Measuring Soil Saturated Hydraulic Conductivity

for On-Site Wastewater Treatment Systems

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EXTENSION

Background

An estimation of the soil percolation rate or infiltration rate is required for on-site wastewater treatment systems (OWTS), commonly referred to as septic tanks or septic systems. For OWTS, homesites approved by the Georgia Department of Public Health (GDPH) for OWTS that are being developed or redeveloped require a site-specific measurement of the soil percolation rate (*Manual for On-site Sewage Management Systems*, 2019). To estimate soil percolation rates or infiltration rates, the soil saturated hydraulic conductivity must be known.

Objective

The objective of this bulletin is to describe a recommended procedure to measure soil saturated hydraulic conductivity (K_s) with a borehole permeameter and convert this value to estimates of percolation rate for OWTS. *Saturated hydraulic conductivity* is a fundametal hydraulic parameter for soil water flow and it is defined as the ratio of the water velocity to the hydraulic gradient ("Hydraulic conductivity," 2020).

Borehole permeameters

Commercially available borehole permeameters (Figure 1) are used to measure K_s below the soil surface in the unsaturated zone (Reynolds & Elrick, 2002). They consist of a Mariotte siphon, or some other device that maintains water at a constant level in a borehole, and a water reservoir that allows measurement of the rate of discharge into the soil. References for this method include Amoozegar (1997), Division of Public Health (2014), Reynolds and Elrick (2002), and Thomas et. al. (2016).

Water will pond in the borehole to a depth H set by the user (Figure 2). Water will infiltrate the surrounding soil and form a saturated bulb of infiltrating water that extends in all directions (Figure 3). The discharge rate should decline to a steady value, but it may take as long as an hour or more for this to happen. The measured K_s will depend on the soil area within all the wetted area, but primarily the saturated bulb, so the borehole should be augered to a depth within the soil horizon where K_s is to be measured. It is important to locate the measurement zone in the soil horizon of interest, as contrasting soil properties (e.g., texture, structure) can have very different K_s and measuring at horizon transitions could lead to inaccurate measurements and improper interpretations.

Figure 1. Example of a commercially available borehole permeameter (manufactured by Ksat, Inc., Raleigh, NC) showing borehole.

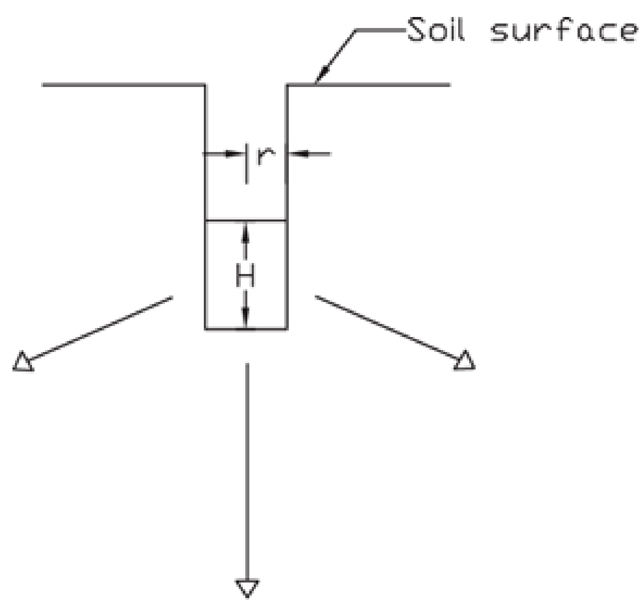

Figure 2. Diagram of a borehole with radius r and depth of ponding *H* in the borehole.

