Electronic Delivery
February 6, 2024
Mr. Richard S. Novak, Chair
Sherborn Zoning Board of Appeals
Town Hall
19 Washington Street
Sherborn, MA 01770

RE: Proposed Farm Road Homes, Sherborn, MA
55-65 Farm Road, Sherborn, MA
Review of Predicted K Values

Dear Mr. Novak:

Thank you for hearing my comments at the February 5, 2024 joint meeting with the Board of Health and the ZBA. As requested at the meeting, below is a summary of my concerns with regard to the hydraulic conductivity analysis, mounding, and nitrogen (and other contaminant) transport values used by the Farm Road Homes developer in the February 2, 2024 Creative Land & Water Engineering, LLC (CLAWE) responses to the ZBA Civil Engineering Peer Review Letter of October 27, 2023 (Tetra Tech), as well as the CLAWE Appendix Supplementary Data for Groundwater Mounding Analysis and Updated Groundwater Mounding Analysis.

The use of mathematical formulas to predict true hydraulic conductivity (K) is limited, and needs to be confirmed in the field in the actual area of the proposed soil absorption system, in order to more accurately define the K value. This is due to many factors including natural stratigraphic layers in the subsurface, gradation of the soils, the inability of the formulas to consider all relevant soil characteristics, and other factors that in-situ field testing can provide. In the case of the method used for Farm Road Homes, the published limitations of the model as well as the results of the Particle Size Distribution Report (sieve analyses), the analysis completed to determine K for the Farm Road Homes project is not valid as I discuss below.

For a project of this magnitude in our town, the mathematical modeling conducted to date needs to be backed up with field testing to gain relevant data on the ability of the soils at the site to manage the large volume of septic waste proposed for this project (8,360 gal/day). I have attached and summarized below technical articles on the insufficiency of the Hazen and various other predictive models to determine hydraulic conductivity values. Changes in variables that are applied to the predictive equations can dramatically change the resulting K value.

The importance of determining a valid K value cannot be overemphasized in predicting mounding, the ability of soil to treat septic waste, transport of contaminants, and even the risk of ground surface breakthrough of septic waste. There are critical limitations to the methods used by the developer to determine the capacity of the soil to accept and treat the volume of sewerage proposed. In fact, the Hazen method used to determine the K value is not valid for the soil conditions at the Farm Road Homes site as discussed herein. A properly designed and implemented field testing program is necessary to determine K values, including field (not laboratory) falling head or static head borehole permeability testing, aquifer pump tests or a combination of these.

Obviously, I do not know now what the outcome of the field hydrological assessments will show. But I believe that proper in situ hydrogeologic field testing is necessary to reflect the real K value at the site.

Published K values and C coefficient values

Attached to this letter are published K values for different soil types (*Applied Hydrogeology,* Third Edition, C.W. Fetter, 1994 pg.98). Based on the developer's grain size analyses conducted and descriptions of the soil at Farm Road Homes, the range of hydraulic conductivity that can be anticipated at the site is 10^{-3} to 10^{-5} cm/sec for silty sands, fine sands. This corresponds to a K value of roughly 0.3 ft/day to 0.003 ft/day. The K value developed and used by Farm Road Homes is 24 ft/day.

Also attached is a table from the same textbook that presents "C" coefficient values used in the Hazen formula: $K = C (D10)^2$. The published C value for fine sand with appreciable fines is 40-80, and for medium well sorted sand it is 80-120 (although the soil at the site is not well sorted, therefore the lower numbers are likely more applicable). The C coefficients used in the Farm Road Homes analysis of samples S-1 and S-2 to determine the K value were 93 and 143, respectively.

Articles on the Applicability of Formulas to Predict K Values

A few articles are attached to this letter that discuss the deficiency in using formulas only to predict hydraulic conductivity. The article titled "*Evaluation of Actual and Estimated Hydraulic Conductivity of Sands with Different Gradation and Shape"* describes and reviews various formulas to estimate hydraulic conductivity including the Hazen method and eight other methods. I highlighted some portions of the attached text. The limitations of use for the Hazen method include the need to review the c_u value of the soil, the uniformity coefficient, in order to evaluate whether the Hazen method can be used. The c_u value is the ratio of the 60% finer grainsize (D60) to the 10% finer grainsize (D10) value, and provides a value of the relative uniformity of the soil (D60/D10). As noted on Table 4 pg. 5 of the article, the limitations of the Hazen formula are that the c_u value should be less than 5. The Hazen method is only applicable to uniform soils. The samples from the Farm Road Homes soil absorption system S-1 and S-2 had c_u values of 52 and 120, respectively, significantly greater than 5. This is consistent with the descriptions of the soil and the sieve analysis results which show a heterogeneous mixture of soil with gravel, sand and silt grain sized materials (as opposed to a uniform sand, for example). Sample S-1 has 41% gravel, 52% sand, and 7% silt/fines, and S-2 has 38 % gravel, 43% sand, and 18% silt/fines. **The Hazen method is not a valid predictive model to use to find K values for the soil at Farm Road Homes.** The Farm Road Homes analysis also referenced a Kenney method of estimating K. Kenney was not one of the nine methods explored in this article, and I did not find relevant literature that would support the use of this formula to determine hydraulic conductivity at the site.

Conclusions of the article were that applications of these "empirical formulae to the same porous medium material can yield different values of hydraulic conductivity because of the difficulty of including all possible variables in porous media." Nine equations to predict K values were reviewed and the same conclusions were drawn regarding the limitations of formulas to predict true hydraulic conductivity.

Another article attached titled "*Assessing Hydraulic Conductivity of Soils from Particle Size Data"* highlights some of the potential pitfalls if K values are derived from the Hazen method, and if the values are used in dewatering design and other geotechnical problems. This article discusses that features of the soil pores including the size distribution and tortuosity of the pore spaces, and the shape and roughness of the soil particles can not be measures by gradation (sieve) analyses and formulas. The article also describes that Hazen's rule was not designed for naturally existing soil at all, it was intended for granular filter media for water treatment systems. Hazen himself stated that his rule was applicable over the range of D10 particle size 0.1mm to 3.0 mm and "for soils having a uniformity coefficient (D60/D10) less than five." (pg. 3). The article also discusses general pitfalls of using formulas to predict K values including the effects of soil structure or fabric (pg. 7).

The last attachments to this letter are pages from the Farm Road Homes S-1 and S-2 sample sieve analyses and permeability estimates calculation sheets for reference.

In summary, the predictive mathematical models are just a first glance at the possible range of hydraulic conductivities of the soils and do not replace solid field hydrologic studies. Published coefficients and values used in formulas to calculate K values have large ranges, and results can vary widely by several orders of magnitude depending on the values selected. There are also other limitations to the hydraulic conductivity calculations and restrictions on the appropriateness of their use (uniformity of grain size), and the Hazen method is not an appropriate model to use for soils at the Farm Road Homes site.

Oversimplified predictive phase analysis and calculations alone are not sufficient to design the sewerage treatment system at the Farm Road Homes site. Not discussed in this letter are the added loads from the nearby upgradient proposed stormwater detention Basin A that is approximately 100 feet to the north. Review of the other proposed stormwater management systems is also not covered in this letter. Field hydrogeological studies are needed to properly identify appropriate K values in an effort to design an appropriate and successful soil absorption system for a wastewater treatment system of the size proposed by Farm Road Homes.

Sincerely,

Andrea D. Stiller, LSP

Attachments

Published Ranges in Hydraulic Conductivities (*Applied Hydrogeology,* Third Edition, C. W. Fetter, pg.98)
Hazen method C coefficient values (*Applied Hydrogeology,* Third Edition, C. W. Fetter, pg.99)
Article: *Evaluation of Actual and Estimated Hydraulic Conductivity of Sands with Different Gradation and Shape,* Ali First Cabalar and Nurullah Akbulut, National Library of Medicine, 2016
Blog: *Assessing Hydraulic Conductivity of Soils from Particle Size Data,* Preene Groundwater Consulting, 2014
Excerpts from Farm Road Homes CLAWE S-1 and S-2 Sieve Analyses and K Estimate Calculations

cc: Ms. Daryl Beardsley, Chair, Sherborn Board of Health

PUBLISHED K AND C VALUES

TABLE 4.6 Ranges of intrinsic permeabilities and hydraulic conductivities for unconsolidated sediments

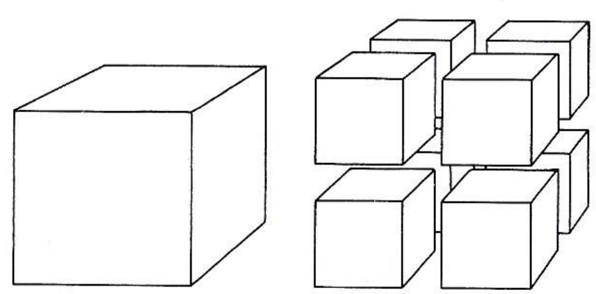
Material	Intrinsic Permeability (darcys)	Hydraulic Conductivity (cm/s)
Clay	10^{-6}–10^{-3}	10^{-9}–10^{-6}
Silt, sandy silts, clayey sands, till	10^{-3}–10^{-1}	10^{-6}–10^{-4}
Silty sands, fine sands	10^{-2}–1	10^{-5}–10^{-3}
Well-sorted sands, glacial outwash	1–10^{2}	10^{-3}–10^{-1}
Well-sorted gravel	10–10^{3}	10^{-2}–1

4.4.3 Permeability of Sediments

Unconsolidated coarse-grained sediments represent some of the most prolific producers of ground water. Likewise, clays are often used for engineering purposes, such as lining solid-waste disposal sites, because of their extremely low intrinsic permeability. There is obviously a wide-ranging continuum of permeability values for unconsolidated sediments (Table 4.6).

The intrinsic permeability is a function of the size of the pore opening. The smaller the size of the sediment grains, the larger the surface area the water contacts (Figure 4.13). This increases the frictional resistance to flow, which reduces the intrinsic permeability. For well-sorted sediments, the intrinsic permeability is proportional to the grain size of the sediment (Norris & Fidler 1965).

For sand-sized alluvial deposits, several factors relating intrinsic permeability to grain size have been noted (Masch & Denny 1966). These observations would hold true for all sedimentary deposits, regardless of origin of deposition.



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1. As the median grain s to larger pore openin
2. Permeability will dec dard deviation of par deviation indicates a material can fill the v
3. Coarser samples sho increase in standard
4. Unimodal (one domin than bimodal (two do poorer sorting of the indicates.

