The consistency of current regulations for compacted clay liners

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Abstract

The current requirements for a liner beneath any municipal, industrial or hazardous waste disposal site to be constructed in South Africa usually include at least one compacted clay layer. The required performance of these compacted clay layers is specified in terms of a maximum allowable hydraulic conductivity. This paper discusses two issues related to achieving this requirement; these are the acceptance criteria for quality control tests and the number of tests that must be carried out to ensure that a required standard of quality is achieved.

The inherent variability of the hydraulic conductivity of a clay must be accounted for when interpreting acceptance criteria. This may best be addressed by invoking the concept of an equivalent hydraulic conductivity, the definition of which requires a statistical evaluation of the field hydraulic conductivity variability. The benefit of using indirect (or surrogate) measurements of hydraulic conductivity, such as *in situ* density, may provide an acceptable method of characterising the clay's variability, provided these surrogate measurements are correlated with *in situ* hydraulic conductivity measurements.

Two techniques are discussed for deciding on the required number of quality control tests. It is shown that a statistical approach provides a quantifiable measure of the level of confidence that may be attached to a particular series of measurements, unlike conventional approaches that merely specify a required number of tests per unit area.

It is argued that the adoption and utilisation of the concepts described in this paper will lead to a more consistent and rational approach to the quality control of compacted clay liners.

Introduction

The increasing volumes of waste being produced in South Africa, both domestic and industrial, and the need to dispose of this waste in an environmentally acceptable manner has led to the development of regulations that govern the disposal by landfilling of these wastes. These guidelines have been published as the *Minimum Requirements for Waste Disposal by Landfill* (DWAF, 1994).

One of the primary concerns with regard to landfills is the perceived potential for groundwater pollution. As is the case in many other countries, the South African regulations attempt to ensure that the risk of escape of leachate from an engineered landfill is minimised by specifying a mandatory physical separation between the waste body and the groundwater regime. This inevitably requires the construction of some form of liner, (DWAF, 1994). The form of the liner depends on issues such as size and climatic location of the proposed landfill, e.g. a large urban landfill located in a water-surplus region of the country (a so-called GLB^+ landfill) requires a much more comprehensive liner than a similar landfill in a water-deficient part of the country (GLB^-). Differences in cost between the above two lining systems are typically R76/m^2 and R3.50/m^2 respectively, without bentonite addition, and R115/m^2 for GLB^+ sites if bentonite is required.

Current requirements for a landfill liner

An integral part of the lining system for a GLB^+ landfill, as stipulated in the *Minimum Requirements* document, is a compacted clay liner (CCL) that is 0.6 m thick. The document states that this layer, 'must be so constructed that it permits no more than a specified maximum rate of flow of leachate to pass through its layers'. For a GB^+ landfill this flow rate must not exceed 0.3 m/y (10^{-6} cm/s) (DWAF, 1994). This implies a performance criterion for the liner, i.e. that outflow from beneath the liner must not exceed a certain flowrate. Similarly, on the same page of the *Minimum Requirements* document it is stated that: 'Because the design will usually have to be made at a time when only laboratory test data are available, the expected outflow rate will usually have to be based on permeability coefficients measured in the laboratory on specimens constituted in the laboratory. These estimates must, however, be validated by field tests, once the liner has been constructed'. Further it states: 'To validate the design, *in situ* permeability tests using double ring infiltrometers must be carried out on every compacted soil layer that forms part of a liner'. Once again, the document requires a certain level of performance.

However, in Appendix 8.2 of the document it requires that the CCL 'must be compacted to a minimum density of 100% Proctor maximum dry density at a water content of Proctor optimum to optimum +2%'. This stipulation is clearly prescriptive, i.e. certain procedures must be followed. The quality control requirements for CCLs therefore fall somewhere between truly performance-based requirements and prescriptive requirements.

The problem of specifying acceptance criteria for clay liners

When one considers statements of required acceptance criteria for clay liners such as those above, there are two fundamental questions that need to be answered:

i) 'Is the specified (threshold) hydraulic conductivity ($K_{threshold}$) not to be exceeded under any circumstances?' Put another way, 'should a compacted soil liner be rejected outright if the $K_{threshold}$ is exceeded in any one test?'

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At first this question may appear trivial. After all, a specified acceptance limit is there to be met and any non-compliance constitutes failure. However, as discussed later, hydraulic conductivity has an extremely high inherent variability and it would be foolish to regard it as a single-valued parameter. If we accept that the $K_{threshold}$ is in fact the lowest allowable value, what we are in effect saying is that the required mean hydraulic conductivity is up to one order of magnitude lower than the specified value, as will be illustrated later in the paper. Therefore, if a regulatory authority specifies a hydraulic conductivity of 10^{-7}cm/s, what they in fact require from the relevant contractor is a liner compacted to such a quality that the mean value of hydraulic conductivity may be as low as 10^{-8}cm/s or even lower. If specified values are indeed lowest acceptable values, then the consequential implications (outlined above) at least need to be made clear to the engineering community.

ii) 'How many tests (whether they be laboratory tests or in-situ tests) need to be performed to satisfy the required specification with an acceptably low risk that this specification will not be exceeded at any point in the liner?' This question, as with the statement from the *Minimum Requirements* noted earlier, invokes concepts of statistical analysis.

The inherent variability of hydraulic conductivity and how it affects our attempts to answer the above two questions forms the focus of this paper.

