Compaction Control Criteria for Clay Hydraulic Barriers

MAJDI A. OTHMAN AND SCOTT M. LUETTICH

Compacted clays are commonly used as hydraulic barriers. In the construction of a clay hydraulic barrier it is important to use a water content–dry unit weight criterion that results in low hydraulic conductivity. Recently several compaction criteria have been proposed for the construction of soil hydraulic barriers. Discrepancies exist, however, in the acceptable water content–dry unit weight zones defined by these criteria. Three of these criteria are reviewed and compared. The advantages and disadvantages of each criterion are discussed with emphasis on efficiency, effectiveness, and practicality of use during construction. An evaluation is presented that suggests that a criterion based on achieving a minimum initial degree of saturation (i.e., the leftmost boundary of the water content–dry unit weight zone is a contour of constant degree of saturation) has desirable attributes and has several advantages over the other approaches. Laboratory and field data on compaction and hydraulic conductivity of several clay soils are examined to evaluate the validity of the degree-of-saturation approach. The data show that this approach provides good control over the quality of compacted clays in the field and is more accommodating to natural variations in soil composition and compaction characteristics than are the other approaches. A case history is presented that illustrates the degree-of-saturation compaction criterion.

Compacted clays are commonly used as hydraulic barriers. Examples include the cores of earth dams, liners and covers of landfills, and liners of surface impoundments. Because the main purpose of a hydraulic barrier is to minimize flow, its hydraulic conductivity is of paramount importance.

Traditionally clay hydraulic barriers have been compacted in the field to achieve a minimum dry unit weight within a specified range of water content (typically wetter than the optimum water content). This approach has been criticized because it is unnecessarily restrictive and does not ensure low hydraulic conductivity (*1,2*). This approach is based primarily on achieving a minimum dry unit weight for adequate strength and limited compressibility instead of achieving a low hydraulic conductivity. Therefore the traditional compaction criterion is not considered acceptable for construction of hydraulic barriers and thus is not addressed further in this paper. For the clay hydraulic barrier to perform well, it must have a low hydraulic conductivity. Therefore a compaction criterion that is primarily based on hydraulic conductivity should be used for its construction.

Recently new criteria for the compaction of clay hydraulic barriers have been proposed that require defining a water content–dry unit weight zone that corresponds to the required hydraulic conductivity. Discrepancies exist, however, in the approaches proposed to determine the acceptable water content–dry unit weight zone. Three of these approaches are reviewed and compared in this paper. The advantages and disadvantages of each criterion are discussed with emphasis on efficiency, effectiveness, and practicality of use during construction. It should be noted that these criteria are based on hydraulic conductivity only. Other considerations such as shear strength and resistance to desiccation or freeze-thaw also need to be considered as part of the compaction criteria, but are not addressed in detail in this paper.

The first criterion defines the water content–dry unit weight zone corresponding to the required hydraulic conductivity graphically from laboratory compaction data for a range of compactive effort. The second criterion is based on the line of optimums, which identifies the leftmost boundary of the acceptable water content–dry unit weight zone. In the third criterion, the leftmost boundary of the zone is a contour of constant degree of saturation.

Background information on the effects of compaction variables on the hydraulic conductivity of soils is summarized. The three modern criteria described previously are presented and discussed, and an evaluation of these criteria is presented that suggests that the degree-of-saturation approach has desirable attributes and has several advantages over the other approaches.

Laboratory and field data on compaction and hydraulic conductivity of many clays are examined to evaluate the validity of the degree-of-saturation approach. The data show that this approach provides good control over the quality of compacted clays in the field, and is more accommodating to natural variations in soil composition and compaction characteristics than are the other approaches. A case history that illustrates the degree-of-saturation compaction criterion is presented.

COMPACTION VARIABLES AND HYDRAULIC CONDUCTIVITY

Factors affecting the hydraulic conductivity of compacted clays have been studied extensively (*3–7*). All studies have shown that molding water content and compactive effort have the greatest effect on hydraulic conductivity. Typical relationships among water content, compactive effort, dry unit weight, and hydraulic conductivity are shown in Figure 1 (*4*). Figure 1(*b*) shows that the dry unit weight of the soil reaches a maximum value at an "optimum water content" for a certain compactive effort. The line connecting the optimum water content points on compaction curves for various compaction efforts is commonly referred to as the "line of optimums." This line is usually almost parallel to the line of full saturation (i.e., the zero air void line).

The hydraulic conductivity of the soil decreases with the increase of water content or compactive effort, as shown in Figure 1 (*a*). For water contents dry of optimum, the hydraulic conductivity is large and it decreases sharply as water content approaches optimum water content. When the soil is wetter than optimum, the hydraulic con-

---

GeoSyntec Consultants, 5775 Peachtree Dunwoody Road, Suite 200F, Atlanta, Ga. 30342.

