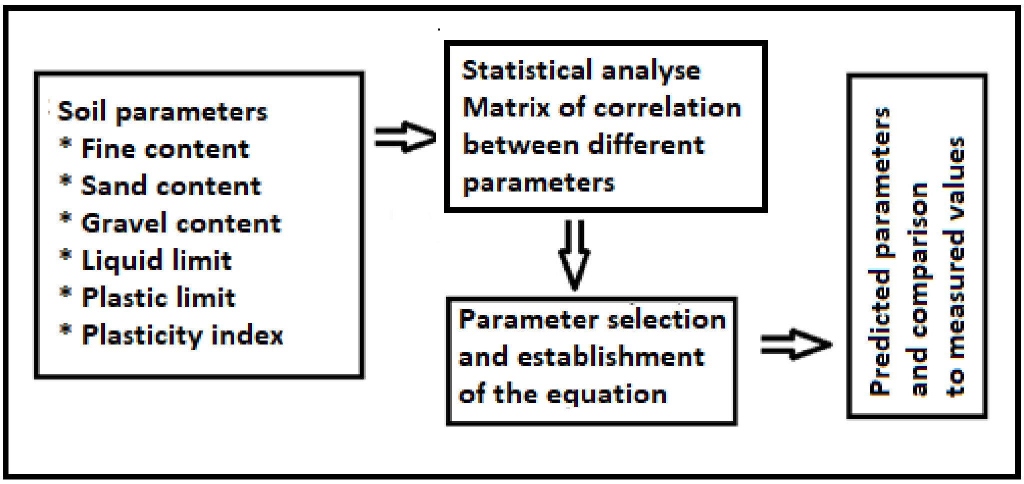

Figure 1. Steps to determine the proposed equation used in the prediction of the γ_{dmax} and w_{Opt}.

In Equation (1), xm is the mean value of the x_i variable values and ym is the mean value of the yi variable values.

A value of r greater than about 0.56 usually indicates a strong correlation between two parameters.

After the evaluation of the parameter's correlations, the Lab Fit Software [21] was used to establish the mathematical equations that best relate the various parameters (based on the considerations described above). To simplify the formulations, the number of correlated parameters was limited to two and this selection was based on the higher correlation between the selected parameters.

An identical approach, with correlation analyses, was used by [22–29] to establish links between analyzed parameters.

3. Investigation Results

The correlation between the different parameters was performed using the XLSTAT software [20] and results of this investigation are presented in Table 2. This last table shows that w_{Opt} is correlated positively to w_L, w_P, I_P and w_{Opt} and negatively to γ_{dmax}. The γ_{dmax} is correlated negatively to all the other parameters (see Table 2).

Table 2. Correlation matrix between different parameters.

	w_L	w_P	I_P	w_{Opt}	γ_{dmax}	Fines Content
w_L	1					
w_P	0.957	1				
I_P	0.804	0.942	1			
w_{Opt}	0.833	0.802	0.678	1		
γ_{dmax}	−0.803	−0.782	−0.673	−0.961	1	
Fines content	0.54	0.490	0.385	0.594	−0.550	1

The highest values in the correlation matrix were used as the starting point to investigate relationships between pairs of parameters. The results obtained suggest that γ_{dmax} and w_{Opt} can be estimated from w_L, w_P, I_P and fine-grained content due to their higher correlation (see Table 2). In the following, the number of retained parameters used to establish the mathematical correlations with γ_{dmax} and w_{Opt} was limited to two (to facilitate the application of the correlations). These parameters correspond to w_L, and w_P due to their higher correlation with γ_{dmax} and w_{Opt} (see Table 2).

The Lab Fit software [29] was used to establish the mathematical equations that best relate the various parameters (based on the considerations described above). The equations obtained can be expressed as follows:

$$\gamma_{dmax} = \mathrm{A}\,(w_L w_P)^{\mathrm{B}} \tag{2}$$

$$w_{Opt} = \frac{w_L}{\mathrm{A} + \mathrm{B} * w_P} \tag{3}$$

The values of the parameters A and B and their uncertainties are presented in Table 3.

Table 3. Parameters A and B and their uncertainties (Parameters A and B correspond respectively to the first and second constant in Equations (2)–(4)).