Satisfying the specified (threshold) value of hydraulic conductivity

In South Africa, as in many other countries, a maximum allowable hydraulic conductivity is specified for CCLs used as liners for waste disposal facilities. In South Africa the *Minimum Requirements* document specifies hydraulic conductivities ranging from 10^{-6} cm/s to 10^{-7} cm/s and liner thicknesses of 300 mm to 1 200 mm, depending on factors such as daily rate of deposition of waste at the site and the waste classification. In the United States, a hydraulic conductivity for CCLs of 10^{-7} cm/s is required by Federal regulations (USEPA, 1988) and Donald and McBean (1994) stated that in Canada the Ministry of the Environment in Ontario specified that the hydraulic conductivity for the Keele Valley landfill in Metropolitan Toronto should not exceed 10^{-8} cm/s. It is thus not uncommon to specify a single, threshold value for the hydraulic conductivity.

Donald and McBean (1994) explored the possible interpretations of specifying a limit to hydraulic conductivity. The three possible interpretations they discussed are:

- All measured values are less than the threshold value.
- The geometric mean of the measured values is less than or equal to the threshold value.
- The equivalent hydraulic conductivity, K_E, (which is discussed later in the paper) of the measured values is less than or equal to the threshold value.

Methods of measuring hydraulic conductivity

Harrop-Williams (1985) considered four options to test the suitability of a particular soil for use in a liner. These were field permeability testing of field-compacted soils, laboratory permeability testing of undisturbed samples of field-compacted soils, laboratory permeability testing of laboratory-compacted soils, and estimating permeability from more easily measured soil properties. Option 3 has proved to be unreliable and unconservative, as discussed later. The fourth option is advantageous, as it provides a quick basis for accepting soil placement activities in the field and its possible use is discussed in more detail later. The first two options, although providing a direct measure of compacted clay permeability, slow down the rate of construction. For example, a double ring infiltrometer test on a clay liner may require three months to produce steady state results. It is, nevertheless, widely used. Wang and Benson (1995) state that the most common test being conducted to assess the saturated hydraulic conductivity of compacted clay liners and test pads at waste disposal facilities in the USA is the sealed double ring infiltrometer test. In South Africa, double ring infiltrometer tests were conducted on the bentonite-modified compacted clay liners constructed for the Waste-Tech (Pty) Ltd Chloorkop hazardous landfill site, and the Transvaal Suiker Beperk Komati Mill landfill site, amongst others. It is also, as mentioned earlier, the preferred testing method according to the *Minimum Requirements* (DWAF, 1994).

The problem posed by the inordinately long testing time required by the double ring infiltrometer may be addressed by using equipment that tests a smaller volume of soil. Examples are the Guelph permeameter (Reynolds and Elrick, 1985) and the tension infiltrometer (Dixon, 1975). Comparisons of field saturated hydraulic conductivity measured with both a double ring infiltrometer and a Guelph permeameter are given by Fourie and Strayton (1996) for six different soils. Very good correlation was obtained for all 'placed' materials, i.e. those that had been transported and placed mechanically. These were all waste materials. Poorer correlation was obtained for tests on residual soils, where in-situ fabric influenced drainage paths and thus the measured conductivity. Since this paper is concerned with CCLs, the use of equipment such as the Guelph or tension infiltrometers may be a significant improvement on current practices, at least as regards the number of tests that may be conducted in a given time period.

As discussed earlier, the *Minimum Requirements* make allowance for characterisation of the hydraulic conductivity of a liner by the use of laboratory tests on reconstituted specimens. Laboratory tests, however, only test a very small volume of soil and are less likely to include inhomogeneities such as fissures. For example, Day and Daniel (1985) determined the hydraulic conductivity of two prototype clay liners by ponding water on the liners and measuring the rate of seepage, by carrying out ring infiltration tests and by performing laboratory tests on handcarved samples removed from the liners after draining the ponds. The field measured values of the liners were 900 and 2 000 times those yielded by laboratory tests on the first and second liners respectively. Thus while laboratory tests may be useful in comparing alternative soils for use as a CCL, the absolute values are likely to be lower than achievable in the field and thus unconservative.

The inherent difficulties of measuring hydraulic conductivity must clearly be borne in mind when planning a quality control programme for construction of a CCL. It is not only the measurement of hydraulic conductivity at a particular point that may be problematical, but its variation over a given area to be tested.

The variability of hydraulic conductivity and its characterisation

Compliance with a specified threshold value of hydraulic conductivity for a CCL is complicated by the spatial variability of this parameter. For example, Fig. 1 illustrates the variability of hydraulic conductivity measured on a 10 m by 25 m test pad by Rogowski (1990). Tests on the compacted cherty clay were carried out on 1 m x 1 m cells, each one fitted with an individual underdrain. As can be seen from Fig. 1, the measured conductivity varied by three orders of magnitude. When considering appropriate field testing programmes for the measurement of hydraulic conductivity, this inherent variability must be taken into account.

A probability distribution is required to describe this spatial variability of hydraulic conductivity. A commonly used probability distribution is the two-parameter log-normal distribution (Bogardi et al. (1989)). This means that the logarithms of hydraulic conductivity are normally distributed. Benson (1993) found that several authors (Boutwell and Hedges (1989), Krapac (1989), Johnson et al. (1990)) had previously suggested that the log-normal assumption was applicable to the hydraulic conductivity of compacted soils. However, he cautioned that, "They based this conclusion on the visual similarity of a histogram of ln *K* and the shape of the normal distribution function fitted to the data, but they did not perform a goodness-of-fit test to evaluate the hypothesis of log normality. Although a visual comparison between a histogram and a density function is useful in identifying plausible distributions, it does not provide statistical evidence that a distribution adequately describes the data." In order to validate the use of the two-parameter log-normal distribution for hydraulic conductivity, Benson (1993) compared this with four alternative distributions: the three-parameter log-normal distribution, generalised extreme value, the three-parameter gamma and inverse Gaussian. Analyses of data collected from 57 landfill liners and covers throughout the United States of America were used for this purpose. Goodness-of-fit tests (using the skewness test, the kurtosis test and the probability plot correlation coefficient test) were employed to determine the validity of the possible distributions. Benson's analyses show that the three-parameter log-normal and generalised extreme value distributions resulted in superior fit to the data.