The hydraulic conductivity grain-size distribution curve by th applicable to sands where the effe 0.1 and 3.0 mm. The Hazen appro

where

K is hydraulic conductiv

d_{10} is the effective grain s

C is a coefficient based

Very fine sand, p
Fine sand with ap
Medium sand, we
Coarse sand, poo
Coarse sand, well

The work of Hazen (1911) be related to the square of a char (1989) analyzed data from 18 publis been related to grain size. He found formula

where

C is a shape factor

d_{50} is the mean grain size

1. As the median grain size increases, so does permeability. This is due to larger pore openings.
2. Permeability will decrease for a given median diameter as the standard deviation of particle size increases. The increase in standard deviation indicates a more poorly sorted sample, so that the finer material can fill the voids between larger fragments.
3. Coarser samples show a greater decrease in permeability with an increase in standard deviation than do fine samples.
4. Unimodal (one dominant size) samples have a greater permeability than bimodal (two dominant sizes) samples. This is again a result of poorer sorting of the sediment sizes, as the bimodal distribution indicates.

The hydraulic conductivity of sandy sediments can be estimated from the grain-size distribution curve by the **Hazen method** (Hazen 1911). The method is applicable to sands where the effective grain size (d_{10}) is between approximately 0.1 and 3.0 mm. The Hazen approximation is

$$K = C(d_{10})^2 \qquad \textbf{(4–19)}$$

where

K is hydraulic conductivity (cm/s)
d_{10} is the effective grain size (cm)
C is a coefficient based on the following table

Very fine sand, poorly sorted	40–80
Fine sand with appreciable fines	40–80
Medium sand, well sorted	80–120
Coarse sand, poorly sorted	80–120
Coarse sand, well sorted, clean	120–150

The work of Hazen (1911) demonstrated that hydraulic conductivity could be related to the square of a characteristic dimension of a sediment. Shepherd (1989) analyzed data from 18 published studies where hydraulic conductivity had been related to grain size. He found that all studies could be related to the general formula

$$K = Cd_{50}^{j} \qquad \textbf{(4–20)}$$

where

C is a shape factor
d_{50} is the mean grain size (mm)

Applied Hydrogeology

Third Edition

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ARTICLES ON PREDICTING K VALUES

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Evaluation of actual and estimated hydraulic conductivity of sands with different gradation and shape

Ali Firat Cabalar and Nurullah Akbulut

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Abstract

Go to:

Hydraulic conductivities of sands with different gradation and grain shape were estimated experimentally at a relative density (D_r) of about 40 % and a 22 ± 2 °C of constant temperature. Narli Sand (NS) with 0.67 of sphericity (S) and 0.72 of roundness (R), and Crushed Stone Sand (CSS) with 0.55 of S and 0.15 of R values were artificially graded into sixteen different grain-size fractions (4.75–2, 2–1.18, 1.18–0.6, 0.6–0.425, 0.425–0.3, 0.3–0.075, 4.75–0.075, 2–0.075, 1.18–0.075, 0.6–0.075, 0.425–0.075, 4.75–0.6, 2–0.6, 4.75-0.425, 2–0.425, 1.18–0.425 mm). Hydraulic conductivities of the NS estimated by use of constant head test ranged from 1.61 to 0.01 cm/s, whilst those of the CSS estimated by the same test ranged from 2.45 to 0.012 cm/s. It was observed that the hydraulic conductivity values of the NS are lower than those of the CSS samples, which is likely to be the result of differences in shape, particularly in R values. The results clearly demonstrated that the hydraulic conductivity can be significantly influenced by grading characteristics (d_{10}, d_{20}, d_{30}, d_{50}, d_{60}, c_u, c_c, n, I_o). Furthermore, comparisons between results obtained in the present study and hydraulic conductivity estimated with other formulas available in the literature were made. The comparisons indicated that the best estimation of hydraulic conductivity changes based on the gradation and shape properties of the sands tested.

Keywords: Hydraulic conductivity, Sand, Gradation, Shape

Background

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Hydraulic conductivity, which represents the ability of a porous media to transmit water through its voids, is one of the most significant key parameters of geomaterials for many natural phenomena including the management of water resources, drinking water supply, safety of waste repositories, basin-scale hydrogeologic circulation, stability analyses, and many other problems on subsurface hydrology and geotechnical engineering (Terzaghi and Peck 1964; Moore et al. 1982; Wintsch et al. 1995; Person et al. 1996; Boadu 2000; Chapuis 2012). There have been attempts to estimate hydraulic conductivity based on grain size distribution (Mualem 1976; Freeze and Cherry 1979; Uma et al. 1989; Salarashayeri and Siosemarde 2012). Empirical (Hazen 1911; Krumbein and Monk 1942; Alyamani and Sen 1993) and predictive methods (Kozeny 1927; Carman 1937; Boadu 2000; Goktepe and Sezer 2010) of estimating the hydraulic conductivity using quantitative relations have been developed in the literature. A commonly accepted equation was proposed by Hazen (1911) and given $k = cd_{10}^2$ for predicting the hydraulic conductivity of saturated sands. Where k is hydraulic conductivity, c is constant, and d_{10} is effective diameter at which 10 % of the grains are finer. Krumbein and Monk (1942) gave an expression for the hydraulic conductivity of unconsolidated sands by an empirical equation of the form $k = (760d_w^2)\exp(-1.3\sigma_\psi)$, where d_w is geometric mean diameter by weight in millimetres, σ_ψ is standard deviation of the ψ distribution function. Masch and Denny (1966) proposed the use of d_{50} median grain size as the representative size to correlate hydraulic conductivity with grain size. Kozeny (1927) and Carman (1937), which is widely accepted derivation for hydraulic conductivity, developed a semi-empirical formula for predicting the permeability of porous media. Koltermann and Gorelick (1995) stated that the use of geometric mean overpredicts hydraulic conductivity by several orders of magnitude for soils with significant fines content, whilst the harmonic mean grain size under predicts k by several orders of magnitude for soils with less fines content. Shepherd (1989) performed a series of statistical power regression analyses on 19 sets of published data on hydraulic conductivity of unconsolidated sediments versus grain size. Alyamani and Sen (1993) proposed an equation based on analysis of 32 samples incorporating the initial slope and the intercept of the grain-size distribution curve. Sperry and Peirce (1995) developed a model for delineating the significance of particle size/shape, and porosity in explaining the variability of hydraulic conductivity of a granular porous medium. Ishaku et al. (2011) have employed several empirical formulae to specify the hydraulic conductivity of aquifer materials in the field. Although many different techniques have been proposed to determine hydraulic conductivity value, including field methods, applications of these empirical formulae to the same porous medium material can yield different values of hydraulic conductivity because of the difficulty of including all possible variables in porous media (Vukovic and Soro 1992).

It has been long understood that grain shape characteristics have a significant effect on certain engineering properties of soils (Terzaghi 1925; Gilboy 1928; Lees 1964; Olson and Mesri 1970; Abbireddy et al. 2009; Clayton et al. 2009). Terzaghi is one of the first engineers to perform a research to understand the influences of shape characteristics by employing flat-grained constituents (Terzaghi 1925). The observations, conducted by Gilboy (1928), that any system of analysis neglecting the effect of grain shape would be incomplete. Numerous researches have been conducted due to the significance of grains' shape and its role in the behaviour of soils for both practicing engineers and researchers. Holubec and D'Appolonia (1973) indicated that the results of dynamic penetration tests in sands depend on grains' shape characteristics. Cornfort (1973), and Holtz and Kovacks (1981) pointed out how grain shape affects the internal friction angle (φ). Cedergen (1989) stated that grain shape affects the permeability. Grain shape also plays an important role in liquefaction potential (Kramer 1996). Wadell (1932), Krumbein (1941), Powers (1953), Holubec and D'Appolonia (1973), Youd (1973), and Cho et al. (2006) have introduced detailed explanations of grain shape. Two independent properties are basically used to describe the shape of a soil grain: (1) Roundness, a measure of the extent to which the edges and corners of a grain has been rounded (2) Sphericity (form), a measure of the extent to which a grain approaches a sphere in shape. Wadell (1932) proposed a simplified sphericity (S) parameter ($D_{max\text{-}insc}/D_{min\text{-}circ}$), where $D_{max\text{-}min}$ is the diameter of a maximum inscribed circle and $D_{min\text{-}circ}$ is the diameter of a minimum sphere circumscribing a gravel particle. Wadell (1932) defined roundness (R) as $D_{i\text{-}ave}/D_{max\text{-}insc}$, where $D_{i\text{-}ave}$ is the average diameter of the inscribed circle for each corner of the particle. Figures 1, 2 and 3 describe R, S and a chart for comparison between them to identify grain shape (Krumbein 1941; Powers 1953).

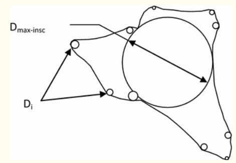

Fig. 1

Graphical representation of roundness, R (redrawn from Muszynski and Stanley, 2012)

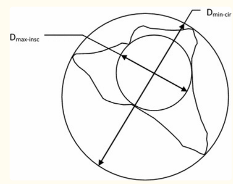

Fig. 2

Graphical representation of sphericity, S (redrawn from Muszynski and Stanley, 2012)

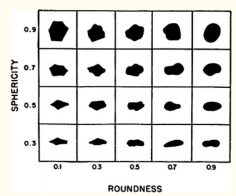

Fig. 3

Comparison chart (Santamarina and Cho 2004)

Although many field and laboratory determinations of hydraulic conductivity have been performed by engineers, geologist, hydrogeologist, and soil scientists, the fundamental relationships between the gradation and shape properties of grains and flow through them remain poorly understood and inadequately quantified. Actually, these approaches cannot yield consistent results with respect to actual hydraulic conductivity values. Therefore, this study aims to evaluate a new conceptual approach for quantifying the inherent coupling between gradation/shape of sand grains changes and hydraulic conductivity by exploiting constant head permeability tests on sixteen different grain-size fractions (4.75–2, 2–1.18, 1.18–0.6, 0.6–0.425, 0.425–0.3, 0.3–0.075, 4.75–0.075, 2–0.075, 1.18–0.075, 0.6–0.075, 0.425–0.075, 4.75–0.6, 2–0.6, 4.75–0.425, 2–0.425, 1.18–0.425 mm) of sands having two distinct shapes (rounded and angular). Furthermore, comparisons between results obtained in the present study and hydraulic conductivity estimated with other formulas available in the literature were made.