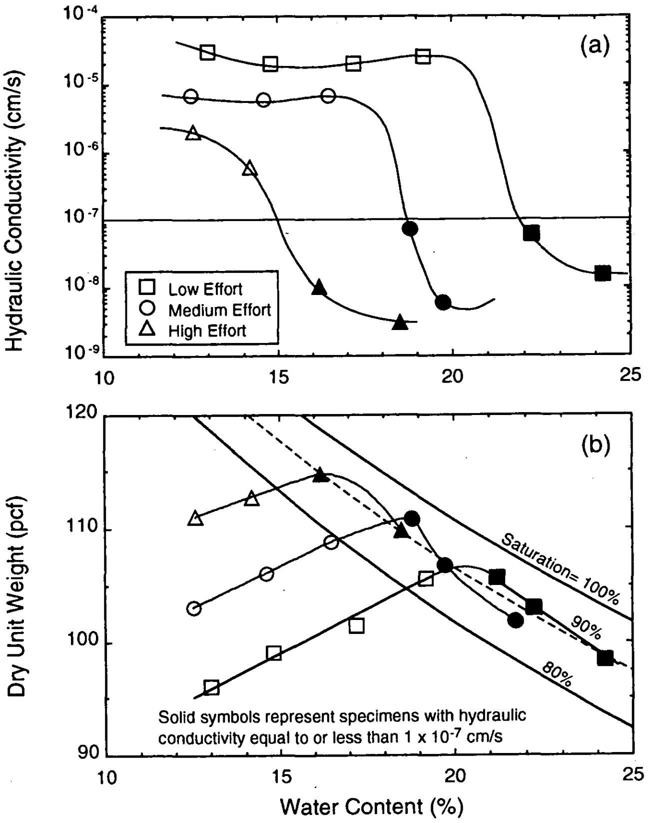

FIGURE 1 Data from Mitchell et al. (*4*) for silty clay soil: (*a*) hydraulic conductivity versus molding water content; (*b*) dry unit weight versus molding water content (1 pcf = 0.157 kN/m³).

ductivity is low. The hydraulic conductivity also decreases significantly with the increase in the compactive effort.

The cause of the change in hydraulic conductivity from high to low with dry to wet-of-optimum water content and with the increase of compactive effort is due to the change in the pore size distribution. On the dry side of optimum water content, the clay aggregates have higher strength and thus are more resistant to deformation during compaction. As a result, the clay has a heterogeneous network of macroscopic pore and hence high hydraulic conductivity (*5,7,8*). On the wet side of optimum, the clay aggregates deform easily during compaction, which results in a dense, relatively homogeneous mass with a very fine pore size (*7,9,10*). The fine (perhaps microscopic) pore size limits the conduction of fluid.

To further demonstrate the effects of compaction variables on hydraulic conductivity, all data points in Figure 1 corresponding to an arbitrarily selected maximum hydraulic conductivity of 1×10^{-7} cm/sec have been represented by solid symbols (a design hydraulic conductivity of 1×10^{-7} cm/sec is typical for hydraulic barriers and therefore is used throughout this paper). As shown in Figure 1 (*b*), these data points plot in a narrow zone that extends almost parallel to the line of full saturation (i.e., zero air void line) and the line of optimums. The leftmost boundary of the zone coincides with the 83 percent degree-of-saturation contour line. Therefore for this particular soil, to achieve a maximum hydraulic conductivity of 1×10^{-7} cm/sec, the soil must be compacted to an initial degree of saturation in excess of 83 percent.

Throughout the paper, reference is made to degree of saturation. This is the initial (i.e., as compacted) degree of saturation and not the degree of saturation of the soil during or after permeation.

MODERN COMPACTION CONTROL CRITERIA

Graphical Approach

Daniel and Benson (*1*) proposed a graphical approach for determining the acceptable water content–dry unit weight zone. This approach is illustrated in Figure 2 for the data of Mitchell et al. (*4*). The approach consists of the following steps:

1. Specimens are compacted using three broad compactive efforts that are representative of efforts used in construction. Approximately five to six different specimens are compacted with each effort.
2. The compacted specimens are permeated to determine their hydraulic conductivity. The compaction curves and water content–hydraulic conductivity curves are plotted as shown in Figure 2.
3. Different symbols are used to distinguish between specimens with hydraulic conductivity greater than the maximum acceptable value and specimens with hydraulic conductivity less than or equal to the maximum acceptable value. In Figure 2, the maximum acceptable hydraulic conductivity is arbitrarily shown as 1×10^{-7} cm/sec.

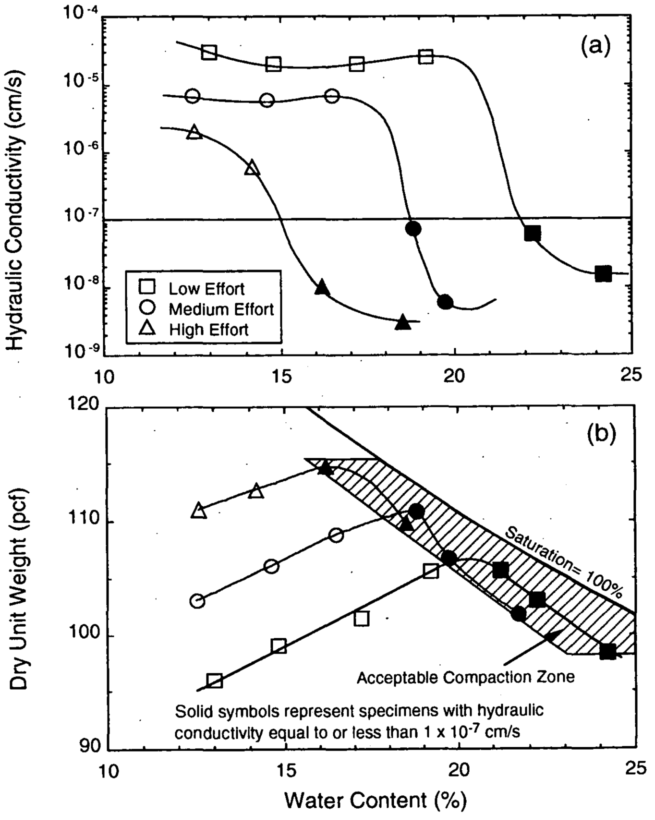

FIGURE 2 Graphical approach illustrated for data of Mitchell et al. (*4*): (*a*) hydraulic conductivity versus molding water content; (*b*) dry unit weight versus molding water content showing acceptable compaction zone (1 pcf = 0.157 kN/m³).