	Parameter A	SD of A	Parameter B	SD of B
γ_{dmax} (w_L, w_P)	0.4237×10^{2}	0.3285×10^{1}	-0.1159×10^{0}	0.9958×10^{-2}
w_{Opt} (w_L, w_P)	0.1733×10^{1}	0.13256×10^{0}	0.9085×10^{-2}	0.1622×10^{-2}
w_{Opt} (γ_{dmax})	0.8605×10^{3}	0.7594×10^{2}	-0.3264×10^{2}	0.4530×10^{1}

For the different comparison between measured and estimated values for each parameter, r is calculated using Equation (1).

A comparison between measured values and estimated values using Equations (2) and (3) are presented in Figures 2 and 3, respectively, for γ_{dmax} and w_{Opt}. It is important to note that for the presented figures, confidence intervals of 95% are also presented.

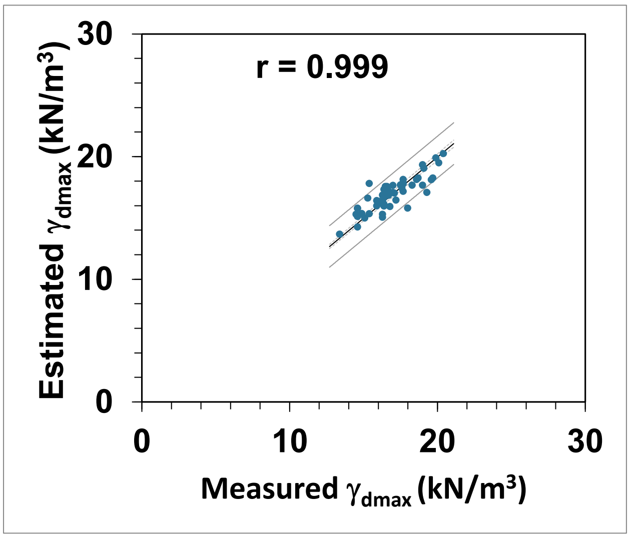

Figure 2. Correlation between measured and estimated γ_{dmax} using data from [19].

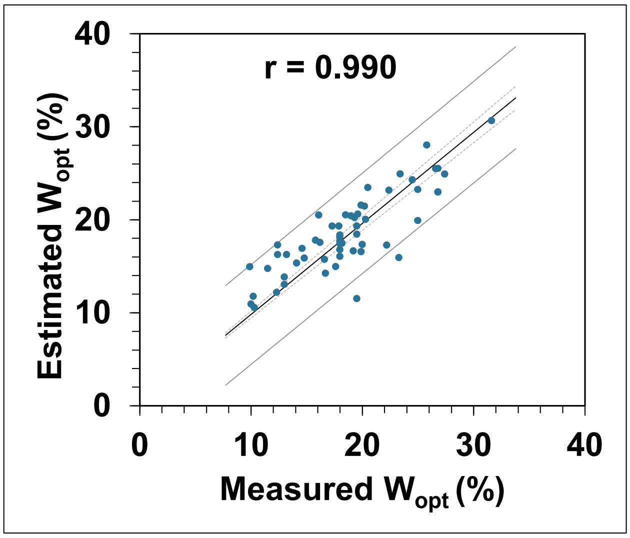

Figure 3. Correlation between measured and estimated w_{opt} data from [19].

For γ_{dmax}, one can observe that the correlation between measured and estimated values is very high, and the obtained r is about 0.999, confirming that this parameter can be estimated with high accuracy.

For w_{Opt}, one can observe that the correlation between measured and estimated values is in the same range as the one obtained for γ_{dmax}. The obtained r is about 0.990 and can be considered as an excellent correlation.

Based on the matrix of correlation (see Table 2), where one can observe that the correlation between γ_{dmax} and w_{Opt} is very high (r = −0.96), a new equation was proposed to estimate w_{opt} by using only estimated γ_{dmax}. The proposed tool for the estimation of the w_{Opt} is given in Equation (4) and the values of parameters A and B are presented in Table 3.

$$w_{Opt} = \frac{A}{\gamma_{dmax}} + B \tag{4}$$

For this new estimation of w_{Opt} by using the estimated γ_{dmax} from Equation (2), one can observe that the correlation between measured and estimated values is very high and the obtained r is about 0.990 (Figure 4). This r is similar to the one obtained by using w_L

and w_p. This higher correlation confirms that this parameter can be estimated with high accuracy only by using the estimated γ_{dmax}.