Whether a two-parameter log-normal, a three-parameter log-normal or an extreme value distribution provide the best fit to the spatial variability of conductivity is not as important as a realisation that such a variation exists, and that due cognisance is taken of this variability when specifying threshold values. A typical log-normal probability distribution of hydraulic conductivity is shown in Fig. 2. Due to the logarithmic shape of the distribution, the mean value occurs at a relatively low value of conductivity. There are values of hydraulic conductivity that are easily four times larger than the mean value. Once again this poses the question: 'what value does the threshold, required value of conductivity correspond to?' Is it the mean, the upper limit or some value of 'equivalent conductivity?'

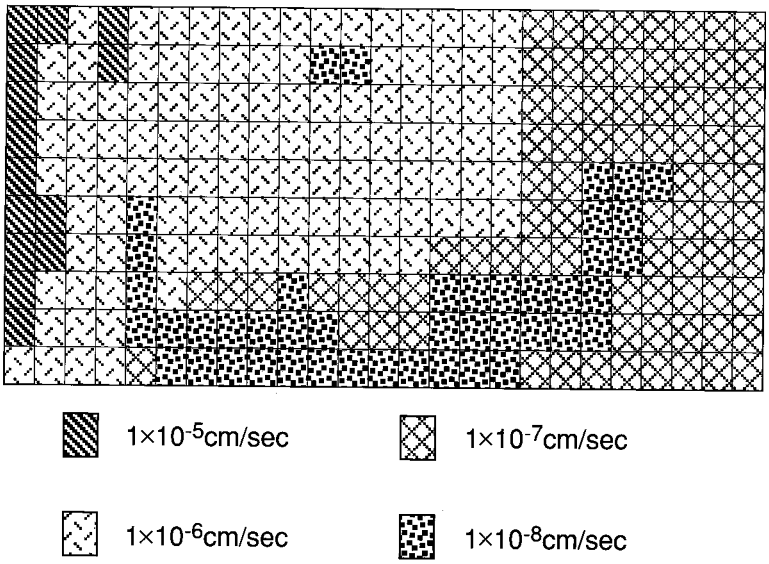

Figure 1
Hydraulic conductivities from Rogowski's (1990) test pad

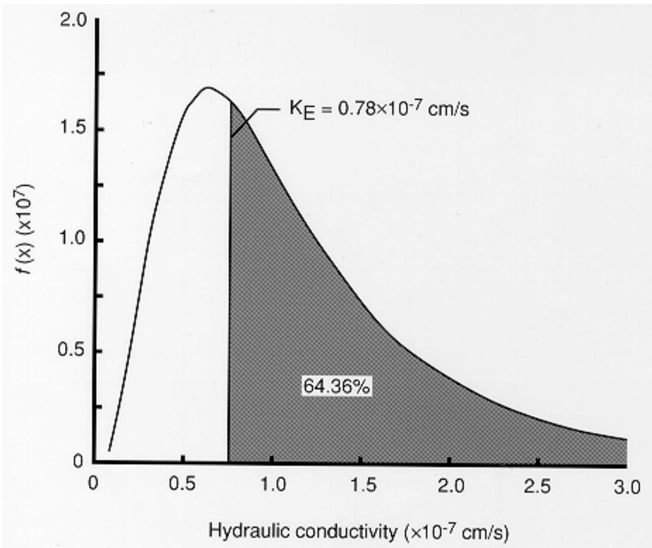

Figure 2
Illustration of the variability of hydraulic conductivity and the location of the equivalent hydraulic conductivity K_E for results reported by Donald and McBean (1994)

Definition of an equivalent hydraulic conductivity, K_E

The equivalent hydraulic conductivity (K_E) may be defined as being "that value of conductivity, such that when used to define a homogeneous clay liner, gives the same flow through it as does the statistical representation of that liner" (Donald and McBean 1994)). Alternatively, Benson et al. (1994b) define K_E as the hydraulic conductivity that is obtained by dividing the total rate of flow emanating from the base of the liner (Q) by the cross-sectional area of the liner (A) and the average hydraulic gradient (i):

$$K_E = \frac{Q_\ell}{iA_\ell} \tag{1}$$

These two definitions are essentially the same. Of interest is the location of the K_E in Fig. 2 (which is for the particular case of the Keele Valley landfill in Toronto, Canada (Donald and McBean, 1994)). Should K_E perhaps be the target threshold value for a CCL?

Benson et al. (1994b) obtained an expression for K_E by simulation using a modified version of the computer program MODFLOW, with the liner discretised into layers and cells.

Random fields of hydraulic conductivity were generated using the Monte Carlo method. For each field of point-scale hydraulic conductivity simulated, MODFLOW was used to compute flow rates emanating from cells at the base of the liner. The flow rates were summed to obtain Q from the base of the liner, and K_E was computed using Eq. (1). The geometric mean of the estimated K_E values was computed to define K_E for specified mean μ_y, and variance σ_y^2 and number of lifts, i.e.:

$$K_E = \exp\left\{\frac{\sum_{i=1}^{N_r} \ln(K_{E,i})}{N_r}\right\} \tag{2}$$

where:

N_r is the number of realisations

$K_{E,i}$ is the ith realisation of K_E.

A sensitivity analysis by the authors revealed that 350 realisations were sufficient to obtain a stable estimate of K_E with small standard error.