4. The "acceptable" water content–dry unit weight zone is drawn to encompass the data points representing specimens with hydraulic conductivity equal to or less than the maximum acceptable hydraulic conductivity.
5. Although not addressed in this paper, Daniel and Benson (*1*) do make provisions to limit the acceptable zone to account for other considerations such as shear strength, shrinkage, swelling, and desiccation or settlement cracking.

This approach is clearly superior to the traditional approach because it is based primarily on hydraulic conductivity. This criterion can be used effectively in the construction of hydraulic barriers with low hydraulic conductivity as long as the soil used to construct the hydraulic barrier does not exhibit significant variability in compaction characteristics. It is the experience of the authors and several researchers (*11,12*), however, that in many cases the compaction characteristics of soil from the same borrow source may vary considerably because of slight changes in sand or gravel contents.

In these cases construction quality assurance technicians in the field find that the water content—dry unit weight relationship (i.e., the compaction curve) shifts during the course of construction, even when soil from one borrow source is used. Therefore the previously established acceptable water content–dry unit weight zone may not be valid for all soils excavated from the same borrow area. A new acceptable zone must be established for each soil excavated. Establishing a new zone can be expensive and may delay construction.

Problems can also arise from the inability to detect variations in the soils used to construct the hydraulic barrier in cases where testing frequencies are inadequate and soil variations are not visually recognized. In these cases using the established criterion may be restrictive or may not ensure low hydraulic conductivity. Even if all soils from the borrow area to be used in the construction of the hydraulic barrier were identified and an acceptable zone were defined for each one of them, having several compaction zones may be confusing to the technician in the field. The technician must be able to identify new soils excavated with certainty to determine which of the acceptable compaction zones should be used for its construction.

Line-of-Optimums Approach

Mundell and Bailey (*13*) and Benson and Boutwell (*2*) proposed criteria that are based primarily on compacting the soil wet of the line of optimums. On the wet side of optimum the soil has lower shear strength and thus the clods are easier to remold. This results in a dense, relatively homogeneous mass with a very fine pore size and thus low hydraulic conductivity (*7,9,10*). On the dry side of optimum the clods are harder and thus are typically more difficult to remold. Therefore soil compacted on the dry side of optimum contains larger pores, and as a result the hydraulic conductivity is higher.

In many cases, however, the maximum allowable hydraulic conductivity can still be achieved if the soil is compacted on the dry side of optimum. Figure 3 shows the acceptable water content–dry unit weight zone based on the line-of-optimums approach for the data of Mitchell et al. (*4*). The solid symbols represent soil specimens with hydraulic conductivity less than or equal to 1×10^{-7} cm/sec. As shown in Figure 3, four of the eight specimens that have hydraulic conductivity less than or equal to 1×10^{-7} cm/sec plot outside the acceptable zone based on the line-of-optimums approach. Other laboratory and field data presented in this paper also suggest that, depending on the type of clay, low hydraulic conductivity can be achieved by compaction on the dry side of the line of optimums.

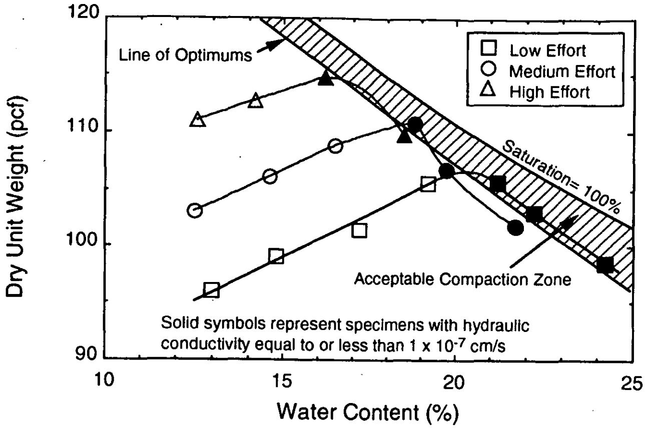

FIGURE 3 Line-of-optimums approach illustrated for data of Mitchell et al. (*4*) (1 pcf = 0.157 kN/m³).

Therefore the line-of-optimums approach may be restrictive in some cases. It is especially restrictive when considerations other than achieving low hydraulic conductivity, such as adequate shear strength or resistance to desiccation or freeze-thaw cracking, are also significant. For example, a soil liner placed on a steep slope may need to be compacted as dry as possible, while still achieving the required hydraulic conductivity, in order to gain the necessary shear strength for its stability. Similarly, recent research has shown that compacting the soil as dry as possible increases its resistance to desiccation and freeze-thaw damage (*14,15*).

Degree-of-Saturation Approach

As discussed earlier, the hydraulic conductivity of a compacted soil decreases with increasing degree of saturation. The degree of saturation combines the effects of water content and dry unit weight in one parameter. As the molding water content and dry unit weight are increased, so is the degree of saturation, and thus hydraulic conductivity decreases. An examination of Figure 1 suggests that degree of saturation can be used as a criterion for the compaction of clay hydraulic barriers. For the data shown in Figure 1, to achieve a hydraulic conductivity equal to or less than 1×10^{-7} cm/sec, the soil must be compacted to a minimum degree of saturation of 83 percent.

Several researchers found strong correlations between hydraulic conductivity and degree of saturation for specimens obtained from compacted clay liners. Boutwell and Hedges (*16*) performed regression analyses on hydraulic conductivity data for Shelby tube specimens taken from liners from several sites. They found the logarithm of hydraulic conductivity to be inversely proportional to the degree of saturation to the third power. Similarly, Benson et al. (*17*) collected and analyzed data from more than 50 sites to identify variables with the greatest effect on hydraulic conductivity. They also found the hydraulic conductivity to decrease with the increase of degree of saturation. They found that at degrees of saturation greater than 90 percent, nearly all specimens had hydraulic conductivities of less than 1×10^{-7} cm/sec.