Experimental study

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The materials used in the tests described in this study were Narli Sand (NS) and Crushed Stone Sand (CSS) having the distinct shapes and sizes falling between 4.75 and 2 mm, 2 and 1.18 mm, 1.18 and 0.6 mm, 0.6 and 0.425 mm, 0.425 and 0.3 mm, 0.3 and 0.075 mm, 4.75 and 0.075 mm, 2 and 0.075 mm, 1.18 and 0.075 mm, 0.6 and 0.075 mm, 0.425 and 0.075 mm, 4.75 and 0.6 mm, 2 and 0.6 mm, 4.75 and 0.425 mm, 2 and 0.425 mm, 1.18 and 0.425 mm. Narli Sand (NS) was quarried in and around Narli, Kahramanmaras in southern-central of Turkey. A commercially available Crushed Stone Sand (CSS) was supplied from the same region of Turkey, which is widely consumed in earthworks in the region. The specific gravity of the grains were found to be 2.65 for Narli Sand, and 2.68 for Crushed Stone Sand. Scanning Electron Micrograph (SEM) pictures show the physical differences/similarities among the sands used during this investigation (Fig. 4). As can be seen from the Fig. 4, Narli Sand grains have rounded, whereas the Crushed Stone Sand grains have angular shape. Figure 5 indicates the grain size distribution of the sands used during the experimental study. Roundness (R) and sphericity (S) estimations based on the study by Muszynski and Stanley (2012) were found to be 0.43, 0.67, and 0.16, 0.55 for the NS and CSS grains, respectively. The sands were tested in a constant head permeability testing apparatus at a relative density (R_d) of about 40 % and constant room temperature (20 ± 2 °C). The specimens, which were placed in a perspex cylindrical cell of about 50 cm^2 cross-sectional area (A), rest on a wire mesh at bottom of the cell.

The volume of the water (q) flowing during a certain time (t) is measured, when a steady vertical water flow, under a constant head, is maintained through the soil specimen. Then, k values of the specimens tested were calculated using Darcy's law ($k = ql/Ah$). Tables 1 and 2 present some physical characteristics of the NS and CSS samples, respectively. As can be seen from these tables the hydraulic conductivity is affected by grading characteristics d_{10}, d_{20}, d_{30}, d_{50}, d_{60}, c_u, c_c, n, and I_o.

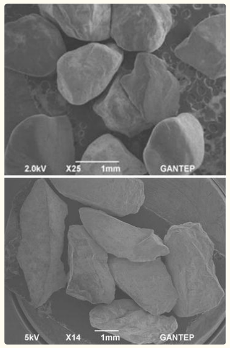

Fig. 4

SEM pictures of the (*top*) CSS and (*bottom*) NS used during the experimental study

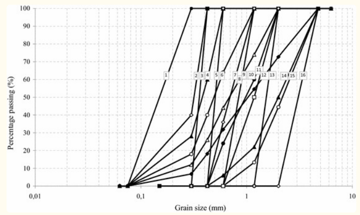

Fig. 5

Grain size distributions for the sands used during the experimental study

Table 1

Some physical characteristics of the NS samples

Gradation (mm)	d_{10} (mm)	d_{20} (mm)	d_{30} (mm)	d_{50} (mm)	d_{60} (mm)	c_u	c_c	n	e_{max}	e_{min}	e_{test}
4.75–2	2.20	2.40	2.60	3.10	3.30	1.50	0.93	0.46	0.95	0.70	0.86
2–1.18	1.25	1.30	1.38	1.63	1.70	1.35	0.89	0.45	0.92	0.66	0.82
1.18–0.6	0.64	0.69	0.74	0.84	0.90	1.41	0.93	0.44	0.85	0.62	0.77
0.6–0.425	0.43	0.45	0.47	0.50	0.51	1.19	1.00	0.42	0.79	0.60	0.72
0.425–0.3	0.32	0.33	0.34	0.35	0.37	1.16	0.98	0.37	0.61	0.52	0.60
4.75–0.075	0.33	0.44	0.59	1.00	1.45	4.39	0.73	0.47	0.97	0.70	0.87
2–0.075	0.24	0.36	0.46	0.69	0.87	3.63	1.01	0.45	0.92	0.63	0.82
1.18–0.075	0.17	0.31	0.38	0.50	0.59	3.47	1.44	0.44	0.89	0.61	0.79
0.6–0.075	0.13	0.20	0.31	0.39	0.43	3.27	1.74	0.41	0.80	0.52	0.70
0.425–0.075	0.11	0.16	0.22	0.32	0.34	3.09	1.29	0.39	0.74	0.44	0.63
0.3–0.075	0.09	0.10	0.12	0.16	0.18	2.07	0.92	0.36	0.63	0.42	0.56
4.75–0.6	1.00	1.33	1.60	2.20	2.60	2.60	0.98	0.43	0.83	0.59	0.74
2–0.6	0.69	0.79	0.90	1.18	1.33	1.93	0.88	0.40	0.76	0.52	0.67
4.75–0.425	0.70	1.10	1.40	2.00	2.30	3.28	1.22	0.34	0.57	0.42	0.52

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Table 2

Some physical characteristics of the CSS samples

Gradation (mm)	d_{10} (mm)	d_{20} (mm)	d_{30} (mm)	d_{50} (mm)	d_{60} (mm)	c_u	c_c	n	e_{max}	e_{min}	e_{test}
4.75–2	2.20	2.40	2.60	3.10	3.30	1.50	0.93	0.51	1.12	0.83	1.02
2–1.18	1.25	1.30	1.38	1.63	1.70	1.35	0.89	0.50	1.08	0.82	0.99
1.18–0.6	0.64	0.69	0.74	0.84	0.90	1.41	0.93	0.49	1.04	0.80	0.96
0.6–0.425	0.43	0.45	0.47	0.50	0.51	1.19	1.00	0.48	0.88	0.75	0.83

0.425–0.3	0.32	0.33	0.34	0.35	0.37	1.16	0.98	0.45	1.08	0.80	0.98
4.75–0.075	0.33	0.44	0.59	1.00	1.45	4.39	0.73	0.48	1.02	0.69	0.91
2–0.075	0.24	0.36	0.46	0.69	0.87	3.63	1.01	0.48	1.03	0.69	0.91
1.18–0.075	0.17	0.31	0.38	0.50	0.59	3.47	1.44	0.46	0.97	0.64	0.86
0.6–0.075	0.13	0.20	0.31	0.39	0.43	3.27	1.74	0.44	0.91	0.56	0.79
0.425–0.075	0.11	0.16	0.22	0.32	0.34	3.09	1.29	0.43	0.86	0.52	0.74
0.3–0.075	0.09	0.10	0.12	0.16	0.18	2.07	0.92	0.40	0.78	0.47	0.67
4.75–0.6	1.00	1.33	1.60	2.20	2.60	2.60	0.98	0.46	0.97	0.66	0.86
2–0.6	0.69	0.79	0.90	1.18	1.33	1.93	0.88	0.44	0.91	0.60	0.80
4.75–0.425	0.70	1.10	1.40	2.00	2.30	3.28	1.22	0.41	0.78	0.57	0.71

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Results and discussion

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Table 3 gives a summary of the specimens used in the tests reported here. The initial relative densities of all specimens were around 40 %. The specimens were loose to medium dense. Sixteen different sizes of artificially graded NS and CSS sands, which have exactly the same gradation characteristics (d_{10}, d_{20}, d_{30}, d_{50}, d_{60}, c_u, c_c, I_o) (Fig. 5) within the specified ranges, have been classified as 'poorly graded' (*SP*) based on the Unified Soil Classification System (USCS9. Based on the roundness criteria and values proposed by Powers (1953), and Youd (1973), the specimens used during the experimental investigation were found to be very angular and rounded for CSS and NS grains, respectively.

Table 3

Summary of specimen data

Gradation (mm)	Hydraulic conductivity (k, cm/s)										
	Hazen		K–C		Terzaghi		Chapuis		Slitcher		NAVFA
	NS	CSS	NS	CSS	NS	CSS	NS	CSS	NS	CSS	NS
4.75–2	5.95	8.39	4.93	12.36	2.38	4.85	6.31	6.33	1.78	3.55	8.48
2–1.18	2.39	2.95	2.79	5.19	1.20	1.89	1.87	1.86	0.88	1.37	3.16
1.18–0.6	0.67	0.79	0.86	1.49	0.35	0.53	0.48	0.49	0.26	0.38	0.87
0.6–0.425	0.32	0.37	0.46	0.74	0.18	0.25	0.21	0.22	0.13	0.18	0.47
0.425–0.3	0.18	0.21	0.29	0.44	0.11	0.15	0.12	0.12	0.08	0.11	0.31
4.75–0.075	0.13	0.16	0.10	0.16	0.05	0.07	0.12	0.11	0.04	0.05	0.08
2–0.075	0.08	0.09	0.07	0.11	0.03	0.05	0.06	0.06	0.02	0.03	0.06
1.18–0.075	0.04	0.05	0.05	0.07	0.02	0.03	0.03	0.03	0.02	0.02	0.04
0.6–0.075	0.03	0.03	0.04	0.05	0.02	0.02	0.02	0.02	0.01	0.01	0.03
0.425–0.075	0.02	0.03	0.03	0.04	0.01	0.01	0.01	0.01	0.01	0.01	0.03
0.3–0.075	0.01	0.02	0.02	0.03	0.01	0.01	0.01	0.01	0.01	0.01	0.02
4.75–0.6	1.16	1.51	0.89	1.73	0.44	0.75	1.18	1.15	0.33	0.55	1.17
2–0.6	0.71	0.87	0.78	1.44	0.34	0.54	0.54	0.54	0.25	0.39	0.79