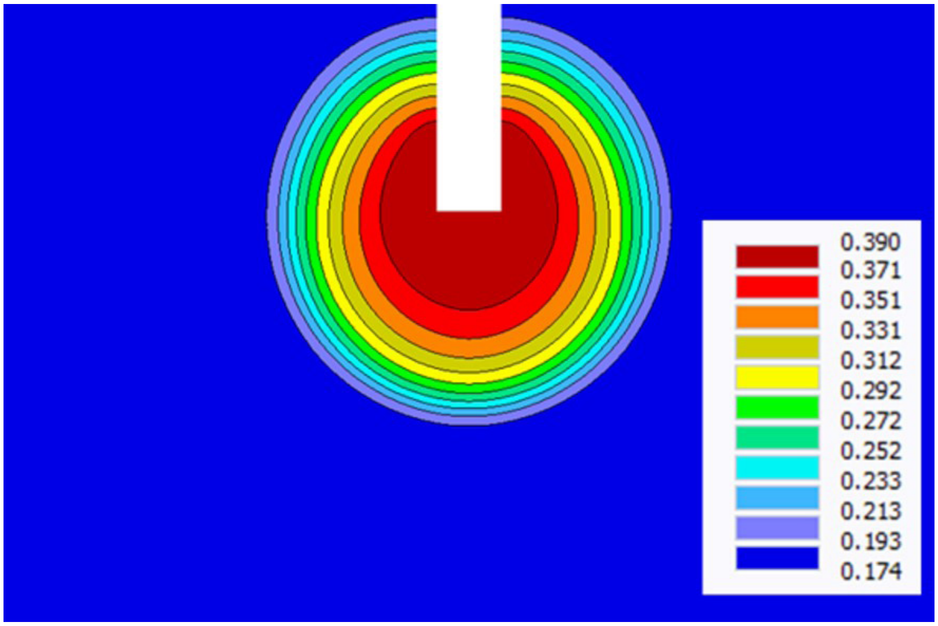

Figure 3. HYDRUS model simulation of infiltration from a borehole in a loamy sand soil after 1.3 hr. The diagram shows the volumetric water contents extending from the borehole center line out into the soil (the hole is the white notched area; HYDRUS runs only provide half of this image, but this figure provides a full view of the simulated infiltration). The borehole extends to a depth of 30 cm and water is ponded in the borehole to a height *H* = 10 cm above the bottom of the borehole.

Evaluation Procedure

Preparing the borehole

Construction of the borehole is typically done with a bucket auger equipped with two cutting teeth slightly larger than the bucket barrel. This allows the material to be extracted without compacting the borehole wall. Buckets with heavily worn teeth should not be used. Typical diameters for bucket augers are 2.25 and 2.75 in. (6 and 7 cm).

The auger is operated with minimal downward pressure, allowing the teeth to lift the material into the bucket (let the teeth do all the work). Auger extraction is in the exact reverse direction to avoid sidewall smearing. Pushing down hard on the auger or rocking it back and forth during collection or extraction will compact and/or smear the bottom and sidewall, distorting measured values.

The borehole method is a destructive technique and some disturbance is unavoidable. A nylon bottle brush or similar tool with a diameter similar to the hole can be used to gently brush the sides and bottom to mitigate these effects to some extent. The minor debris created by brushing should be extracted with a single, gentle half-turn of the auger, taking care not to touch the sidewall.

Dry to moist soil conditions are required for representative results. Measurements should not be conducted under saturated or nearly saturated conditions. These conditions introduce unaccounted water volume into the test and increase compaction and smearing. If the soil is saturated, this is probably not a suitable soil for an OWTS.

Measurement location and replication

Field assessment of the variability of soil type, landscape position, and proposed system capacity by the approved professional determines the appropriate location of measurements and number of replicates necessary to characterize the hydraulic conductivity of the primary absorption field and repair area. Guidance from the NRCS *Field Book for Describing and Sampling Soils*, version 3.0, suggests five or more K_s measurements are required to capture natural variation (Schoeneberger et al., 2012).

For daily design peak flow ≤ 750 gallons per day (gpd), the GDPH recommends measurements of K_s at five locations that best characterize the soil and site conditions within the area to be used for the primary and repair drainfield at the site. If the area to be used for the proposed primary and secondary systems is not contiguous, GDPH advises taking measurements at an additional five locations in the secondary area.

For daily design peak flow > 750 gpd, GDPH recommends measurements of K_s at five locations that best characterize the soil and site conditions within the area to be used for the primary OWTS installation at the site. Additionally, measure K_s at five locations within the area to be used for the secondary drainfield installation, regardless of whether the secondary system area is contiguous with the primary area.

Measurement depths

Measurements should be made in the most restrictive soil horizon that encounters the proposed absorption trench sidewall and at 1 ft below the proposed absorption trench bottom elevation. Because of potential water flow to the surface, only K_s measurements at depths greater than 6 in. (15 cm) from the ground's surface are generally considered valid. When possible, measurements should be made within a single horizon. Thin horizons with similar soil properties may be bridged if necessary. Select the depth of water in the hole as described in the recommendations outlined in the respective procedures and maintain it constantly throughout the test. For commercial devices, consult the manufacturer's manual for selecting an appropriate water depth.