Lahti et al. (*18*) performed laboratory and field hydraulic conductivity tests on a liner constructed using low-plasticity clay till at the Keele Valley Landfill at Maple, Ontario. The liner was required to achieve a hydraulic conductivity of 1 × 10^{-8} cm/sec. The soil was compacted at water contents 2 to 3 percent wetter than optimum water content and to a dry unit weight greater than 95 percent of the maximum dry unit weight based on the standard Proctor (ASTM D698) compactive effort. Laboratory tests performed on Shelby tube specimens obtained from the liner showed a geometric mean hydraulic conductivity of 8 × 10^{-9} cm/sec. Field hydraulic conductivity tests consisted of six 15-m × 15-m lysimeters. The geometric mean hydraulic conductivity calculated from flow rates in the lysimeters was 9 × 10^{-9} cm/sec. Lahti et al. (*18*) concluded that to achieve the acceptable hydraulic conductivity of 1 × 10^{-8} cm/sec, the clay till must be compacted at water contents greater than the optimum water content based on the standard Proctor compactive effort and to a degree of saturation of 95 percent or more.

On the basis of the findings of these researchers and others, it appears that the degree-of-saturation approach can be used to control and predict hydraulic conductivity of compacted clay barriers. The degree-of-saturation approach has several desirable practical characteristics. First, with this approach one parameter—degree of saturation—replaces the two parameters used in the other approaches—water content and dry unit weight.

The second advantage of this approach is that it is numerical. The technician in the field can easily and accurately determine whether the soil passes or fails the compaction criteria by comparing the actual degree of saturation to the minimum required degree of saturation. Nuclear moisture/density gauges, which are commonly used to measure water content and dry unit weight in the field, can also be programmed by manufacturers to calculate and display degree of saturation.

The third advantage of this approach is that the minimum degree of saturation required to achieve the maximum design hydraulic conductivity is not sensitive to natural variations in soil composition. A small change in sand or gravel content has little effect on saturation–hydraulic conductivity relationships as long as the sand and gravel fractions are not dominant (*11*). Therefore, unlike the graphical approach, where variability in soil compaction characteristics may require defining multiple acceptance zones, with the degree-of-saturation approach, one criterion can be used for soils with only small variations in composition.

LABORATORY DATA

Compaction and hydraulic conductivity data from several laboratory studies have been analyzed to establish a relationship between hydraulic conductivity and degree of saturation. Table 1 summarizes the properties of the soils used in these studies and shows that the soils vary in composition and compaction characteristics.

Figures 4 through 6 show the compaction and hydraulic conductivity–water content relationships for Wisconsin soils A, B, and C studied by Othman and Benson (*19*). These relationships are similar to those shown in Figure 1 and are typical of clays. The solid symbols in the figures represent specimens with hydraulic conductivity equal to or less than 1 × 10^{-7} cm/sec. As shown in Figures 4 (*b*), 5 (*b*), and 6 (*b*), these data points plot generally parallel to the line of full saturation.

The effect of degree of saturation on hydraulic conductivity of the Wisconsin soils is shown in Figure 7. The two lines shown in Figure 7 encompass the data points and assist in showing the trend exhibited by the data. Although the three clays are significantly different in composition and compaction characteristics, they demon-

TABLE 1 Characteristics of Soils Used in Laboratory Studies and Soil Specimens from Liners of Several Landfills

Reference	Soil	USCS Classification	LL(%)[a]	PI(%)[a]	P_{200}(%)[b]	5μm Clay Fraction (%)	Optimum Water Content[c] (%)	Maximum Dry Unit Weight (pcf)[c]
				Laboratory Studies				
19	Wisconsin A	CL	34	16	85	58	16.0	114.5
	Wisconsin B	CL	42	19	99	77	18.5	107.0
	Wisconsin C	CH	84	60	71	58	26.0	93.5
20	Wisconsin A	CL	36	19	88	61	15.0	116.0
1	Type A	-	55	27	-	-	29.0	92.0
	Type B	-	34	18	-	-	17.0	109.0
4	Silty Clay	CL	37	14	-	-	-	-
				Field Soil Specimens				
	1	CL	45	24	82	42	18.8	106.6
	2	CL	35	12	57	-	14.3	116.8
	3	CH	63	42	96	53	20.5	103.9
	4	ML	37	12	64	33	-	-
	5	GC	26	8	16	5	-	-
	6	SC	32	10	14	5	-	-
	7	SW-SM	30	7	10	3	-	-

[a] LL = Liquid Limit; PI = Plasticity Index

[b] Percent Passing No. 200 Sieve (0.075 mm)