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Table 4 shows the empirical equations and their limitations for hydraulic conductivity estimates which were used to obtain the results given in Table 3. Equations developed by Hazen (1892), Kozeny-Carman (1956), Terzaghi (Odong 2007), Chapuis (2004), Slichter (1898), USBR (Vukovic and Soro 1992), NAVFAC (1974), Alyamani and Sen (1993), and Breyer (Kresic 1998) were employed in this study. Hazen (1892) proposed his formula in order to estimate the hydraulic conductivity of uniformly graded loose sand with effective grain size (d_{10}) between 0.10 and 3.0 mm, and c_u less than 5. As can be seen from the Table 3 that hydraulic conductivity values ranged from 5.95 to 0.01 cm/s for the NS samples falling specified gradations, whilst those ranged from 8.39 to 0.02 cm/s for the CSS samples falling the same gradations. Although, presence of porosity (n) in the formula seems an advantage of the formula, this approach does not give an accurate estimates for the sands due to the limits of c_u indicated in Table 4. The authors consider that influence of the parameter c_u was neglected in his study, and thereby the grain size distribution results could yield the same c_u for various sands. Kozeny–Carman (K–C) formula, which is not applicable for neither clayey soils nor soils with effective size more than 3 mm, is one of the commonly employed approaches developed for hydraulic conductivity estimates (Carrier 2003). Actually, the Kozeny (1927) and Carman (1937) equations have been modified by certain researchers (Collins 1961; Bear 1972; de Marsily 1986), whom included the influence of both particle diameter and porosity on hydraulic conductivity. Koltermann and Gorelick (1995) compared five different approaches and found that the original Kozeny–Carman equation (Carman 1937; Bear 1972) lies approximately in the center of the possible relations. Koltermann and Gorelick (1995) used the geometric and harmonic means to calculate representative particle diameters for the high and low fraction of the coarse component, respectively. However, this approach produces a discontinuity when the fraction of the coarse component is at the intermediate level. Therefore, the authors employed the original Kozeny–Carman equation, then the Table 3 released that hydraulic conductivity values ranged from 4.93 to 0.02 cm/s for the NS samples, while those ranged from 12.36 to 0.03 cm/s for the CSS samples falling the same gradations. Estimated hydraulic conductivity values (k) by employing Terzaghi's approach varied from 2.38 to 0.01 cm/s for the NS samples, whilst the k values varied from 4.85 to 0.01 cm/s for CSS samples. Cheng and Chen (2007) pointed out that Terzaghi's formula is most applicable for large-grain sand. However, comparing the experimental results and the k values obtained via Terzaghi's approach revealed that Terzaghi's equation, which has no limitations reported (Table 4), gives more accurate results than the other equations employed for both NS and CSS samples between 1.18 and 0.075 mm, and 0.6 and 0.075 mm. Surprisingly, it gives much less accurate results for larger grains of both NS and CSS samples, including the size of 4.75–2, 2–1.18, and 4.75–0.425 mm. Therefore, the authors interpreted that grain size would not be the only parameter to make an accurate hydraulic conductivity estimate. Estimated *k* values via Chapuis formula gives the best correlation with measured *k* values for the NS samples between 0.425 and 0.075 mm. Generally speaking, estimated *k* values using Chapuis's approach ranged from 6.31 to 0.01 cm/*s* for the NS samples, whilst those ranged from 6.33 to 0.01 cm/*s* for the CSS samples falling the same gradations. In the light of the Goktepe and Sezer (2010), which indicated that Chapuis method best estimates the hydraulic conductivity of fine sands, the predictions were found to be acceptable for the NS samples but not for the CSS samples. The authors considered that such difference could be because of shape properties of the sand grains. Although Goktepe and Sezer (2010) indicated that the Chapuis and Slitcher approaches are in harmony with the results, the present study shows remarkable differences between these two approaches. Considering the differences in relative density values employed in these studies, the authors' interpretation is that such differences in the approaches could be the reason of high successes of the empirical equations. For example, the present study shows that Slitcher formula is the best fitted to the hydraulic conductivity of NS samples between 4.75 and 2 mm, 2 and 1.18 mm, 4.75 and 0.075 mm, 2 and 0.075 mm, 4.75 and 0.6 mm, 2 and 0.6 mm, 4.75 and 0.425 mm, 2 and 0.425 mm, 1.18 and 0.425 mm, and the hydraulic conductivity of CSS samples between 4.75 and 2 mm, 4.75 and 0.075 mm, 2 and 0.075 mm, 4.75 and 0.6 mm, 4.75 and 0.425 mm, 2 and 0.425 mm. However, Chapuis approach does not give similar results. The Naval Facilities Engineering Command (NAVFAC) suggested a chart to estimate the hydraulic conductivity of clean sand and gravel based on the *e* and d_{10}. Predicted *k* values using NAVFAC varied from 8.48 to 0.01 cm/s for the NS samples, and 13.24 to 0.04 cm/s for the CSS samples. The approach proposed by the United States Bureau of Reclamation (USBR 1990) estimates *k* values using the effective grain size (d_{20}), and it does not depend on the porosity (Table 4). Cheng and Chen (2007) stated that this approach is most suitable for medium-grain sand with c_u less than 5. Estimated *k* values using the USBR formula were found to be same for NS samples and CSS samples, which ranged from 4.46 to 0.01 cm/s, as they have the same gradations. It was observed that the USBR approach gave its best results for relatively large grain samples including those between 2 and 1.18 mm, 1.18 and 0.6 mm, 0.6 and 0.425 mm, and 1.18 and 0.425 mm. Alyamani and Sen (A–S), which is one of the widely known approaches to estimate the hydraulic conductivity, employs the grain size properties d_{10}, d_{50} and I_o. Alyamani and Sen (1993) proposed their equation based on different samples that incorporates the initial slope and the intercept of the grading curve. Estimated *k* values using the Alyamani and Sen approach ranged from 6.16 to 0.01 cm/sec for both type of sands. As can be seen from Table 3 that the A–S approach results in same estimates for both NS and CSS samples, as they have same grading curves. Similarly, Breyer method gave the same *k* values for both NS and CSS samples due to the same d_{10} value employed in this equation. The predicted *k* values ranged from 7.21 to 0.01 cm/s. Plots presented in Figs. 6 and 7 indicate comparisons of measured hydraulic conductivity (*k*) with predictions from various models for NS samples, and CSS samples, respectively.

Table 4

Empirical equations and their limitations for permeability estimates

Researcher/organization	Equation	Limitations
Hazen	$k = 6 \times 10^{-4} \times \frac{g}{v} \times [1 + 10(n - 0.26)] \times (d_{10})^2$	$C_u < 5$ $0.1 < d_{10} < 3.0$
Kozeny-Carman	$k = 8.3 \times 10^{-3} \times \frac{g}{v} \times [\frac{n^3}{(1-n)^2}] \times (d_{10})^2$	$0.5 < d_{10} < 4.0$
Terzaghi	$k = 0.0084 \times \frac{g}{v} \times [\frac{n-0.13}{\sqrt[3]{1-n}}]^2 \times (d_{10})^2$	–
Chapuis	$k = 1.5 \times (d_{10})^2 \times \frac{e^3}{1+e} \times \frac{1+e_{max}}{(e_{max})^3}$	–
Slitcher	$k = 1 \times 10^{-2} \times \frac{g}{v} \times n^{3.287} \times (d_{10})^2$	$0.01 < d_{10} < 5.0$
USBR	$k = 4.8 \times 10^{-3} \times \frac{g}{v} \times (d_{20})^{0.3} \times (d_{20})^2$	$C_u < 5$
NAVFAC	$k = 10^{1.291e-0.6435} \times (d_{10})10^{(0.5504-0.2937e)}$	$2 < C_u < 12$ $0.1 < d_{10} < 2.0$ $0.3 < e < 0.7$ $1.4 < \frac{d_{10}}{d_5}$
Alyamani and Sen	$k = 1300 \times [I_0+0.025(d_{50}-d_{10})]^2$	–
Breyer	$k = 6 \times 10^{-4} \times \frac{g}{v} \times \log[\frac{500}{C_u}] \times (d_{10})^2$	$0.06 < d_{10} < 0.6$ $1 < C_u < 20$

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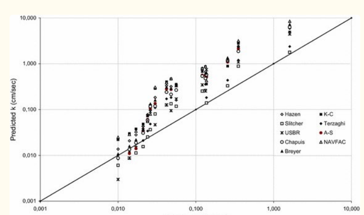

Fig. 6

Comparison of measured hydraulic conductivity (k) with predictions from various models for NS samples (*straight line* represents line of perfect equality)

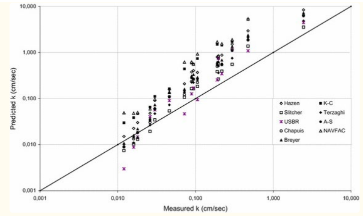

Fig. 7

Comparison of measured hydraulic conductivity (k) with predictions from various models for CSS samples (*straight line* represents line of perfect equality)

The differences between measured and predicted hydraulic conductivity values using various equations were because of either inaccuracy in measured soil parameters or deficiency in the predictive equations. Therefore, Table 5 and 6 were complied in order to present a comparative study for the NS and CSS samples using all the formulas employed in this study, respectively. The Tables 5 and 6 show the results of calculations performed with the objective of determining hydraulic conductivity according to the nine different approaches (Hazen, Slitcher, K–C, Terzaghi, USBR, Chapuis, A–S, Breyer, NAVFAC), expressed as a relative ratio of the difference between estimated and calculated values to the estimated hydraulic value of the NS and CSS samples at sixteen different gradations (4.75–2, 2–1.18, 1.18–0.6, 0.6–0.425, 0.425–0.3, 0.3–0.075, 4.75–0.075, 2–0.075, 1.18–0.075, 0.6–0.075, 0.425–0.075, 4.75–0.6, 2–0.6, 4.75–0.425, 2–0.425, 1.18–0.425 mm). The nine approaches used for comparison were listed from the best fitting on left to the worst fitting on right. For example, the best estimation of hydraulic conductivity for the NS samples between 4.75 mm and 2 mm was found to be based on Slitcher equation, followed by Terzaghi, USBR, Kozeny–Carman, Hazen, Alyamani–Sen, Chapius, Breyer, and NAVFAC equations, respectively. The authors have observed that, as an overall view, Slitcher and Terzaghi's approaches give the best correlation with measured *k* values for both NS and CSS samples, whilst Kozeny–Carman and NAVFAC approaches give the worst correlation with measured *k* values for both NS and CSS samples for any gradation.