Donald and McBean (1994) developed a method for determining K_E of the clay liner by comparing the flux of leachate through a homogeneous representation of the clay with the flux obtained by Monte Carlo analyses. The Monte Carlo method repeatedly solves the steady state flow equation using numerical methods for different realisations of the stochastic process and equates the mean of the output performance measure to the single value obtained from a deterministic run with the equivalent hydraulic conductivity. Alternatively, analytical methods may be used in the place of the Monte Carlo approach, which solve directly the steady state equation as a stochastic partial differential equation in which the hydraulic conductivity is regarded as a random variable.

In Fig. 2, the location of the equivalent hydraulic conductivity determined by Donald and McBean (1994) using this method is shown relative to the input statistical distribution of the clay liner (i.e. it is only directly applicable to the particular liner configuration studied, the Keele Valley landfill liner). Nevertheless, it illustrates some important concepts. Integrating the curve between K_E and infinity reveals that approximately 64% of the distribution lies above K_E. The authors note that the K_E value calculated is less than the geometric mean K_G. Considering the required threshold for the hydraulic conductivity of a landfill liner, this finding illustrates that provided that no more than 64% of the liner samples examined have a hydraulic conductivity greater than or equal to the specification value, the liner may be assumed to be acceptable. This is substantially more lenient than the hypothetical case, discussed in the introductory section, where even a single field test yielding a conductivity above the threshold value may be sufficient to warrant rejection of a CCL (or part thereof). However, this assumption is only valid if the clay liner being considered has been sampled completely, which is not realistic. This focuses attention on the issue of sample size and the calculation of confidence limits, and the effect on the calculated K_E. This topic is dealt with in more detail later.

Surrogate approach

Harrop-Williams (1985) identified the problem of time constraints imposed by *in situ* permeability testing, which makes it highly impractical for clay liner construction monitoring. Spatial variability of permeability also requires that many tests be made to adequately assess the performance of the clay liner. The determination of compaction characteristics, such as water content and dry density, can be made immediately and *in situ*, allowing for almost immediate acceptance of a clay liner section when using an equation relating these parameters to hydraulic conductivity. These regression equations may be determined using laboratory data from hydraulic conductivity and compaction tests, although the limitations of laboratory tests remain a concern. Methods developed by Wang and Huang (1984) and Harrop-Williams (1985) may be used for this purpose.

Wang and Huang (1984) developed correlation equations relating permeability, maximum dry density and optimum moisture content with classification properties of the soil. These equations were developed from the results of classification, compaction and permeability tests, as well as statistical analyses of blends of bentonite, limestone dust, sand and gravel. Three sets of correlation equations were developed, for permeability, maximum dry density and optimum moisture content, using two different prediction models for each set of equations. From a comparison with test data obtained, Wang and Huang (1984) conclude that predictions of hydraulic conductivity within the 95% confidence interval can be obtained from the models developed.

Bogardi et al. (1989) note that soil liner reliability could be based on other performance parameters, such as the travel time of pollutants through the liner. The objective of the reliability analysis is to provide that event $K_{actual} < K_{threshold}$ with reasonable confidence for the design life of the liner. Bogardi et al. (1989) make the common assumption that hydraulic conductivity is described by a two-parameter log-normal probability distribution. The methodology presented by the authors relates hydraulic conductivity to soil moisture at compaction, and to compacted dry density only, so that the method must be adjusted should the liner be subject to other adverse conditions, such as desiccation cracking.

The problem of choosing the surrogate parameters that best correlate with hydraulic conductivity has been discussed by Majeski and Shackelford (1997). They evaluated the correlation between laboratory hydraulic conductivity and three different methods of interpreting results from water content - dry unit weight compaction tests for 13 clay soils. They found best correlation was achieved with the 'line of optimums' approach (LOA). This approach is based on finding the dividing line between water contents wet of optimum and those dry of optimum, regardless of the compactive effort. A minimum of three compaction curves for three sufficiently different compactive efforts were recommended in order to reasonably establish this dividing line. The area between this line (joining the optimum points on each compaction curve) and the zero air voids curve is then regarded as the acceptable region for compacted water content - dry density values in the CCL.

Benson et al. (1994b) describe a hydraulic-conductivity-based method which comprises three steps. The first step estimates the statistics describing the variability of point-scale hydraulic conductivity from material properties, using a regression equation. Secondly, K_E was computed for a three-dimensional multi-lift liner from the statistics that describe spatial variability of point-scale hydraulic conductivity.

A function F was used to relate statistics characterising spatial variability of the point-scale hydraulic conductivities measured to the K_E of a liner. This step is subject to uncertainty as K_E can only be estimated from the data collected. The third step of the method is to estimate the precision of K_E and determine the number of samples corresponding to an acceptable risk of exces-