[c] Standard Proctor (ASTM D698), 1 pcf = 0.157 kN/m^3

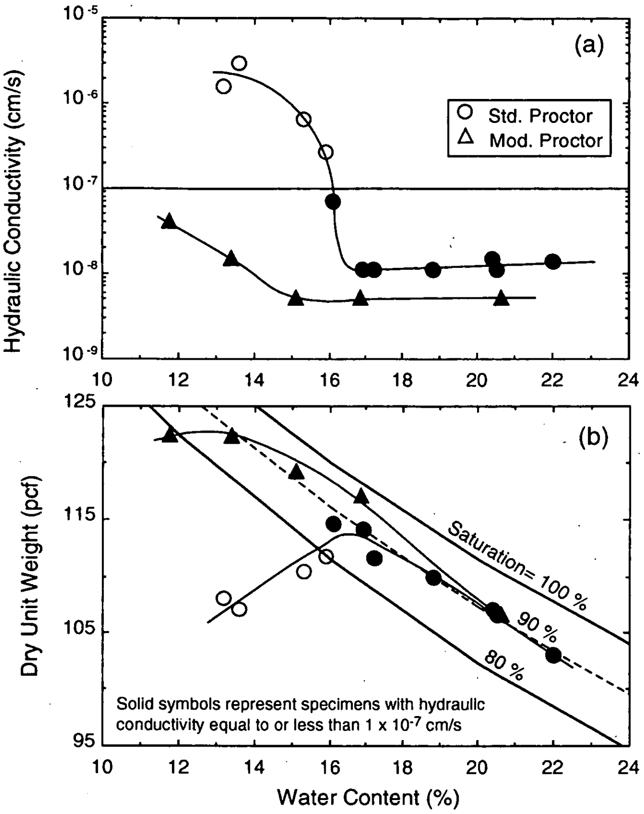

FIGURE 4 **Data from Othman and Benson (*19*) for Wisconsin soil A: (*a*) hydraulic conductivity versus molding water content; (*b*) dry unit weight versus molding water content (1 pcf = 0.157 kN/m³).**

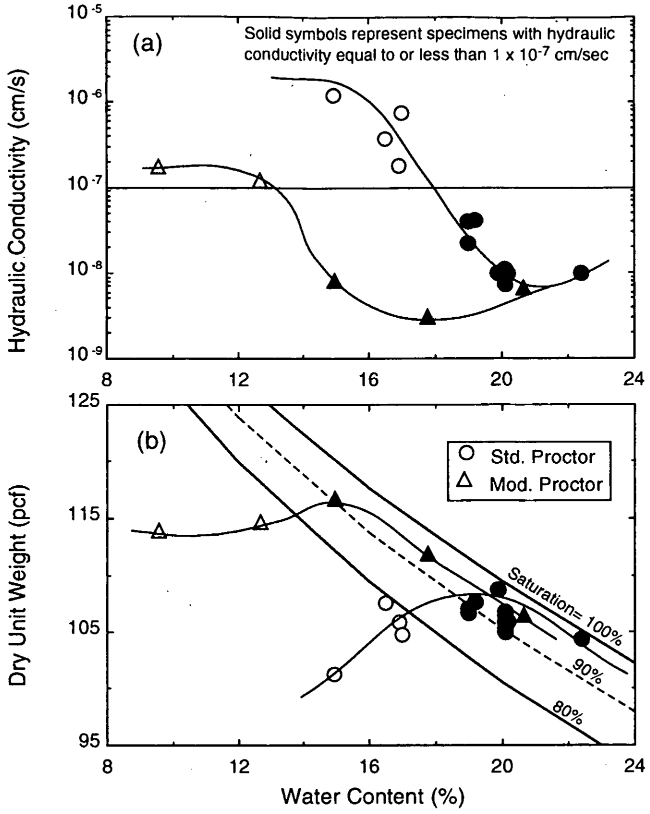

FIGURE 5 **Data from Othman and Benson (*19*) for Wisconsin soil B: (*a*) hydraulic conductivity versus molding water content; (*b*) dry unit weight versus molding water content (1 pcf = 0.157 kN/m³).**

strate almost the same relationship between hydraulic conductivity and degree of saturation. As the degree of saturation increases, hydraulic conductivity decreases. For the three clays, maximum hydraulic conductivities of 1×10^{-6}, 1×10^{-7}, and 1×10^{-8} cm/sec are achieved at degrees of saturation of approximately 77, 88, and 100 percent, respectively. Therefore, to ensure that the hydraulic conductivity of any of these soils is less than 1×10^{-7} cm/sec, for example, the soil must be compacted to a degree of saturation greater than 88 percent.

Figure 8 (*a*) shows the relationship between hydraulic conductivity and degree of saturation for data from laboratory studies on all the soils listed in Table 1. As shown, some variability exists in the data; however, a trend of decreasing hydraulic conductivity with increasing degree of saturation is evident.

FIELD DATA

Hydraulic conductivity tests were conducted on specimens obtained from compacted clay liners at several sites, and the data were collected and analyzed to evaluate the degree-of-saturation approach and to confirm findings based on the laboratory data. Table 1 summarizes the properties of the soils used at the different sites and shows that the soils vary in composition and compaction characteristics.

Figure 8(*b*) shows the relationship between degree of saturation and hydraulic conductivity for all of the field and laboratory specimens. Laboratory and field data show similar degree of saturation–hydraulic conductivity relationships. There is a clear trend in Figure 8 (*b*) of decreasing hydraulic conductivity with increasing degree of saturation.

CASE HISTORY

A test fill program was performed for a landfill in the western United States to fulfill permit conditions that require that a compacted clay liner test fill be constructed before secure cell construction. In accordance with Environmental Protection Agency (EPA) guidance documents, construction of the test fill was performed using the same soil, equipment, and procedures that will be used to construct the compacted clay components of the secure cell liner system. The EPA guidance documents also required that the hydraulic conductivity of the test fill be evaluated using field testing techniques.

The test fill program consisted of the following steps:

1. A preconstruction laboratory testing program was performed to quantify index properties of the soil and to establish an acceptable compaction zone (ACZ) on the basis of laboratory hydraulic conductivity tests conducted on laboratory-compacted (i.e., remolded) specimens.
2. A construction-phase laboratory testing program was conducted to confirm index properties of the soil and to evaluate the ACZ on the basis of laboratory hydraulic conductivity tests conducted on samples obtained from the test fill.