Table 5

Comparisons for the NS samples

Gradation (mm)	Approaches used for comparison from the best fitting to the worst fitting							
	1 (best)	2	3	4	5	6	7	8	9 (worst)
4.75–2	Slitcher	Terzaghi	USBR	K–C	Hazen	A–S	Chapuis	Breyer	NAVFAC
2–1.18	Slitcher	USBR	Terzaghi	Chapuis	A–S	Breyer	Hazen	K–C	NAVFAC
1.18–0.6	USBR	Slitcher	Terzaghi	Chapuis	A–S	Breyer	Hazen	K–C	NAVFAC
0.6–0.425	USBR	Slitcher	Terzaghi	Chapuis	A–S	Breyer	Hazen	K–C	NAVFAC
0.425–0.3	USBR	Slitcher	Terzaghi	Chapuis	A–S	Breyer	Hazen	K–C	NAVFAC
4.75–0.075	Slitcher	Terzaghi	NAVFAC	USBR	K–C	A–S	Chapuis	Hazen	Breyer
2–0.075	Slitcher	Terzaghi	NAVFAC	USBR	Chapuis	A–S	Breyer	K–C	Hazen
1.18–0.075	Terzaghi	Slitcher	Chapuis	A–S	NAVFAC	Breyer	USBR	Hazen	K–C
0.6–0.075	Terzaghi	Chapuis	USBR	A–S	Breyer	Slitcher	Hazen	NAVFAC	K–C
0.425–0.075	Chapuis	Breyer	Terzaghi	A–S	USBR	Slitcher	Hazen	NAVFAC	K–C
0.3–0.075	Breyer	A–S	Chapuis	Terzaghi	Hazen	Slitcher	USBR	K–C	NAVFAC
4.75–0.6	Slitcher	Terzaghi	K–C	A–S	USBR	Hazen	NAVFAC	Chapuis	Breyer
2–0.6	Slitcher	Terzaghi	USBR	Chapuis	A–S	Breyer	Hazen	K–C	NAVFAC
4.75–0.425	Slitcher	Terzaghi	K–C	NAVFAC	A–S	Hazen	Chapuis	Breyer	USBR
2–0.425	Slitcher	Terzaghi	USBR	Chapuis	A–S	Breyer	NAVFAC	Hazen	K–C
1.18–0.425	Slitcher	USBR	Terzaghi	Chapuis	A–S	Beryer	Hazen	NAVFAC	K–C

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Table 6

Comparisons for the CSS samples

Gradation (mm)	Approaches used for comparison from the best fitting to the worst fitting								
	1 (best)	2	3	4	5	6	7	8	9 (worst)
4.75–2	Slitcher	USBR	Terzaghi	A–S	Chapuis	Breyer	Hazen	K–C	NAVFAC
2–1.18	USBR	Slitcher	Chapuis	Terzaghi	A–S	Breyer	Hazen	K–C	NAVFAC
1.18–0.6	USBR	Slitcher	Chapuis	Terzaghi	A–S	Breyer	Hazen	K–C	NAVFAC
0.6–0.425	USBR	Slitcher	Chapuis	Terzaghi	A–S	Breyer	Hazen	K–C	NAVFAC
0.425–0.3	USBR	Slitcher	Chapuis	A–S	Terzaghi	Breyer	Hazen	K–C	NAVFAC
4.75–0.075	Slitcher	Terzaghi	USBR	A–S	Chapuis	Breyer	NAVFAC	Hazen	K–C
2–0.075	Slitcher	Terzaghi	USBR	Chapuis	A–S	Breyer	Hazen	NAVFAC	K–C
1.18–0.075	Terzaghi	Slitcher	Chapuis	A–S	Breyer	USBR	Hazen	NAVFAC	K–C
0.6–0.075	Terzaghi	Chapuis	USBR	Breyer	A–S	Slitcher	Hazen	K–C	NAVFAC
0.425–0.075	Breyer	Terzaghi	Chapuis	A–S	Slitcher	Hazen	USBR	K–C	NAVFAC
0.3–0.075	Breyer	Terzaghi	Hazen	Chapuis	A–S	Slitcher	USBR	K–C	NAVFAC
4.75–0.6	Slitcher	Terzaghi	A–S	USBR	Chapuis	Breyer	Hazen	K–C	NAVFAC
2–0.6	USBR	Slitcher	Terzaghi	Chapuis	A–S	Breyer	Hazen	K–C	NAVFAC
4.75–0.425	Slitcher	Terzaghi	A–S	Chapuis	Breyer	Hazen	USBR	K–C	NAVFAC
2–0.425	Slitcher	USBR	Terzaghi	Chapuis	A–S	Breyer	Hazen	K–C	NAVFAC
1.18–0.425	USBR	Slitcher	Terzaghi	Chapuis	A–S	Breyer	Hazen	K–C	NAVFAC

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Nevertheless, despite the good predictions in certain grading of samples, the authors interpreted that reliability of these approaches is relatively low as that any system of analysis neglecting the effect of grain shape would be incomplete. Effect of gradation as well as grain shape on hydraulic conductivity values have been presented in Figs. 8 and 9. Effects of five different gradation including 4.75–2, 2–1.18, 1.18–0.6, 0.6–0.425, and 0.425–0.3 mm on hydraulic conductivity of NS and CSS samples were illustrated in Fig. 8. The highest value of hydraulic conductivity for the NS was found to be for the samples between 4.75 and 2 mm, and then followed by the samples between 2–1.18, 1.18–0.6, 0.6–0.425, and 0.425–0.3 mm, respectively. Effects of grain shape on hydraulic conductivity values was clearly seen in Fig. 9, which proves that samples with two different shapes could have a unique hydraulic conductivity value, likely due to the differences in shape characteristics (R, S) leading to the different void ratios (e).

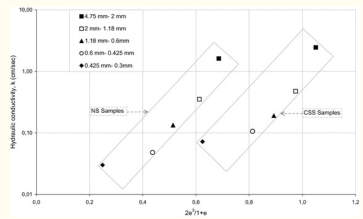

Fig. 8

Effects of gradation on hydraulic conductivity values of NS and CSS samples

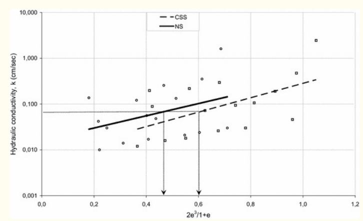

Fig. 9

Effects of grain shape on hydraulic conductivity values of tested samples

Conclusions

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The objective of this research was to study the influences of gradation and grain shape on hydraulic conductivity of soils, which is of importance in relation to certain geotechnical problems including stability analyses, settlement and seepage computations. The samples used in the present study are composed of poorly graded Narli Sand (NS) and Crushed Stone Sand (CSS), which were found to be rounded (R = 0.72, S = 0.67) and very angular (R = 0.15, S = 0.55), respectively. Sixteen ranges of grain sizes (4.75–2, 2–1.18, 1.18–0.6, 0.6–0.425, 0.425–0.3, 0.3–0.075, 4.75–0.075, 2–0.075, 1.18–0.075, 0.6–0.075, 0.425–0.075, 4.75–0.6, 2–0.6, 4.75–0.425, 2–0.425, and 1.18–0.425 mm) of both NS and CSS samples were tested in a constant head permeability testing apparatus at a relative density (D_r) of about 40 %. Moreover, various predictive methods of estimating the hydraulic conductivity values (Hazen, Kozeny–Carman, Terzaghi, Chapuis, Slitcher, USBR, NAVFAC, Alyamani and Sen, and Breyer) have been employed to compare the measured and estimated hydraulic conductivity results. In general, the Slitcher and Terzaghi's approaches give the best correlation with measured *k* values for both NS and CSS samples, whilst Kozeny–Carman and NAVFAC approaches give the worst correlation with measured *k* values for both NS and CSS samples for any gradation. The test results and comparative study reported here in this paper indicate following facets of behavior:

1. The hydraulic conductivity values of the NS samples with rounded grains were lower than those of the CSS samples with very angular grains, which is likely to be the result of shape characteristics leading different void ratios.
2. The hydraulic conductivity can be significantly influenced by grading characteristics including d_{10}, d_{20}, d_{30}, d_{50}, d_{60}, c_u, c_c, n, and I_o.
3. Gradation of the grains have a significant effect on hydraulic conductivity of both NS and CSS samples.
4. The comparative study on the perceptions of estimated and predicted results with other approaches available in the literature indicated that the best prediction of hydraulic conductivity changes based on the gradation and shape properties of the sands tested.

Authors' contributions

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NA carried out the experimental works. AFC prepared the manuscript including figures, tables, and discussing/comparing the results with the other papers in the literature. Both authors read and approved the final manuscript.

Competing interests

Both authors declare that they have no competing interests.

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Thursday 7 August 2014

Assessing Hydraulic Conductivity of Soils from Particle Size Data

This edition of the Preene Groundwater Consulting blog discusses methods for assessing hydraulic conductivity of soils from particle size data and highlights some of the potential pitfalls if these values are used in dewatering design and other geotechnical problems.

Previous blogs have addressed the question what is hydraulic conductivity? and have clarified the terminology. In geotechnical language hydraulic conductivity is often referred to as coefficient of permeability, most commonly shortened to permeability, but for simplicity we will use the term hydraulic conductivity throughout this blog.

There are several methods for assessing hydraulic conductivity as part of site investigation, including:

- Visual assessment – assessing the soil type or grading and, based on experience or published values, estimating an approximate range of hydraulic conductivity;

- Pumping tests – controlled and carefully monitored pumping from one or more wells, recording drawdown in observation wells and pumped flow rate;
- Borehole tests – In-situ tests (rising head, falling head, constant head tests) carried out in boreholes during drilling or later in monitoring wells;
- Laboratory tests – permeameter testing on core samples; and
- Particle size correlations – using empirical correlations to relate particle size distributions in granular soils to hydraulic conductivity.

It is the last of these – correlations between hydraulic conductivity and particle size distributions in granular soils – that will be discussed here.

SOIL AS A POROUS MEDIUM

Soil is a very complex medium. Conceptually it comprises a skeleton of soil particles in contact with each other, leaving a more or less interconnected system of pore spaces between them. When fluid flows through a soil (and if we assume the soil is saturated then that fluid is water) the flow occurs through the pore space (in the vast majority of soils the soil grains themselves can be considered impermeable). The concept of soils as being a 'porous medium' is fundamental to many analysis methods used for groundwater flow problems in soil in the fields of geotechnical engineering and hydrogeology.

Intuitively, it is easy to accept that the ability of a soil to transmit water (i.e. hydraulic conductivity) is controlled, at least in large part, by the nature of the soil pores (the viscosity of water, which will vary with temperature also has an effect, but experience suggests this will be small compared to the effect of the soil type). Features of the soil pores which may have an influence on the flow of water include: the size distribution of the pore space; the tortuosity of the pore space; and the shape and roughness of soil particles forming the edges of the pore space.