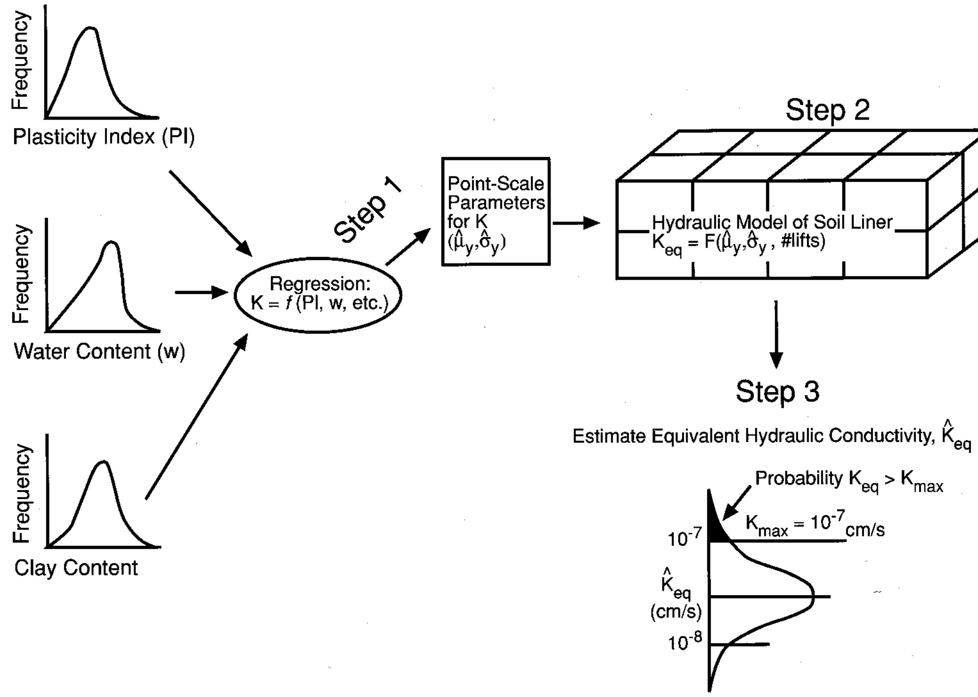

Figure 3
Illustration of Benson et al.'s (1994b) methodology for selecting sampling frequencies

sive hydraulic conductivity.

The methodology presented by Benson et al. (1994b) is illustrated in Fig. 3. To use this method, an equation linking point-scale hydraulic conductivity (K) and construction quality-control measurements is required. The authors assume that the equation has the form:

$$\ln K = Y = \boldsymbol{X}\beta + \varepsilon \quad (3)$$

where:

- Y is a random variable describing the spatial distribution of ln K
- **X** is a vector containing m random variables that describe the spatial distribution of m quality-control measurements related to hydraulic conductivity
- β is a vector of coefficients
- ε is an independent mean-zero Gaussian random error term with variance σ^2.

This relationship may be obtained by regression, for which models have been developed by Wang and Huang (1984), Bogardi et al. (1989; 1990) and Benson et al. (1994a).

The mean (μ_y) and the variance (σ_y^2) of ln *K* can be related to the control data by applying the expectation (E) and variance (var) operators to Eq. (3), i.e.:

$$\mu_y = E(Y) = E(\ln K) = E(\boldsymbol{X})\beta + E(\varepsilon) = \mu_x\beta \quad (4)$$

and

$$\sigma_y^2 = var(Y) = var(\ln K) = var(\boldsymbol{X}.\beta) + var(\varepsilon) = \beta^T \boldsymbol{V}_x \beta + \sigma_\varepsilon^2 \quad (5)$$

where:

- μ_x is the mean vector for X
- V_x is the covariance matrix for X
- σ_ε^2 is the residual variance obtained from regression
- T denotes transpose

If ε and $\mathbf{X}_i.\beta$ in Eq. (3) are independent and normally distributed, then the distribution of K is lognormal with parameters μ_y and σ^2_y. The authors note that the form of Eqs. (3) to (5) also suggests that the mean and the variance logarithm of hydraulic conductivity are estimated from soft measurements, ("hard" measurements refer to direct hydraulic conductivity measurements, while "soft" measurements refer to the measurement of other soil properties that can be correlated to hydraulic conductivity, such as water content, dry unit weight and plasticity index).

The parameters μ_y and σ^2_y are estimated from measurements made during construction. This measurement collection is assumed to contain n sets of m random variables performed at n randomly selected locations in the liner. The authors note that measuring each parameter at each sample point is not practical although it is consistent with the methodology.

The collection of measurements, written as $\mathbf{X}^n = (\mathbf{X}_i$, i = 1, 2, 3, ..., n), is used to estimate μ_y and σ_y^2 via the maximum-likelihood method:

$$\mu_y = \frac{1}{n}\sum_{i=1}^{n} \boldsymbol{X}_i \beta \quad (6)$$

and

$$\sigma_y^2 = \frac{1}{n}\sum_{i=1}^{n} (\boldsymbol{X}_i \beta - \mu)^2 + \sigma_\varepsilon^2 \quad (7)$$

where:

$\mathbf{X}_i$ is the product of the vector of quality-control measurements made at the ith sampling location.

The estimators μ_y and σ_y^2 are uncertain because they are functions of a finite number of random quality control measurements. Consequently, an estimate of K_E based on μ_y and σ_y^2 is also uncertain. However, Benson et al. (1994b) have shown that μ_y and σ_y^2 are asymptotically distributed as normal $(\mu_y, \beta^T V_x \beta)$ and normal $[\sigma^2_y, 2(\beta^T V_x \beta)^2]$. The authors use these properties to determine the asymptotic distribution for K_E and the probability $K_E > K_{threshold}$.

How many tests should be carried out?

In the context under discussion, the term 'sample size' refers to the number of tests carried out as part of the quality control programme, be they field or laboratory tests, hydraulic conductivity or representative surrogate tests.

The sample size depends on the properties of the soil, its spatial variability, and the number of lifts in the liner. Several different approaches can be used to select sample size. Regardless of the method used, the objective of sample size selection is the achievement of a specified level of quality with an acceptably low risk that this objective will not be achieved. Benson et al. (1994b) note that the sample size is selected to ensure that sufficient data are collected so that the probability that excessive K_E is greater than or equal to a predefined maximum value is below the specified $K_{threshold}$ value.

Sample-density method

The sample-density method is commonly included in environmental legislation overseas, as it is easily applied and verified (Benson et al., 1994b). The sample-density method defines the sample size as a fixed number of tests per unit area of compacted clay. For example, US EPA (1988) gives that the Wisconsin Department of Natural Resources recommends testing undisturbed permeability once per acre (~ 4 047 m^2) per lift. This approach is also recommended by Daniel and Koerner (1995). The method is therefore easily applied, both by regulatory bodies and site supervisory staff, but does not necessarily correspond to an acceptably low risk of inferior quality. For example, Benson et al. (1994b) argue that the same sample frequency is used for liners constructed with soils having different compositions, or liners having different frequencies, although both factors influence the hydraulic conductivity of a liner (and its variability). Given that the hydraulic conductivity governs the quality of a liner, the sample size should change when conditions which may result in higher conductivity (or higher variability) are found to exist. This method can therefore be viewed as largely inadequate in the acceptance testing of compacted clay liners, as it may result in a too small or too great sample size, and does not necessarily correspond to an acceptably low risk of inferior quality.