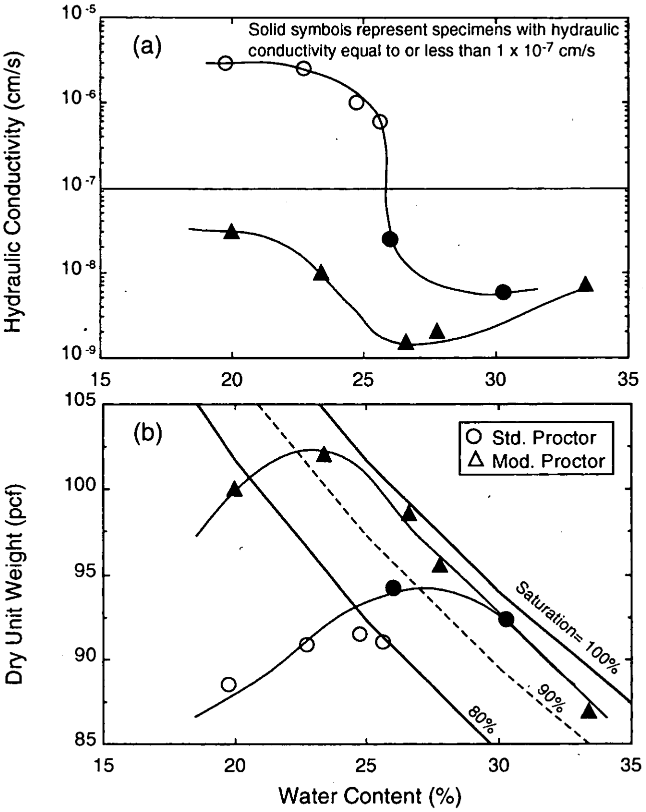

FIGURE 6 Data from work by Othman and Benson (*19*) for Wisconsin soil C: (*a*) hydraulic conductivity versus molding water content; (*b*) dry unit weight versus molding water content (1 pcf = 0.157 kN/m³).

3. A field-scale testing program was performed to evaluate the field-measured hydraulic conductivity of a prototype compacted soil liner.

Results of the preconstruction laboratory testing program indicated that the soil is classified as a clay of high plasticity according to the Unified Soil Classification System. The composition and index properties of the soil are shown in Table 1 (Soil 3). The ACZ established during the preconstruction laboratory testing program (i.e., the "lab ACZ"), shown in Figure 9, indicates that the soil achieves a hydraulic conductivity less than 1×10^{-7} cm/sec when compacted in the laboratory to a wide range of water content–dry unit weight conditions. Preliminary boundaries were also established for the zone shown in Figure 9 to account for shrinkage and shear strength.

Results of the construction-phase laboratory testing program indicated that the ACZ determined from undisturbed field samples (i.e., the "field ACZ") is relatively similar to the lab ACZ established during the preconstruction testing program. Figure 10 shows the relationship between degree of saturation and hydraulic conductivity for the laboratory and field specimens. Clearly both sets of data can be described using the same relationship. Figure 10 indicates that a minimum degree of saturation of approximately 78 percent is required to achieve a hydraulic conductivity of less than 1×10^{-7} cm/sec.

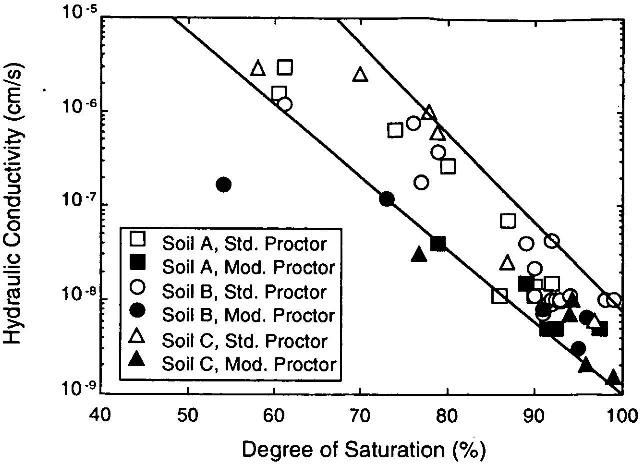

FIGURE 7 Effect of degree of saturation on hydraulic conductivity of three Wisconsin clays.

Information obtained during the preconstruction and construction laboratory testing programs was used to select a set of target compaction (i.e., water content–dry unit weight) conditions for construction of a prototype soil liner. The target conditions, shown in Figure 9, were selected to be within the field ACZ. A prototype soil liner was constructed using the clay soil and the target compaction conditions. Field testing of the hydraulic conductivity of the prototype compacted soil liner was conducted using a sealed double-ring infiltrometer (SDRI). The field-measured hydraulic conductivity of the prototype soil liner from the SDRI test was approximately 2×10^{-8} cm/sec. This value corresponded well with the hydraulic conductivity that would be predicted from both the lab and field ACZ, as shown in Figure 10.

Results of the test fill program conducted using the clay soil were used to establish an ACZ to be used during actual construction of the clay components of the liner system. The ACZ represents the compaction conditions that will yield a high probability of achieving a hydraulic conductivity during construction that is less than 1×10^{-7} cm/sec. In addition, lower-side boundaries were established for the ACZ based on minimum shear strength and workability requirements of the compacted clay component of the liner system.

From the test fill program it is concluded that the acceptable compaction zone may be most efficiently defined in terms of the minimum degree of saturation required to achieve a low hydraulic conductivity. Agreement between laboratory and field data suggests that the degree-of-saturation approach is valid and effective in predicting and controlling hydraulic conductivity of clay hydraulic barriers.