Steady state

Steady state equilibrium is achieved when the change in discharge rate is less than 10% of the median value for three consecutive readings. Practitioners should provide an explanation if steady-state equilibrium is not achieved. Alternately, after allowing saturation of the soil around the hole, flow rate should reach a quasi-steady-state condition during which it varies around an average value. To determine this average, it is best to plot the rate of water flow (or the calculated K_s values) versus time and pass a smooth curve through them using a manually or mathematically best fitted curve. Steady-state flow is reached if the tail end of this fitted curve is nearly horizontal without showing an upward or downward trend. Use the geometric mean flow rate for the last three to five measurements after reaching steady state to calculate K_s. Longer saturation times should be considered for soils with mixed clay mineralogy and moderate to high shrink-swell potential (Amoozegar, 1997) or for measurements during droughty conditions.

Measurement recording frequency

Measure the discharge rate at time intervals outlined in the respective procedures or the manufacturer's instrument-specific manual. In general, for Group I and II soils (Table 1), measure and record at intervals of 15 min (or when at least 100 cm³ of water flows into the soil) for a minimum run time of 1 hr or until steady state is achieved. For Group III and IV soils, measure and record at intervals of 30 min (or when at least 100 cm³ of water flows into the soil) for a minimum run time of 2 hr and until steady state is achieved.

Data analysis

If multiple readings vary by an order of magnitude (10 times) or more, additional measurements should be considered to achieve an acceptable level of confidence as determined by the professional. Because the soil property K_s is logarithmically distributed, the geometric mean of flow measurements must be used for calculations. For example, the geometric mean of the number set {1, 2, 3, 4, 5} would be as follows:

$$\sqrt[5]{1 \times 2 \times 3 \times 4 \times 5} = 2.6$$

Converting Borehole Discharge Rate to Field Saturated Hydraulic Conductivity

Recommended equation for calculating K_s

The saturated conductivity of a soil under steady flow from a borehole can be described by the following equation (Reynolds & Elrick, 2002):

$$K_s = \frac{Q_s}{\left(\pi r^2 + \frac{H\lambda_c}{G} + \frac{H^2}{G}\right)} \quad \text{[Equation 1]}$$

where Q_s is the steady volumetric flow rate in volume of water (cm^3) per time (min), H is the height of water ponded in the borehole (cm), r is the radius of the hole (cm), λ_c is the soil macroscopic capillary length (cm), and G is a unitless geometric factor. Bosch and West (1998) developed an equation to determine the value of G:

$$G = \frac{1}{2\pi}\left[A_1 + A_2\frac{H}{r} + A_3\left(\frac{H}{r}\right)^2 + A_4\left(\frac{H}{r}\right)^3\right] \quad \text{[Equation 2]}$$

The values of the coefficients $A_1 \ldots A_4$ in this polynomial depend on texture and structure and are shown in Table 1, along with values for λ_c.

Table 1. Soil texture/structure descriptions, macroscopic capillary length, and polynomial coefficients for Equation 2 (adapted from Elrick and Reynolds (1992) and Bosch and West (1998).

Soil texture/structure	λ_c (cm)	A_1	A_2	A_3	A_4
Group I. Sands (sand and loamy sand) **Group II.** Coarse loams (sandy loam and loam) May also include some highly structured soils with large cracks and/or macropores	2.8	0.079	0.516	-0.048	0.002
Group III. Fine loams (clay loam, silt loam, sandy clay loam, silty clay loam, silt)	8.3	0.083	0.514	-0.053	0.002
Group IV. Unstructured clays (sandy clay, clay, silty clay with 1:1 minerals)	25	0.094	0.489	-0.053	0.002

Example calculation

Example 1: Calculate the saturated hydraulic conductivity for a structured loam soil that has a steady discharge rate measured with a borehole permeameter of 150 cm^3 measured over 30 min. The radius of the borehole is 3 cm and the depth of ponding is 15 cm.