Idealised view of soil particles (in black) and surrounding pore space

On a micro-scale the pore spaces are probably a vastly complex hydrodynamic environment, and if it were possible to visualise what they really looked like the scene would probably seem like an alien world out of a science fiction movie. The pragmatic solution for practising engineers and hydrogeologists is to 'zoom out' and not to try and discern micro-scale properties but to look for 'average' or 'representative' parameters or depictions of soil properties. These are the hydraulic conductivity values routinely used in dewatering calculations.

In a porous medium the nature and properties of the pore space will be strongly influenced by the size, shape, roughness and other properties of the soil particles themselves. It is therefore a logical step to think that the hydraulic conductivity must be related in some way to the particle size distribution (and the other properties) of the particles. This has the advantage for practising engineers that we can determine the properties of the particles much more easily than we can determine the properties of the soil pores.

So, beginning in the 19th century, various analysts have developed correlations between the properties of the soil particles and hydraulic conductivity. The most well known is Hazen's rule, which dates from the 1890s, but there are many others that have been published, and these correlations are still used widely today.

The rest of this blog will discuss some of these hydraulic conductivity correlations. I am not recommending the correlations that are specifically mentioned here, or dismissing any correlations that I do not mention. The examples are simply used to allow discussion of the overall approach of estimating hydraulic conductivity from particle size distributions in granular soils.

WHERE DO THE HYDRAULIC CONDUCTIVITY RELATIONSHIPS COME FROM?

There are some important aspects about this type of hydraulic conductivity correlation that should be remembered when applying these methods for design purposes.

Most of these correlations are not theoretical, but are empirical – in other words they are based on observation. This may involve obtaining a sample of granular material, determining the properties of the particles (for example by sieving to determine particle size) and separately determining the hydraulic conductivity (for example by testing in a permeameter). When this is done for multiple samples it may be possible to identify relationships between hydraulic conductivity and the soil properties across the group of samples.

Furthermore, some of the correlations, including Hazen's rule, are not for soils at all, in fact they are for granular filter media for water treatment systems. Presumably at some point an enterprising person applied this to a geotechnical problem in sandy soil, liked the results, and the rest is history.

Because these are empirical correlations they are, by definition, applicable only to soils that are similar in nature to those tested in the original study. For example Hazen stated in his work that his rule was applicable over the range of $D10$ particle size 0.1mm to 3.0 mm and for soils having a uniformity coefficient ($D60/D10$) less than five. Unfortunately, this is often forgotten when using Hazen's rule, and there are many examples of it being applied outside its applicable range, where the results for estimated hydraulic conductivity are likely to be unrealistic. Similar limitations in the range of applicable soils apply to most other correlation methods.

By their nature empirical correlations tend to include some type of correlation factor to relate the particle size factors to hydraulic conductivity. There is a tendency to think of these correlation factors as 'constants', while in reality they will rarely be so. Inspection of the original work that developed the correlation often reveals that these factors are not constant but may vary with, for example, temperature and secondary particle characteristics such as angularity and surface roughness.

A final point is that the samples used to develop these correlations were almost certainly not under the same conditions as an in-situ soil. Consider a correlation developed using actual soil samples of a sandy soil (rather than the granular filter media used by, for example, Hazen).

- The first stage of the correlation work is that a soil sample must be obtained from a borehole or trial pit, which will disturb the sample and change its stress state and porosity. Fines may be lost from the sample by drainage, or fines may be added by drilling mud contamination. Part of the sample then has its particle size distribution determined in the laboratory by sieving, and perhaps the particle shape assessed by inspection with a lens or microscope. So we already have the risk that the particle size distribution may be unrepresentative due to the various changes the sample has experienced.
- The second stage is that a different part of the original sample will be tested in the laboratory (for example in a permeameter) to determine its hydraulic conductivity. It can be very difficult to replicate in-situ conditions of a granular soil in the permeameter, due to sample disturbance and stress changes. This introduces another potential error in the correlation. Some correlations may use hydraulic conductivity data from in-situ tests, but there are corresponding potential errors associated with that approach.

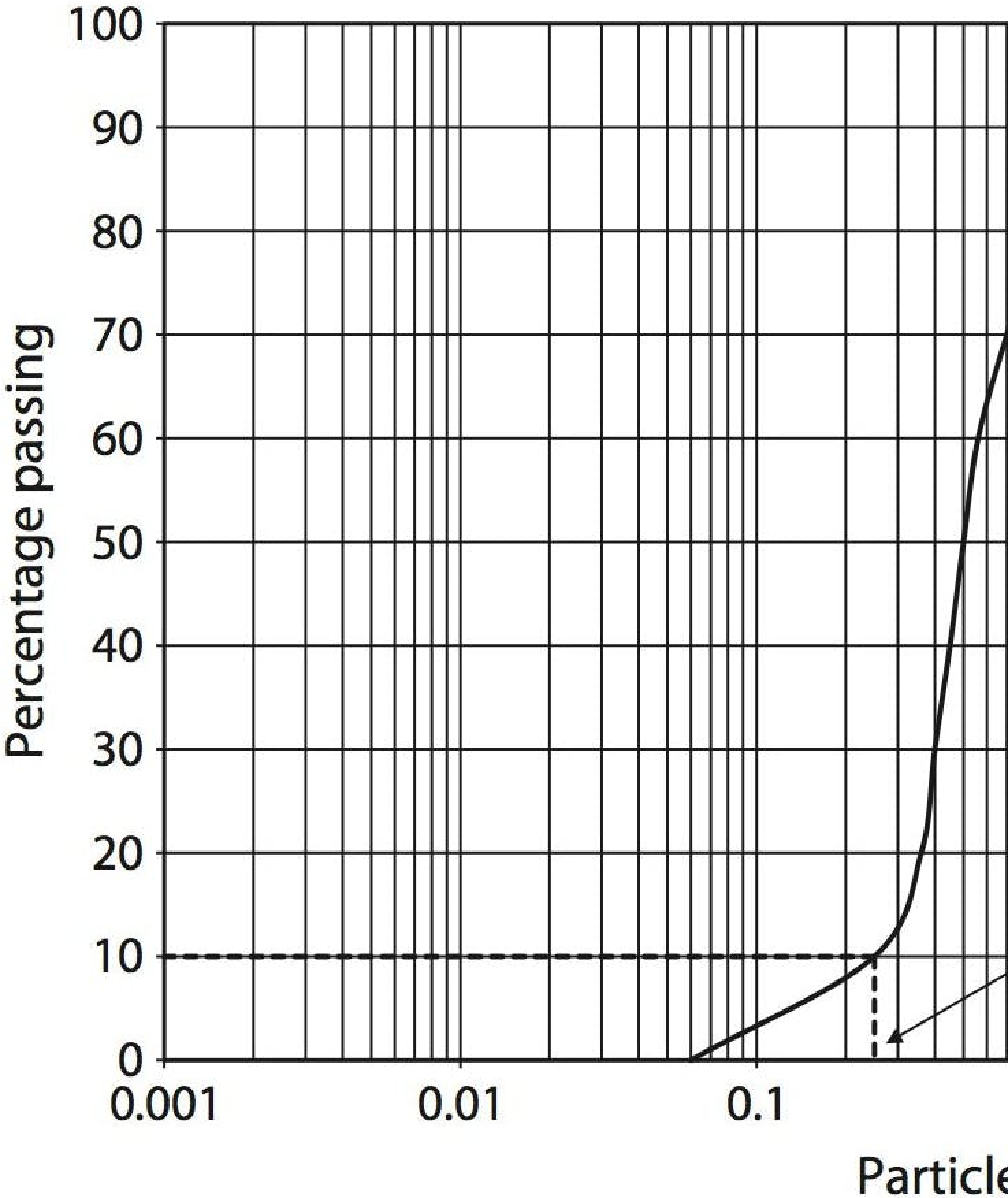
EXAMPLES OF RELATIONSHIPS BETWEEN HYDRAULIC CONDUCTIVITY AND PARTICLE SIZE

Despite these limitations, there are many correlations for granular soils that are widely used, particularly for dewatering design.

At the end of the 19th Century, Allen Hazen, a waterworks and sanitary engineer from New England in the United States was probably the first to propose an empirical correlation for the hydraulic conductivity of sand from its particle size distribution (PSD) curve. Probably due to its simplicity, Hazen's rule is widely used by today's geotechnical practitioners, often without due regard to the limitations that Hazen himself stated in his study, which was intended to determine guidelines for suitable sand gradings for water supply filtration. He determined that the *D10* particle size (called the 'effective grain size') and *D60/D10* (the 'uniformity coefficient') were both important factors. Hazen's rule to estimate hydraulic conductivity *k* is commonly expressed as:

$$k = C(D_{10})^2$$

Where *C* is a correlation factor and *D10* is the 10 per cent particle size taken from the particle size distribution curves (see image below).



Example of particle size distribution curve

Hazen also stated that (when *k* is in m/s and *D10* is in millimetres) the correlation factor *C* could vary between about 0.007 and 0.014. In geotechnical practice, presumably for reasons of simplicity, *C* is commonly taken to be 0.01. It cannot be stressed too strongly that, even within its range of application, Hazen's rule gives approximate hydraulic conductivity estimates only.

In the century following Hazen' s original work several others have developed expressions which relate particle size distributions of sands to hydraulic conductivity. This includes Slichter, Terzaghi, Kozeny and Rose (all reported in Loudon, 1952), Kozeny-Carman (reported in Carrier, 2003), Masch and Denny (reported in Trenter, 1999) and Prugh (originally reported in the first editions of Powers *et al,* 2007 and included in textbooks such as Cashman and Preene, 2012). Unlike Hazen, who did not seek to address in-situ soils, some correlations include for effects of porosity, angularity of the grains and specific surface of the grains. None claim to be relevant to soils other than 'a wide range of sands'.

One interesting source is Loudon (1952), which reviewed various published formulae and supplemented the review with laboratory investigations. This concluded that the error prediction using Hazen's rule could be of the order of plus or minus 200 per cent but that Kozeny's formula – which is similar to that of Terzaghi, though more complicated – was to be preferred to the various others. Loudon stated that an accuracy of about plus or minus 20 per cent can be expected from Kozeny's formula.

Loudon also proposed that his own formula, based on Kozeny, should be used for reasons of simplicity, where *k* is the hydraulic conductivity (in cm/s), n is the porosity of the soil (expressed as a fraction not a percentage), *S* is the specific surface of the particles (surface area per unit volume of particles, in units of cm2 per cm3) and *a* and b are correlation factors with values of 1.365 and 5.15 respectively.

$$\log_{10}(kS^2) = a + bn$$

The porosity of a sample can be very difficult to determine either in the laboratory or in-situ. This is a limitation on the usefulness of Loudon and other similar works and may be an explanation for the somewhat erratic results that they sometimes give.