SUMMARY AND CONCLUSIONS

In this paper, criteria currently used for compacting soil hydraulic barriers are reviewed. Compaction criteria define an acceptable water content–dry unit weight zone. The paper examines three modern compaction criteria that require defining a water content–dry unit weight zone that corresponds to the maximum required hydraulic conductivity. The modern criteria reviewed are the graphical approach, the line-of-optimums approach, and the degree-of-saturation approach. The advantages and deficiencies of each approach are discussed with emphasis on efficiency, effectiveness, and practicality of use in construction. It was concluded

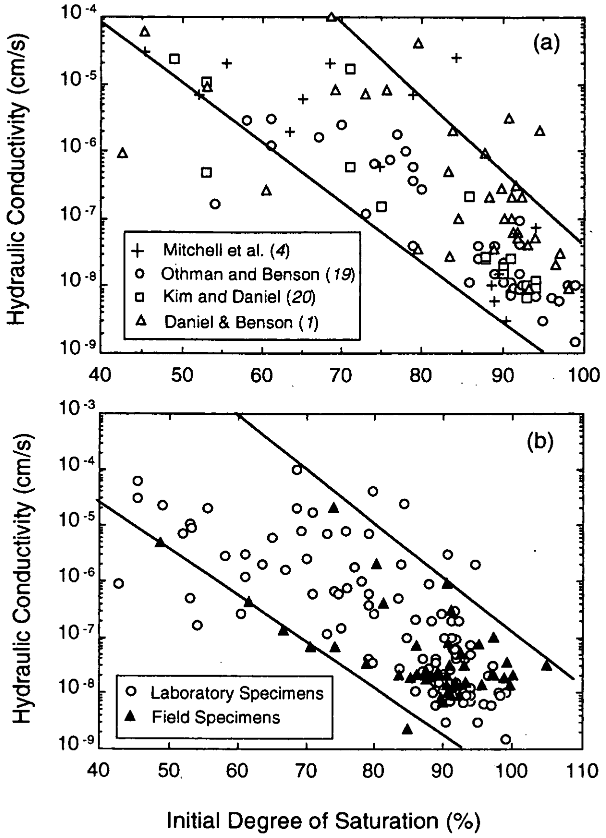

FIGURE 8 Effect of degree of saturation on hydraulic conductivity of (*a*) laboratory specimens; (*b*) laboratory and field specimens combined.

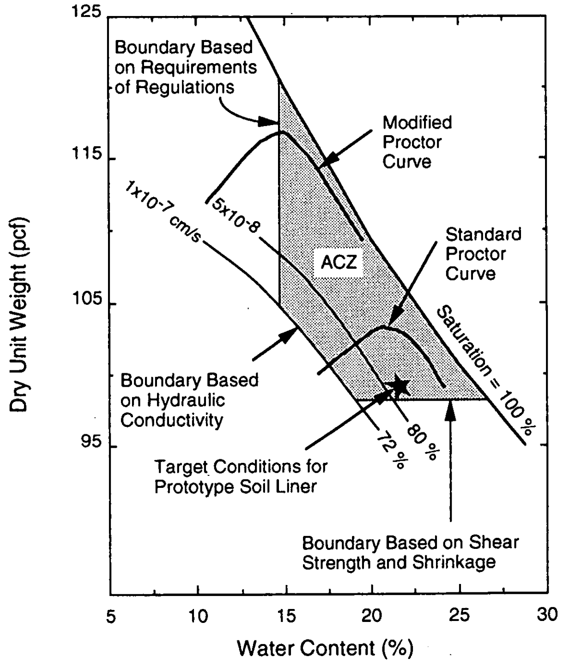

FIGURE 9 Acceptable compaction zone determined from laboratory testing program (1 pcf = 0.157 kN/m^3).

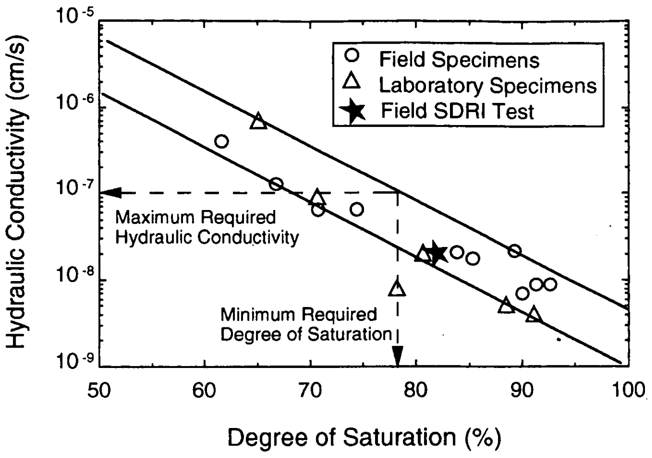

FIGURE 10 Hydraulic conductivity as a function of degree of saturation from tests on laboratory and field specimens and from a field SDRI test.

that the graphical approach may be impractical when the soils in the field exhibit significant variability in compaction characteristics. The line-of-optimums approach may be too restrictive, since the maximum required hydraulic conductivity may be achieved on the dry side of optimum.

The degree-of-saturation approach appears to have desirable attributes and has several advantages over the two other approaches. Only one parameter—the degree of saturation—is used to control and predict hydraulic conductivity. This factor, and the fact that this approach is numerical, makes construction quality control in the field easier and more efficient. Furthermore, unlike the compaction curve, the hydraulic conductivity–degree of saturation relationship is typically not sensitive to the natural variations of soil composition. Therefore, one criterion can be used for soils with small variations in composition.