The first step is to decide which category in Table 1 applies to this soil. Since it is a structured loam, the description for Group III is the best match. Calculate the geometric factor using Equation 2 and the coefficients A1...A4 for a Group III soil from Table 1:

$$\begin{aligned} G &= \frac{1}{2\pi}\left[0.083 + 0.514\left(\frac{15\,\text{cm}}{3\,\text{cm}}\right) - 0.053\left(\frac{15\,\text{cm}}{3\,\text{cm}}\right)^2 + 0.002\left(\frac{15\,\text{cm}}{3\,\text{cm}}\right)^3\right] \\ &= 0.251 \end{aligned}$$

Using Equation 1 and λ_c = 8.3 cm from Table 1, calculate K_s:

$$K_s = \frac{Q_s}{\pi r^2 + \frac{H\lambda_c}{G} + \frac{H^2}{G}}$$

$$= \frac{\frac{150\ \text{cm}^3}{30\ \text{min}}}{\pi(3\,\text{cm})^2 + \frac{(15\,\text{cm})(8.3\,\text{cm})}{0.251} + \frac{(15\,\text{cm})^2}{0.251}}$$

$$= 0.004\,\frac{\text{cm}}{\text{min}}$$

$$= 0.211\,\frac{\text{cm}}{\text{hr}}$$

$$= 0.083\,\frac{\text{in.}}{\text{hr}}$$

Alternatively, an Excel spreadsheet we have developed called the *Borehole Calculator* can be used to calculate K_s using these same equations. An example is shown below.

Example 2: Use the Excel spreadsheet to calculate K_s for the soil in Example 1.

Since this is a Group III soil, copy the values for this row from the first table into the empty orange cells (Figure 4).