Statistical methods

Benson et al. (1994b) describe two precision-of-estimator methods used in the quality control of construction of waste containment systems as the error-of-sampling and the sequential-sampling methods. The objective of these two methods is "to specify the sample size such that an estimate of the parameter of interest (e.g. dry unit weight) will reside within certain bounds or differ from the true value by an acceptable amount with a specified probability." The number of samples selected therefore depends on the precision required.

The difference between the error-of-sampling method and the sequential-sampling method is that the sample size for the former is computed before sampling begins, while the sample size determined by the latter is adjusted based on the data collected. Benson et al. (1994b) point out that sequential sampling therefore takes into account any conditions encountered while sampling, and tends to minimise the amount of sampling required in regions of high or low quality.

The key difference between precision-of-estimator and sample-density methods is that the former only requires that, regardless of volume, the sample size be large enough that the estimate is made with an acceptable precision, while the latter provides a specific number of samples per volume. It is therefore implied in the precision-of-estimator methods that the liner be statistically homogeneous, i.e. that the properties exhibit spatial variability, but do not exhibit trends in their statistical properties. If trends do exist, as may occur due to changes in the source of clay being used or to a variation in construction methods used, then the method must be applied independently to the differing sections of liner.

The precision-of-estimator methods are therefore preferable to the sample-density method, because the sample size selected ensures an acceptable level of precision.

Benson et al. (1994b) recommend that the sample size is estimated such that the estimator of the average hydraulic conductivity is sufficiently precise to ensure that the probability of exceeding the specified hydraulic conductivity is below a specified value. What still requires clarification is what constitutes an 'acceptable probability'. This should be decided by the relevant regulatory authority.

Benson et al. (1994b) developed a detailed procedure for selecting the sampling size for quality-control measurements (e.g. particle size distribution and compaction conditions achieved) to be made during construction of CCLs. These quality-control measurements have to be statistically linked to hydraulic conductivity, (using either existing empirical correlations or site-specific measurements made on a test pad). The method accounts for the properties of the soil being tested, the $K_{threshold}$ and the number of lifts in the liner. As outlined before, the method consists of three distinct steps:

- Using a regression method to relate spatial variability of common construction quality control measurements to the spatial variability of point-scale measurements of hydraulic conductivity.
- Estimation of the K_E of the liner using available point-scale measurements of hydraulic conductivity (once again, as in Benson et al. (1994a), these measurements may be made on a test pad).
- Computation of the estimation error for K_E and the associated probability that K_E exceeds a predefined maximum.

Certain assumptions were necessary in the formulation of this method (e.g. that the simulation model used to obtain the relationship between parameters describing spatial variability of point-scale hydraulic conductivity and K_E is representative of conditions in the field). The assumptions are not restrictive and the method appears to provide a rational approach to selection of sampling size.

Although their formulation is based on a complex statistical formulation, the authors developed a series of charts that facilitate the selection of an appropriate sampling size based on a knowledge of the variability of the quality-control data, the estimated K_E of the liner and the acceptable probability of exceeding the maximum permissible hydraulic conductivity.

To illustrate the implications of the above approach, consider the case of a liner with a K_E of 0.8 x 10^{-7}cm/s that has an estimation error of 2 (which is typical of results reported in the literature and represents a relatively low level of variability). The threshold (required) conductivity value is 10^{-7} cm/s. If the regulatory authority required that the probability of K_E being greater than or equal to the threshold value not exceed 10% ($P(K_E \geq K_{threshold}) \leq 0.1$), then using Benson et al.'s (1994b) charts, n ≈ 65, i.e. each of the quality control parameters included in the initial regression formulation should be measured at 65 randomly located and uncorrelated points on the liner. This is clearly an undesirably large number of tests to be carried out and can be reduced by changing the level of required performance. If, for example, the allowable probability of exceedance was raised to 20%, the required number of tests decreases to 30, (on the other hand, if extremely tight tolerances were specified, e.g. ($P(K_E \geq K_{threshold}) \leq 0.01$), the required number of sampling points increases to 215).

Alternatively, if the required $K_{threshold}$ were increased to the point where ($K_E / K_{threshold}) \leq 0.4$, the required number of sampling points to ensure an allowable probability of exceedance of not more than 10%, drops to only 4 points. This only requires increasing the threshold conductivity to 2 x 10^{-7} cm/s, yet reduces the required *in situ* testing by more than one order of magnitude. This simple example illustrates clearly the need for regulators to be flexible and reasonable when specifying performance criteria such as *in situ* quality-control tests.

An added advantage of the method described by Benson et al. (1994) is that the required number of testing points may be adjusted during construction of the liner. The results of quality control tests may be used to re-calculate the estimation error of the parameters used as quality control variables and thus the required number of tests, n. It should be noted that this number may increase or decrease, depending on the degree of variability of the *in situ* tests.