Laboratory and field data on compaction and hydraulic conductivity of many soils were examined to evaluate the degree-of-saturation approach. The data show that degree of saturation can be used to accurately predict and control hydraulic conductivity. Hydraulic conductivity decreased with increasing degree of saturation for all soils examined. This result is consistent with the findings of other investigators (*16–18*). A case history that illustrates the use of the degree-of-saturation compaction criterion in the construction of a landfill liner is presented. It is concluded that degree of saturation can be used as a compaction control criterion during construction of clay hydraulic barriers.

ACKNOWLEDGMENTS

The authors thank Rudy Bonaparte for his review of the manuscript and Nader Rad for providing some of the data used in this paper. Thanks are also expressed to Karen Rich and Mitzi Jiles for their help with typing the manuscript.

REFERENCES

1. Daniel, D. E., and C. H. Benson. Water Content–Density Criteria for Compacted Soil Liners. *Journal of Geotechnical Engineering,* ASCE, Vol. 116, No. 12, 1990, pp. 1811–1830.

2. Benson, C. H., and G. P. Boutwell. Compaction Control and Scale-Dependent Hydraulic Conductivity of Clay Liners. *Proc., 15th Annual Madison Waste Conference,* Madison, Wis., 1992, pp. 62–83.
3. Lambe, T. Special Technical Publication 163: *The Permeability of Compacted Fine-Grained Soils.* ASTM, Philadelphia, Pa., 1954, pp. 56–67.
4. Mitchell, J. K., D. R. Hooper, and R. G. Campanella. Permeability of Compacted Clay. *Journal of the Soil Mechanics and Foundations Division,* ASCE, Vol. 91, No. SM4, 1965, pp. 41–65.
5. Garcia-Bengochea, I., C. W. Lovell, and A. G. Altschaeffl. Pore Distribution and Permeability of Silty Clay. *Journal of Geotechnical Engineering,* ASCE, Vol. 105, No. 7, July 1979, pp. 839–856.
6. Elsbury, B. R., D. E. Daniel, G. A. Sraders, and D. C. Anderson. Lessons Learned from Compacted Clay Liner. *Journal of Geotechnical Engineering,* ASCE, Vol. 116, No. 11, Nov. 1990, pp. 1641–1660.
7. Benson, C. H., and D. E. Daniel. Influence of Clods on Hydraulic Conductivity of Compacted Clay. *Journal of Geotechnical Engineering,* ASCE, Vol. 116, No. 8, Aug. 1990, pp. 1231–1248.
8. Lambe, T. W. Foundation Engineering. In *Soil Stabilization* (G. A. Leonards, ed.), McGraw Hill, New York, 1962, pp. 351–437.
9. Shackelford, C., and F. Javed. Large-Scale Laboratory Permeability Testing of a Compacted Clay Soil. *Geotechnical Testing Journal,* Vol. 14, No. 2, 1991, pp. 171–179.
10. Haug, M., and L. Wong. Impact of Molding Water Content on Hydraulic Conductivity of Compacted Sand-Bentonite. *Canadian Geotechnical Journal,* Vol. 29, No. 2, 1992, pp. 253–262.
11. Shelley, T. L., and D. E. David. Effect of Gravel on Hydraulic Conductivity of Compacted Soil Liners. *Journal of Geotechnical Engineering,* ASCE, Vol. 119, No. 1, Jan. 1993, pp. 54–68.
12. Houston, S. L., and K. D. Walsh. Comparison of Rock Correction Methods for Compaction of Clayey Soils. *Journal of Geotechnical Engineering,* ASCE, Vol. 119, No. 4, April 1993, pp. 763–778.
13. Mundell, J., and B. Bailey. The Design and Testing of a Compacted Clay Barrier to Limit Percolation Through Landfill Covers. In *Special Technical Publication 874: Hydraulic Barriers in Soil and Rock* (Johnson et al., eds.), ASTM, Philadelphia, 1985, pp. 246–262.
14. David, D. E., and Y.-K. Wu. Compacted Clay Liners and Covers for Arid Sites. *Journal of Geotechnical Engineering,* ASCE, Vol. 119, No. 2, Feb. 1993, pp. 223–237.
15. Bowders, J. J., and M. A. Othman. Molding Water Content and Hydraulic Conductivity of Compacted Soils Subjected to Freeze-Thaw. In *Transportation Research Record 1434,* TRB, National Research Council, Washington, D.C., 1994.
16. Boutwell, G. P., and C. Hedges. Evaluation of Waste-Retention Liners by Multivariate Statistics. *Proc., 12th International Conference on Soil Mechanics and Foundation Engineering,* Rio de Janeiro, Brazil, 1989, pp. 815–818.
17. Benson, C. H., H. Zhai, and X. Wang. Estimating Hydraulic Conductivity of Compacted Clay Liners. *Journal of Geotechnical Engineering,* ASCE, Vol. 120, No. 2, Feb. 1994, pp. 366–387.
18. Lahti, L. R., K. S. King, D. W. Reades, and A. Bacopoulos. Quality Assurance Monitoring of a Large Clay Liner. In *Geotechnical Practice for Waste Disposal '87* (R. D. Woods, ed.), American Society of Civil Engineers, New York, 1987, pp. 641–654.
19. Othman, M. A., and C. H. Benson. Effect of Freeze-Thaw on the Hydraulic Conductivity of Three Compacted Clays from Wisconsin. In *Transportation Research Record 1369,* TRB, National Research Council, Washington, D.C., 1992, pp. 118–125.
20. Kim, W.-H. and D. E. Daniel. Effects of Freezing on Hydraulic Conductivity of Compacted Clay. *Journal of Geotechnical Engineering,* ASCE, Vol. 118, No. 7, July 1992, pp. 1083–1097.

Publication of this paper sponsored by Committee on Transportation Earthworks.