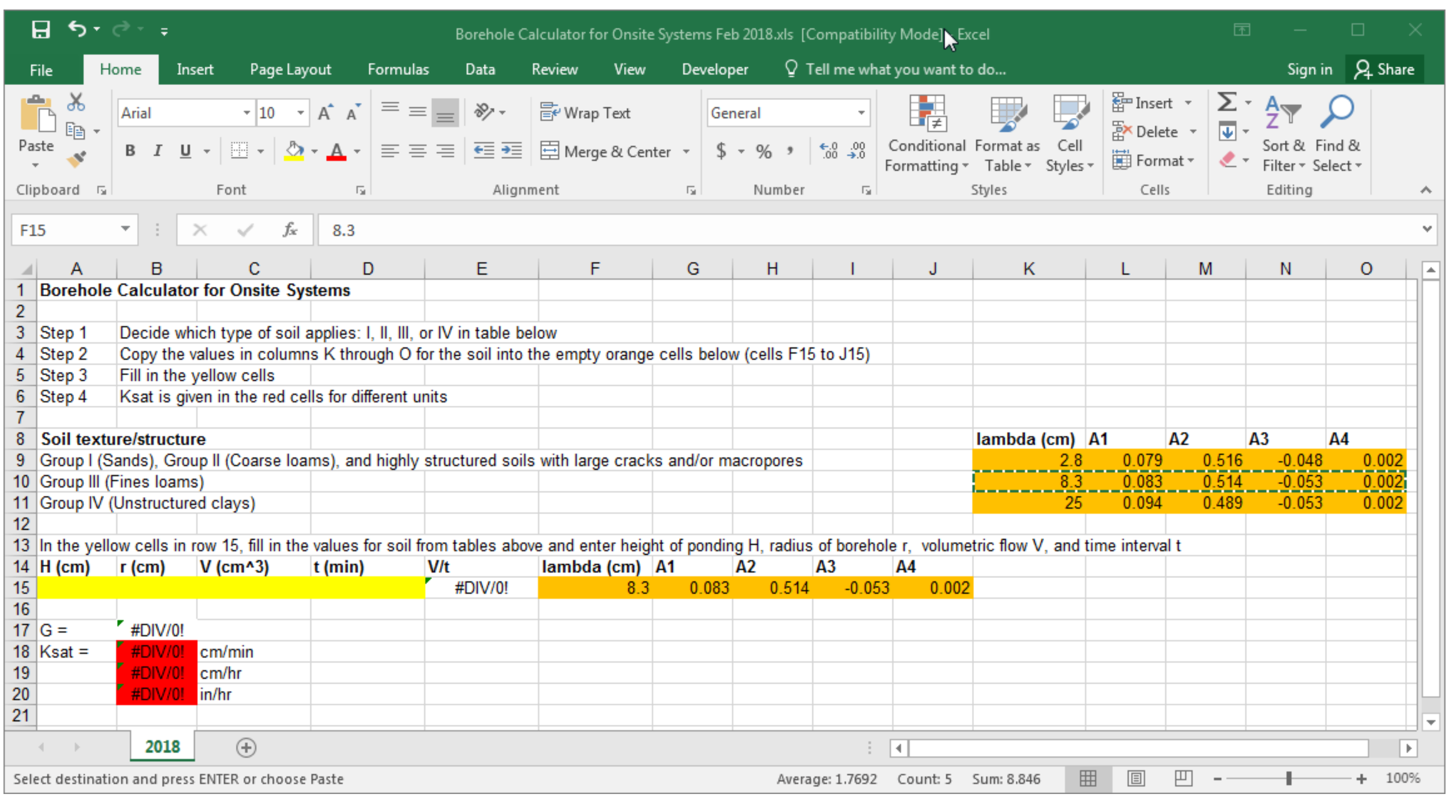

Figure 4. Borehole Calculator Excel spreadsheet: Values for a Group III soil are copied into cells F15-J15.

The third step is to enter the values for the volume (V), time (t), depth of ponding (H), and borehole radius (r) into the yellow cells. Once this is done the value for K_s is calculated automatically and given in various units in the red cells. The K_s for this soil is 0.083 in./hr (Cell B20 in Figure 5).