An apparent anomaly of this method is that it appears to require that the same number of tests be carried out irrespective of the surface area of the CCL, e.g. the same number of tests would be required for a 0.1 ha site as a 10 ha site. This implication is, however, not strictly correct. The larger the volume of clay to be compacted, the larger the borrow area that must be sourced to provide the required quantity of clay. This in turn inevitably results in a greater variability of the clay used in construction of the CCL and thus influences the (statistically) required number of tests to ensure that a certain degree of quality is attained. In certain cases the variation in clay quality from within a large borrow area may be so significant that it is necessary to have separately identified 'sub-borrow areas', each of which is characterised separately. Sections of the total CCL that are derived from each of these separate areas will each have to be tested using the statistically derived number of sampling points. In effect it would be almost as though two (or more) separate CCLs were under construction, requiring two (or more) separate quality control programmes.

Donald and McBean (1994) consider the issue of sample size in terms of calculating the confidence bounds on the K_E using their method discussed earlier in this paper. The authors describe the role of the regulatory agency which has set the design threshold for the hydraulic conductivity, as including determining whether a sufficient number of samples have been obtained to be certain at some level of confidence, α, that K_E is less than or equal to $K_{threshold}$. For the base site conditions adopted in their study (the Keele Valley landfill), the K_E of the clay liner is approximately the 36th percentile of the input hydraulic conductivity distribution, i.e. $K_E = x_{0.36}$. Therefore the number of samples needs to be determined such that the upper confidence limit of the 36th percentile is less than or equal to $K_{threshold}$.

Calculating the confidence limits on the 50th percentile is straightforward. However, finding confidence limits on a percentile other than the mean is more complicated. Donald and McBean (1994) use a method developed by Yevjevich (1972) to calculate the confidence limits of a proportion. Although the authors state that this method is approximate, it is valid for percentiles close to the mean and for small sample sizes.

The confidence bounds representing the upper and lower limits of each percentile were calculated by Donald and McBean (1994). The authors assumed that $\bar{x}$ and s are normally distributed, where $\bar{x}$ and s are calculated from the logarithms of the hydraulic conductivity data:

$$\bar{x} = \frac{1}{n} \sum_{i=1}^{n} logK_i \tag{8}$$

$$s = \sqrt{\frac{\sum (K_i - \bar{x})^2}{n-1}} \tag{9}$$

where the limits of $\bar{x}$, as $\bar{x}_{upper}$ and $\bar{x}_{lower}$, and of s, as s_{upper} and s_{lower} for a given probability level can be determined. By plotting the values of $\bar{x}_{upper}$ and $\bar{x}_{lower}$ at the 50th percentile, and by drawing through them lines with slopes corresponding to s_{upper} and s_{ower} so that all four lines diverge from the straight line fitted to the measured data (line 1 in Fig. 4), the upper and lower confidence limit lines are obtained.

These lines are indicated in Fig. 4, and are obtained as follows: line (2) by using $\bar{x}_{upper}$ and s_{upper}, line (3) by using $\bar{x}_{upper}$ and s_{lower}, line (4) by using $\bar{x}_{lower}$ and s_{upper}, and line (5) by using $\bar{x}_{lower}$ and s_{lower}, where $\bar{x}_{upper}$, $\bar{x}_{lower}$, s_{upper} and s_{lower} are calculated as follows:

$$\bar{x}_{upper} = \bar{x} + \frac{t.s}{\sqrt{n}}$$

$$\bar{x}_{lower} = \bar{x} - \frac{t.s}{\sqrt{n}}$$

$$s_{upper} = s + \frac{t.s}{\sqrt{2n}}$$

$$s_{lower} = s - \frac{t.s}{\sqrt{2n}}$$

where:

t is the student t-value associated with the desired confidence limit, α, and

n-1 are the degrees of freedom.

In the study by Donald and McBean (1994), the authors found that the K_E of the placed liner was less than the threshold set with a level of confidence of 95%.

From the above method adopted by Donald and McBean (1994), the number of additional samples required can be determined, if the K_E achieved is not below the threshold set with an acceptable confidence limit. From Fig. 4, the upper confidence limit is defined by line (3), which was created using $\bar{x}_{upper}$ and s_{lower}, for percentiles less than 50%. In mathematical terms:

$$UL(x_p) = \bar{x}_{upper} - k.s_{lower}$$

where k is the number of standard deviations x_p is from the mean value.

The above equation can be rewritten as:

$$UL(x_p) = \left\{\bar{x} + \frac{t.s}{\sqrt{n}}\right\} - k\left\{s - \frac{t.s}{\sqrt{2n}}\right\}$$

Substituting in the $K_{threshold}$ for the $UL(x_p)$ gives:

$$\left\{\bar{x} + \frac{t.s}{\sqrt{n}}\right\} - k\left\{s - \frac{t.s}{\sqrt{2n}}\right\} \leq \ln (K_{threshold})$$

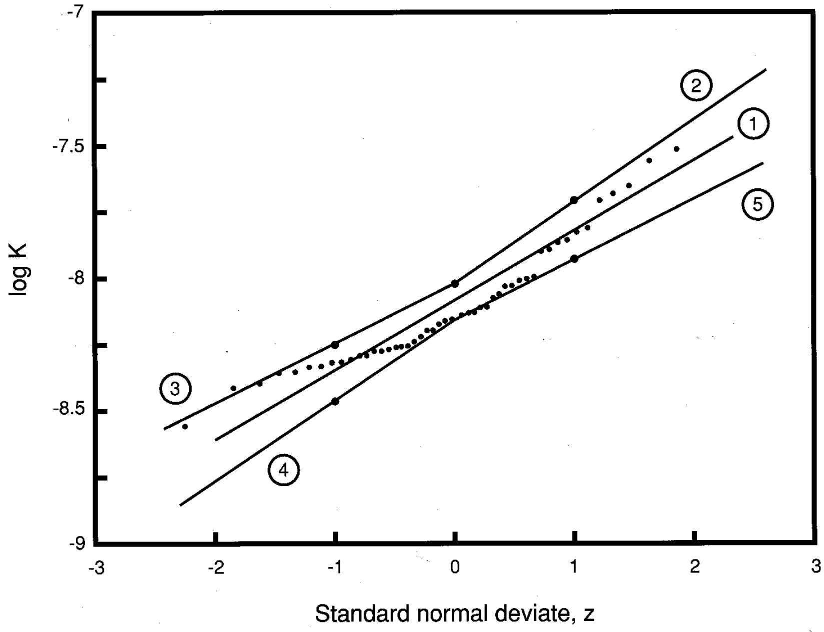

Figure 4
90% confidence bounds on equivalent hydraulic conductivity for data reported by Donald and McBean (1994)