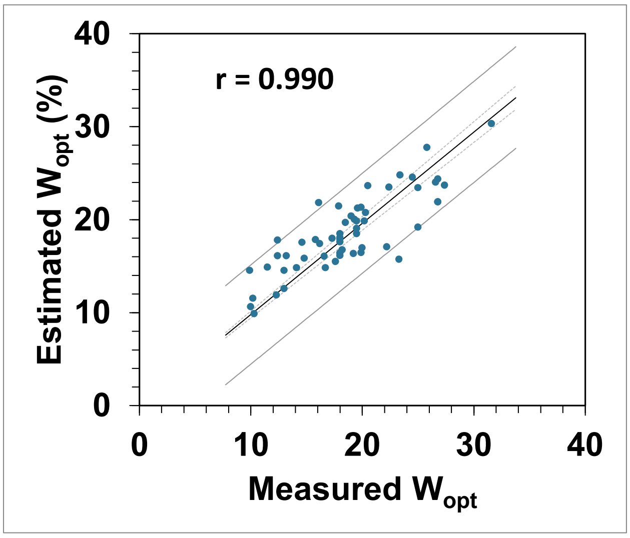

Figure 4. Correlation between measured and estimated w_{opt} using estimated γ_{dmax} with data from [19].

4. Discussion

To complete the evaluation of the proposed equations to estimate w_{Opt} and γ_{dmax}, other data taken from the literature published by [30] were used. These data were not used to build the proposed mathematical equations (Equations (2)–(4)).

For these data, w_L is between 28 and 74%, w_p is between 12 and 39%, I_P varies between 12 and 46%, w_{opt} ranges between 13 and 40% and γ_{dmax} varies between 11.3 and 18.8 kN/m^3 (see Table 4).

Table 4. Statistical parameters of soils taken from [30].

	w_L (%)	w_P (%)	I_P (%)	w_{Opt} (%)	γ_{dmax} (kN/m^3)
Minimum	28	12	12	13	11.3
Maximum	74	39	46	40	18.8
Mean value	46.4	22.0	24.4	20.6	16.3

In addition, the estimated parameters by the proposed equations were compared to those estimated by [30] where Equation (5) and (6) were used. It is important to note that these data (Table 4) were used to build the Equations (5) and (6). Consequently, the correlation between measured and estimated values will be higher.

$$w_{Opt} = 0.94 * w_P \quad (5)$$

$$\gamma_{dmax} = 0.22 * (96.32 - wp) \quad (6)$$

Comparison results are presented in Figures 5 and 6, respectively, for γ_{dmax} and w_{Opt}.

These figures show that the values of r obtained from using the proposed equations by the author (0.998 and 0.984, respectively, for γ_{dmax} and w_{Opt}) are similar to those obtained from the equation proposed by [30] (0.999 and 0.989, respectively, for γ_{dmax} and w_{Opt}).

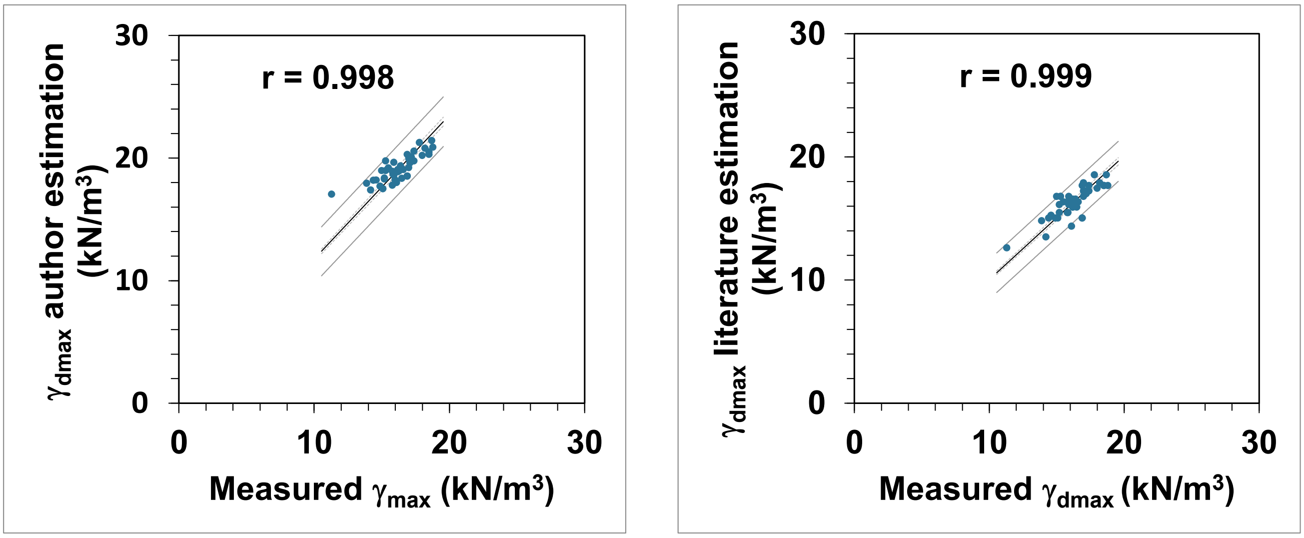

Figure 5. Correlation between measured literature data [30] and estimated γ_{dmax} using the literature estimation [30] and author equations.