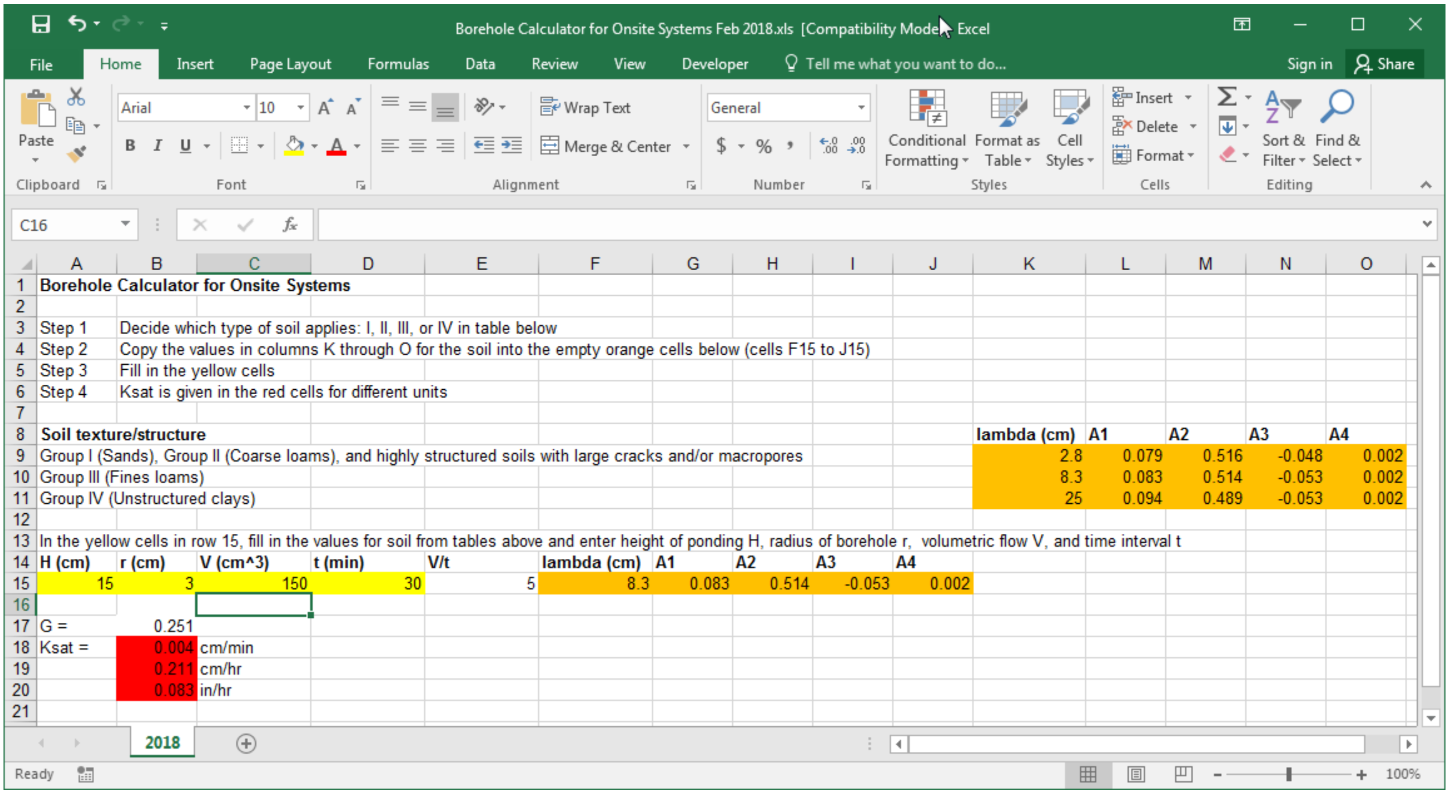

Figure 5. Measured values of *H, r, V,* and *t* are entered into cells A15-D15. The calculated K_s is shown in cells B18-B20 for different units.

Converting K_s to Estimated Percolation Rate

Perc tests

In the past, a percolation or perc test (measured or estimated) was used to estimate the long-term percolation rate for a septic drainfield. A perc test is similar to a borehole infiltration measurement, but the water level in the borehole is allowed to drop. The time that it takes the water level to drop an inch is recorded (instead of calculating K_s with the equations or spreadsheet). The units for a perc rate are usually min/in. (time divided by length). As such, they are the inverse of the units for K_s (length divided by time). It's tempting to think that the perc rate is just 1 over the K_s, but that is not true. The procedure for conducting a perc test is given in section C of the *Manual for On-site Sewage Management Systems* (2019). Table 10.F in the Georgia manual converts perc rates to trench bottom area required per bedroom based on an estimated long-term percolation rate.

Borehole tests

When borehole tests are used, a relationship between K_s and the perc test rates in Table 10.F is needed. We developed this relationship using the equations of Reynolds (2016) that relate perc test results to K_s.
We assumed that the borehole for the perc test had a radius of 5.1 cm (2 in.) and a constant pressure head of 15.2 cm (6 in.). It was also assumed the soil had been prewetted. These conditions match those prescribed in the Modified Taft Engineering Center Method, which is the currently approved method for determining soil percolation rate in the *Manual for On-Site Sewage Management Systems* (2019). The results are shown in Table 2.

Table 2. Percolation rates in min/in. and associated K_s values in cm/day and in./day.

Soil texture/structure	K_s value		Percolation Rate
Soil Group Percolation Rate Ranges (min/in.) **Group I – Sands** Sand and loamy sand < 10 **Group II – Coarse Loams** Sandy loam and loam 10–30 **Group III – Fine Loams** Clay loam, silt loam, sandy clay loam, silty clay loam, silt 30–60 **Group IV – Clays** Sandy clay, clay, silty clay with 1:1 minerals > 60	**(cm/day)**	**(in./day)**	**(minutes/in.)**
	39.55	15.57	5
	19.77	7.78	10
	11.32	4.46	15
	8.49	3.34	20
	6.79	2.67	25
	5.66	2.23	30
	4.85	1.91	35
	4.24	1.67	40
	3.77	1.49	45
	3.39	1.34	50
	3.09	1.22	55
	2.83	1.11	60
	2.61	1.03	65
	2.42	0.95	70
	2.26	0.89	75
	2.12	0.84	80
	1.82	0.71	85
	1.71	0.68	90
	1.62	0.64	95
	1.54	0.61	100
	1.47	0.58	105
	1.40	0.55	110
	1.34	0.53	115
	1.29	0.51	120

Once the perc rate is found in Table 2, the trench bottom area required can be determined using Table 10.F in the *Manual for On-site Sewage Management Systems* (2019). An example of how to use Table 2 is shown below.

Example 3: What is the perc test rate associated with the K_s value from Example 2 (0.083 in./hr)? What is the area of trench bottom required for this soil?

Converting 0.083 in./hr to a daily value, K_s is 1.99 in./day. The value in Table 2 that comes closest to this is 1.91 in./day so the associated perc test value is 35 min/in. In Table 10.F the trench bottom area is 265 ft.

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