This equation can be solved using iteration for n, assuming s, $K_{threshold}$, and an appropriate confidence level is known. This could be used to determine the sample size prior to any sampling being undertaken, but the results would be an estimate only, due to the assumptions necessary for s, $K_{threshold}$, and an appropriate confidence level.

Donald and McBean (1994) note that if trial sections of the liner are constructed and tested, the results could be used to determine an estimate of the sample size required prior to testing of the full-scale liner.

Although the *Minimum Requirements* document in South Africa does not specify the required number of *in situ* hydraulic conductivity tests, it does specify that at least four density tests be conducted per 3 000 m^2 of any compacted 150 mm thick layer. The quality control requirements are therefore based on the sample density method but specify surrogate testing. Whilst this approach implicitly acknowledges the inherent variability of hydraulic conductivity, it does not necessarily correspond to an acceptable risk that the liner is not of inferior quality.

Illustration of a statistical approach to quality control of a CCL

Some of the concepts discussed in this paper may be better appreciated by reference to a particular example. The example chosen is that of the Chloorkop waste disposal site that was constructed near Midrand, Gauteng, in 1993 (Boswell, 1996).

The Chloorkop waste disposal facility was developed as a hazardous waste disposal site. Accordingly, a substantial base liner was designed and installed. This consisted primarily of a number of layers (150 to 200 mm thick) of compacted clayey residual granite. Some of these layers included the addition of 5% sodium bentonite. Full details of the liner design are given by Boswell et al. (1994).

The target $K_{threshold}$ was 10^{-7} cm/s. The quality control programme included measurements of *in situ* density, moisture content and bentonite content (in treated layers). In addition, double-ring infiltrometer tests were carried out on certain of the layers. According to Mabula (1996), two double-ring infiltrometer tests per layer were carried out on the liner in cell number 1, which had a surface area of approximately 1.25 ha. A total of 3 tests should have been carried out to satisfy the USEPA sample-density specification of 2.5 tests/ha (one per acre). The difference is insignificant. Or is it? Assuming the resulting K_E of the Chloorkop liner was 2 x 10^{-8}cm/s (which is not unreasonable remembering that for a log-normal distribution, 64% of the conductivity values may be greater than K_E), then using Benson et al.'s (1994b) charts with an estimation error of 2 (as before), the probability that $K_E > K_{threshold}$ is about 12% if two tests were conducted. However, if the usual norm of 3 tests had been carried out satisfactorily, this probability reduces to about 7%. The difference is clearly not negligible.

Conclusions

The objective of constructing a CCL at the base of a waste disposal facility is to ensure that there is a low permeability barrier between the retained waste and the underlying soil. It is thus the hydraulic conductivity of the CCL that is the parameter of most relevance in this application. This paper has dealt with some of the aspects of specifying the required quality of a CCL and ensuring that this quality is achieved.

There are two main issues addressed in the paper. These relate to the acceptance criteria for quality control tests and the number of tests that must be carried out to ensure that a required standard of quality is achieved. When addressing both these issues, it quickly becomes apparent that the inherent variability of hydraulic conductivity of a soil is crucial to formulating and implementing a reasonable quality control programme. Unlike most soil parameters, e.g. density, shear strength and compression index, the hydraulic conductivity of a particular soil may vary over one or more orders of magnitude. Statistical analyses of large data sets have led to the characterisation of hydraulic conductivity as a log-normally distributed variable (although other, slightly more accurate distributions have also been advocated). Based on the assumption of a log-normal distribution of hydraulic conductivity, it is possible to address the two issues raised above.

When addressing acceptance criteria for quality control tests, it is usual to invoke the concept of the K_E, which is essentially that value of conductivity, such that when used to define a homogeneous clay liner, gives the same flow through it as does the statistical representation of the liner. As discussed in the paper, the specified (or target) value of hydraulic conductivity can then be related to the equivalent conductivity in terms of an acceptance criterion. Specification of a value for K_E is, however, a difficult task as it usually requires that a large amount of data on a specific soil be obtained. In place of undertaking a large number of hydraulic conductivity tests (e.g. on a test section of liner), it is advocated that the 'surrogate' approach be used, whereby other, easily measured and relevant soil properties such as moisture content and density be used, provided that a good correlation between hydraulic conductivity and these properties has been established for the particular soil.

In dealing with the required number of *in situ* tests to be carried out, there are two general approaches. The first is to simply specify a required number of tests per unit surface area of the CCL. This is simple to implement and monitor, but does not guarantee a specific level of confidence in the results obtained. The second approach, termed the precision-of-estimator approach, relates the probability of K_E exceeding the threshold value of hydraulic conductivity to the number of tests carried out, the expected error in the test measurements and the ratio between K_E and the threshold value that is required by the relevant regulator. This approach ensures a specified level of confidence in the results and can be updated during construction (based on *in situ* quality control measurements) in order to optimise the quality control programme.

Although the current Department of Water Affairs and Forestry regulations relating to quality assurance of CCLs are not at variance with the procedures outlined above, it is suggested that a more consistent and justifiable approach to quality control is possible by taking due cognisance of the inherent variability of hydraulic conductivity and its characterisation.

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