POTENTIAL PITFALLS OF THE APPROACH

Even where hydraulic conductivity correlations are applied carefully and to high standards, there are several potential pitfalls to be aware of:

Applying the method to an inappropriate soil type: Any method for correlating hydraulic conductivity with particle size will have a corresponding range of granular soil types to which it is applicable. This will normally be stated in the original source references, and may be defined in terms of ranges of soil parameters such as *D10*, *D50*, *D60*, etc. If a correlation method is applied outside of its range of validity, then significant mis-estimates of hydraulic conductivity may result.

Samples tested for particle size may be unrepresentative of in-situ soil: The samples used for particle size testing may be unrepresentative. When bulk or disturbed samples are recovered from below the water level in a borehole there is a risk that finer particles will be washed from the sample. This is known as 'loss of fines'. Samples affected in this way will tend to give over-estimates of hydraulic conductivity. Loss of fines is particularly prevalent in disturbed samples taken from the drilling tools. Loss of fines is usually less severe for tube samples; these methods may give more representative samples in fine sands. Conversely, invasion of the samples by drilling mud during sampling may increase the fines content and result in under-estimation of hydraulic conductivity.

Effect of soil structure or fabric: Any soil structure or fabric (e.g. thin silt layers or laminations within a sand bed) present in the in-situ soil may be disturbed during sampling. Even if the fabric is well preserved in the sample itself, it will be destroyed by the process of test specimen preparation for particle size testing, when the sample is effectively homogenised. Hydraulic conductivity estimates based on the PSD curve of the resulting homogenised sample are likely to be unrepresentative of the in-situ hydraulic conductivity. For example, if a clean sand deposit does contain laminations of silt or clay, these will become mixed into the mass of the sample during preparation and the PSD curve will indicate clayey or silty sand; hydraulic conductivity may be under-estimated.

Effect of cementing of soil pores: In many parts of the world, such as the Middle East or locations with a tropical climate, some granular soils may have some weak cementing present between the soil particles, due to mineral deposits such as calcite. These mineral deposits forming the cement will take up some of the space within the soil pores, potentially reducing hydraulic conductivity. This cementing effect will be lost when the sample is broken up during test specimen preparation for particle size testing, and hydraulic conductivity correlations may give erroneous results.

CONCLUSION

Most projects that involve excavations in granular soils will have some particle size distribution (PSD) data available as part of the site investigation. Correlations with hydraulic conductivity are easy to apply, and are likely to remain part of dewatering design practice. The objective of this blog was to describe the background to these methods and discuss potential pitfalls. As stated earlier, I am not recommending any correlations that are specifically mentioned in this blog, or dismissing any correlations that are not mentioned, the examples are simply used to allow a discussion of the basis and validity of the approach.

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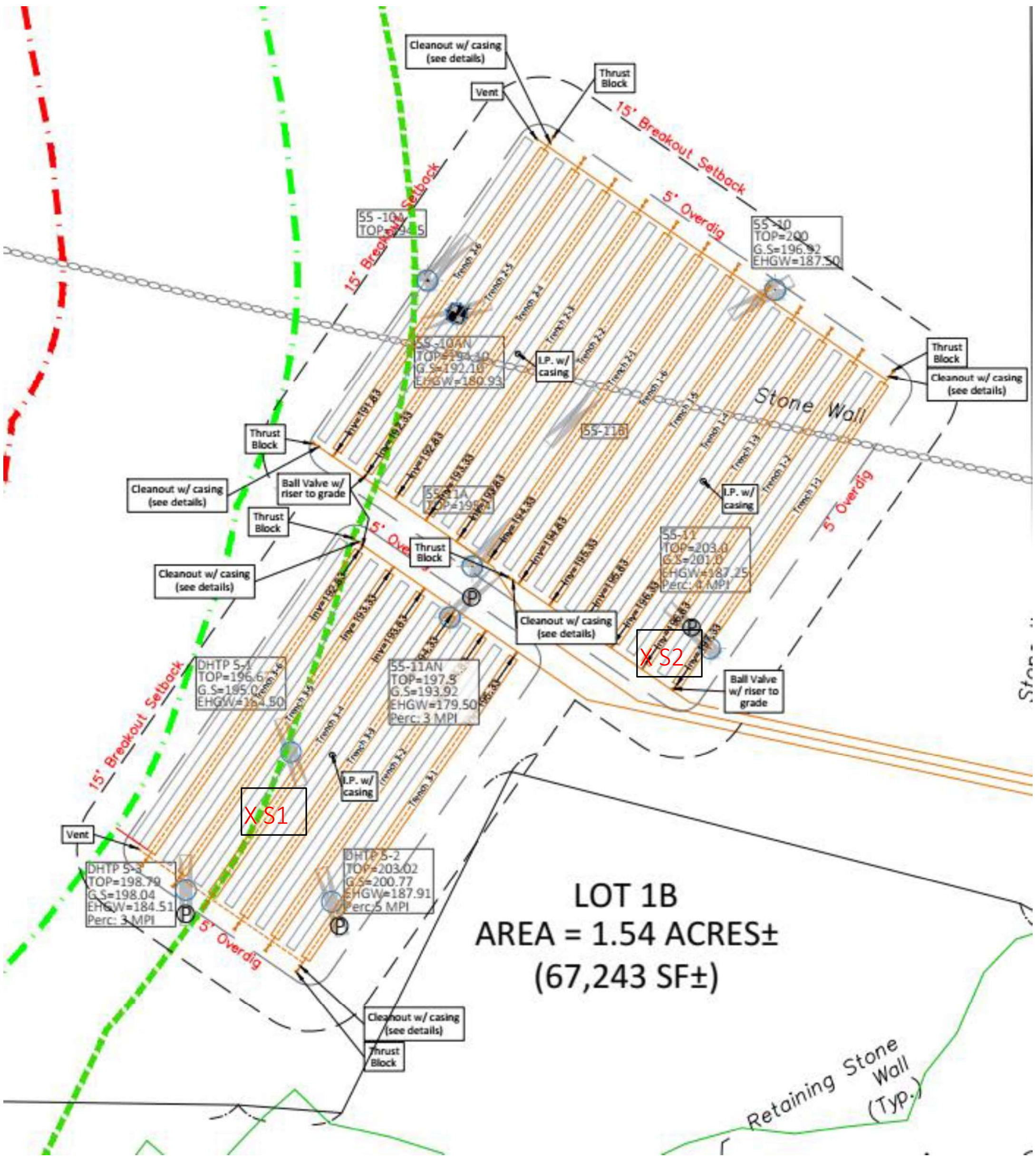
EXCERPTS FROM FEBRUARY 2, 2024 CLAWE
GROUNDWATER MOUNDING ANALYSIS APPENDIX

Table S2. Summary of soil texture analysis based on sieve analysis, 65 Farm Rd, Sherborn, MA

Soil Sample	Location	Sand, silt, and Clay compsition				Soil texture per USDA
		Sand % 0.05-2 mm	Silt % 0.002-0.05mm	Clay % <0.002mm	Total %	
S1	lower edge of SAS	92.53	5.6	1.87	100	medium sand
S2	upper edge of SAS	73.66	24.56	1.78	100	medium loamy sand
SA1	Stormwater Basin A	66.1	30.5	3.4	100	medium sand loam
SB-1	Stormwater Basin B-1	97.91	2.09	0	100	fine medium sand
SB-2	Stormwater Basin B-2	75.64	22.86	1.5	100	medium loamy sand
SC	Stormwater Basin C	91.46	6.71	1.83	100	medium sand



Location of soil samples in SAS area

Creative Land & Water Engineering, LLC
Environmental Science and Engineering
P.O. Box 584, Southborough, MA 01772
Tel: (508)281-1694 clawe@claweng.com

Subject: Permeability Estimate			
65 Farm Road	**Sieve by:** Yankee	**Date:** 1/9/2024	
Sherborn, MA 01770	**Calc.:** DSW	**Date:** 3-Feb-24	
	Job No.: J269-12	**Sheet:** 1 of 1	

Hazen Method

Input report:

Test pit:	S1-SAS	Soil:	Medium to Coarse sand	
Shape factor:	0.011	D10 (cm):	0.00962	Better for range 0.01 to 0.03 cm
Void ratio (e):	0.51	D60 (cm):	0.5	
Design temperature (C.degree):	20	Uniformity coef.(D60/D10):	51.98	Better for less or equal to 5
Gravity acceleration (cm/s^2):	981	D5(cm):	0.005	

Output report:

	Hanzen	Kenney**	Average
Permeability k (cm/s):	Ch*D10^2	Ch*D5^2*10^4/1.02	
Kinematic viscosity at 0 oC (cm^2/s):	0.01792		
Design kinematic viscosity (cm^2/s):	0.01017		
Coef Ch (1/s.cm):	93.21014	1	Average
	(range 100-150)	range 1-5	
Calculated permeability (cm/s):	0.008626 , or	0.25	
	0.00034 ft/sec	0.009843	5.09E-03 ft/s
	29.34 ft/day	850.39	439.87 ft/day
Rawls value	16.54	16.54	16.54 ft/day

Percolation rate: 3 mpi

Recommended Void Ratio for Sandy Soils

Soil	Void ratio
Sand, loose and uniform	0.85
Sand, dense and uniform	0.51
Sand, loose and mixed	0.67
Sand, dense and mixed	0.43
Loamy sand	0.6
Loamy sand, dense	0.4
Sandy loam	0.55
Sandy loam, dense	0.35

Ref. 1. Hazen method
2. Kenney TC, Lau D, Ofoegbu GI (1984) Permeability of compacted granular materials, CanGeotech J 21 (4): 726-729

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Tel: (508)281-1694 clawe@claweng.com

Subject: Permeability Estimate			
65 Farm Road	**Sieve by:** Yankee	**Date:** 1/9/2024	
Sherborn, MA 01770	**Calc.:** DSW	**Date:** 3-Feb-24	
	Job No.: J269-12	**Sheet:** 1 of 1	

Hazen Method

Input report:

Test pit:	S2-SAS	Soil:	Medium loamy sand	
Shape factor:	0.011	D10 (cm):	0.003	Better for range 0.01 to 0.03 cm
Void ratio (e):	0.6	D60 (cm):	0.36143	
Design temperature (C.degree):	20	Uniformity coef.(D60/D10):	120.48	Better for less or equal to 5
Gravity acceleration (cm/s^2):	981	D5(cm):	0.0015	