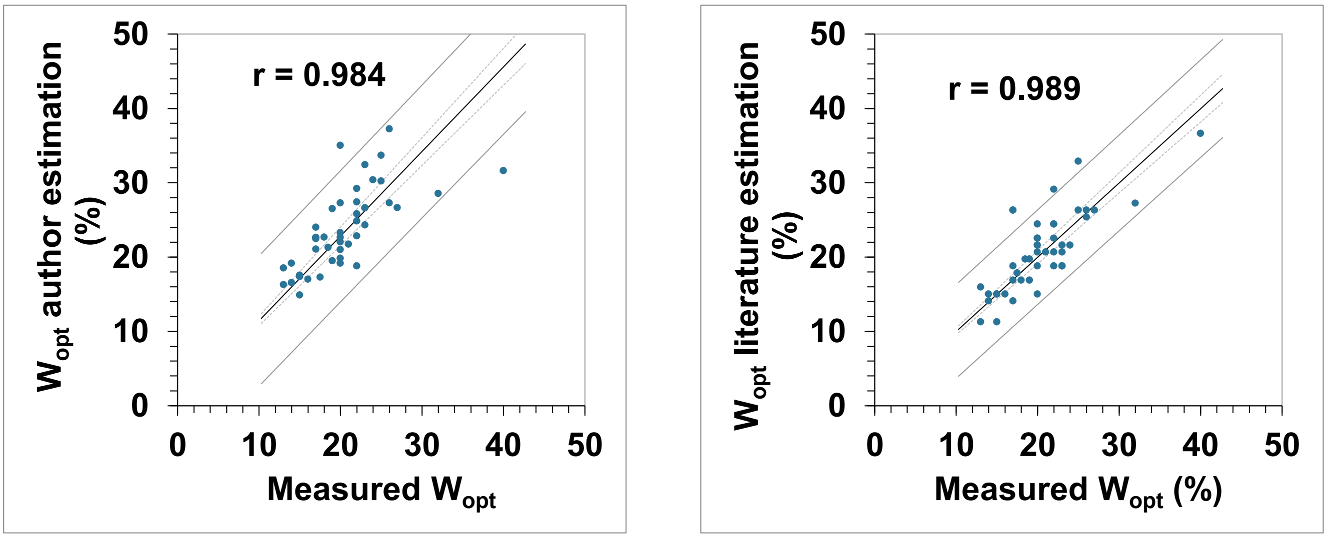

Figure 6. Correlation between measured data from [30] and estimated w_{Opt} using the literature estimation [30] and author equations.

These results confirm the ability of the proposed equations to estimate adequately the compaction optimum point parameters for different soils, where *Ip* is between 7% and 71%.

5. Conclusions

Clay material can be used as a hydraulic barrier in mine site reclamation. These barriers allow limiting water infiltration to reactive tailings. Consequently, the oxidation of sulfide minerals is limited, and the acid mine drainage production is inhibited. The performance of these hydraulic barriers is mainly related to material properties and to compactive effort and molding water content during cover construction. These cover materials must be compacted to the pre-determined dry unit weight that corresponds usually to a certain percentage of the maximum dry unit weight (γ_{dmax}).

During the prefeasibility stage of a cover construction, γ_{dmax} and w_{Opt} can be estimated to obtain an early overview of the conditions that can be anticipated.

The proposed equations in this paper were defined to provide a simple means to estimate parameters of the optimum compacted point using the liquid limit and the plastic limit. The comparison between estimated and measured values shows that the proposed equations lead to good estimation of the maximum dry unit weight and the optimum water content. The proposed equation for the estimation of the compacted optimum parameters would be particularly convenient at the first stage of a project when little information is available.

More work is presently underway to estimate compaction point parameters for other materials with very high plasticity and to estimate the liquid limit and the plastic limit using grain-size parameters.

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