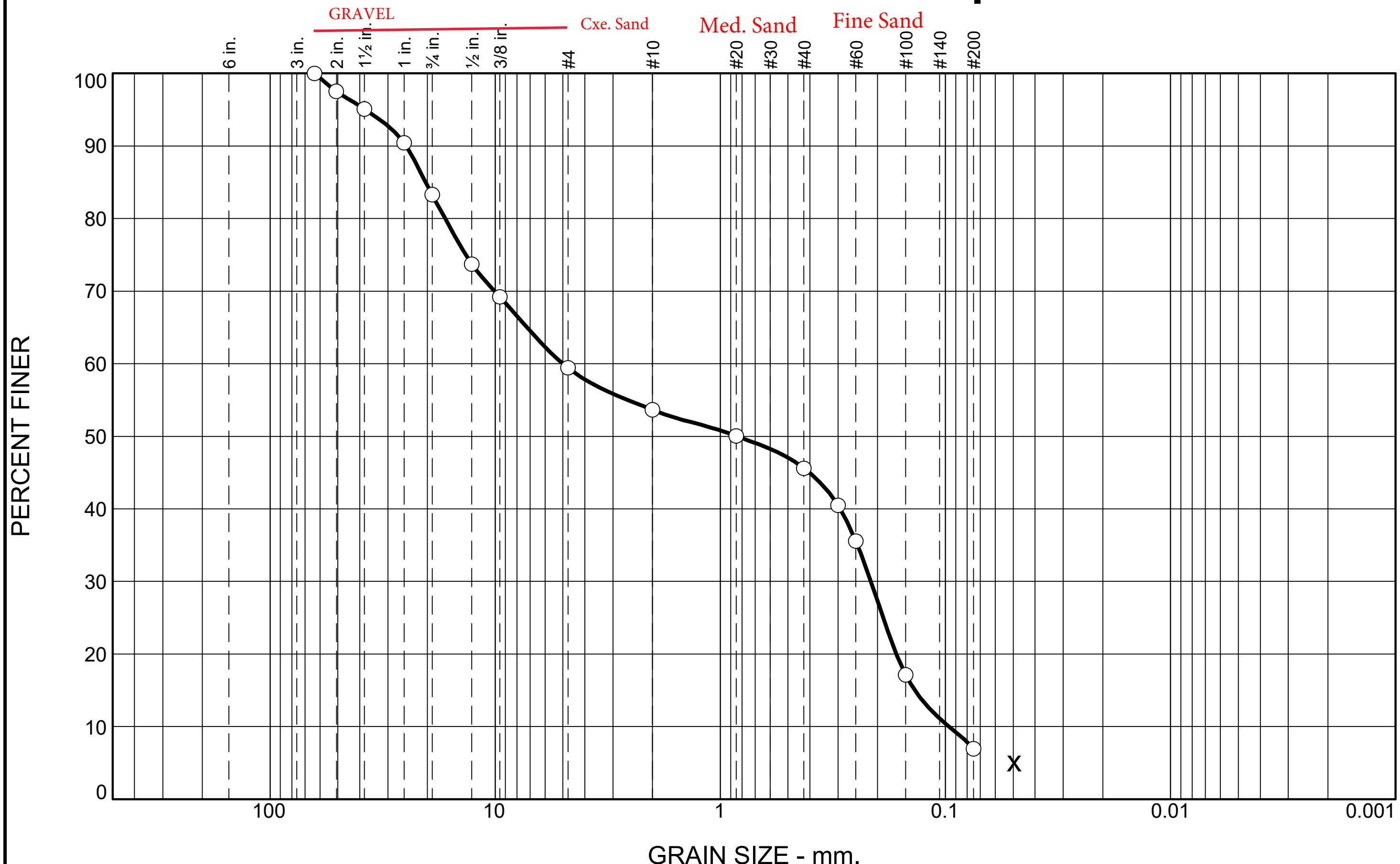
Output report:

	Hanzen	Kenney**	
Permeability k (cm/s):	Ch*D10^2	Ch*D5^2*10^4/1.02	
Kinematic viscosity at 0 oC (cm^2/s):	0.01792		
Design kinematic viscosity (cm^2/s):	0.01017		
Coef Ch (1/s.cm):	143.2397	1	Average
	range (100-150)	range 1-5	
Calculated permeability (cm/s):	0.001289 , or	0.0225	
	5.08E-05 ft/sec	0.000886 ft/s	4.68E-04 ft/s
	4.39 ft/day	76.54 ft/day	40.46 ft/day
Rawls value	4.82	4.82	4.82 ft/day
Percolation rate	5 mpi		

Recommended Void Ratio for Sandy Soils

Soil	Void ratio
Sand, loose and uniform	0.85
Sand, dense and uniform	0.51
Sand, loose and mixed	0.67
Sand, dense and mixed	0.43
Loamy sand	0.6
Loamy sand, dense	0.4
Sandy loam	0.55
Sandy loam, dense	0.35

Particle Size Distribution Report



% +3"	% Gravel		% Sand			% Fines	
	Coarse	Fine	Coarse	Medium	Fine	Silt	Clay
0.0	16.7	23.9	5.8	8.0	38.6	7.0	

SIEVE SIZE	PERCENT FINER	SPEC.* PERCENT	PASS? (X=NO)
2-1/2"	100.0		
2"	97.5		
1.5	95.1		
1	90.4		
.75	83.3		
.5	73.7		
3/8	69.2		
#4	59.4		
#10	53.6		
#20	50.0		
#40	45.6		
#50	40.5		
#60	35.6		
#100	17.1		
#200	7.0		

* (no specification provided)

Material Description

Brown 2.5" max f/m sand and gravel trace silt
USDA Class I Loamy Sand

Atterberg Limits

PL= NP LL= NV PI= NP

Coefficients

D_{85}= 20.3667 D_{60}= 5.0006 D_{50}= 0.8422
D_{30}= 0.2143 D_{15}= 0.1366 D_{10}= 0.0962
C_u= 51.96 C_c= 0.10

Classification

USCS= SP-SM AASHTO= A-1-b

Remarks

Sample submitted by client on 01/03/24

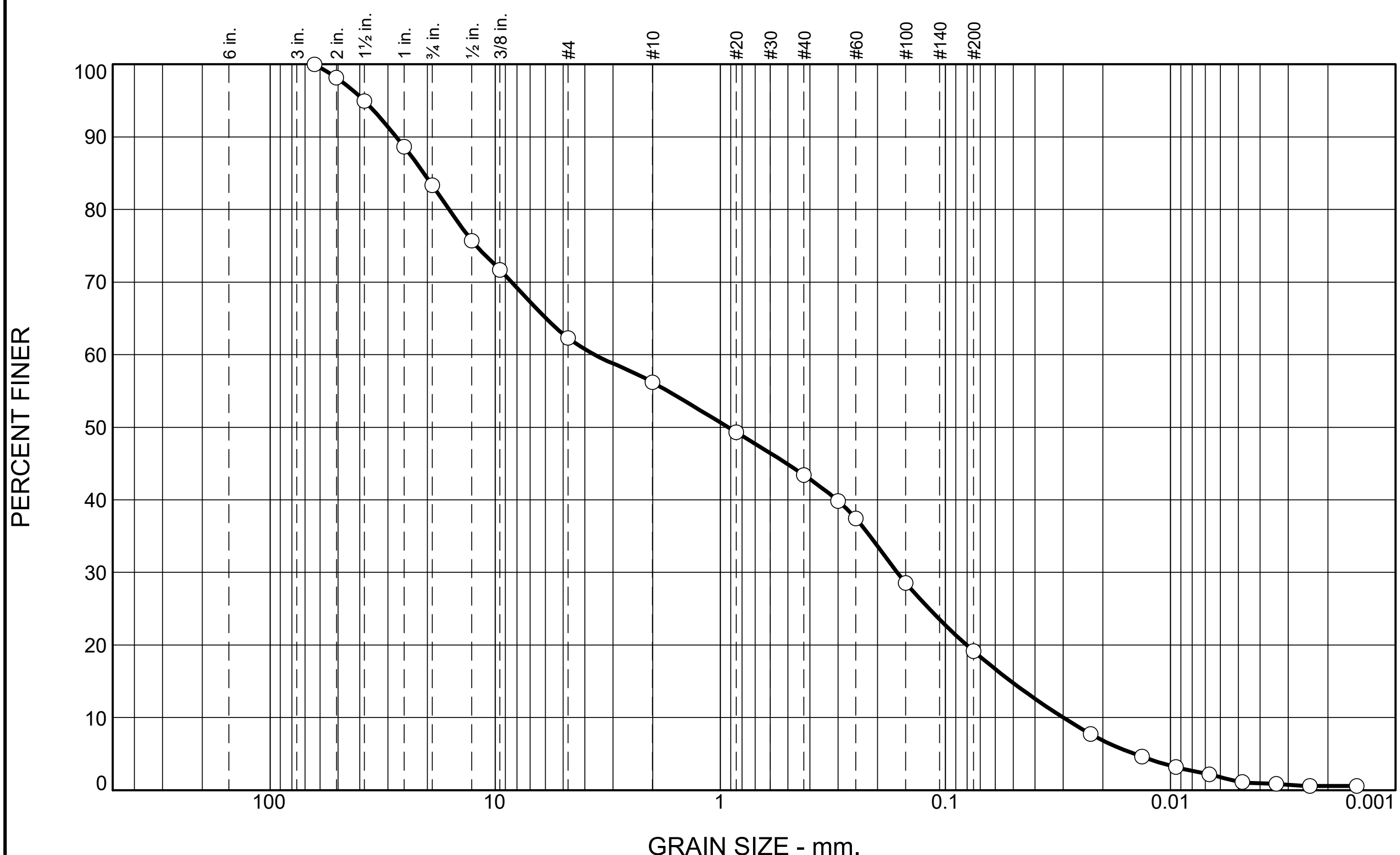
Sample No.: L-33929 **Source of Sample:** Farm Rd - Sherborn MA **Date:** 1/9/24
Location: S-1 Sample **Elev./Depth:** submitted

YANKEE ENGINEERING & TESTING, INC.

Client: Creative Land & Water Eng., LLC
Project: Creative Land & Water Eng., LLC
Various Sites/Projects
Project No: 15027

Tested By: AK **Checked By:** SMM

Particle Size Distribution Report



% +3"	% Gravel		% Sand			% Fines	
	Coarse	Fine	Coarse	Medium	Fine	Silt	Clay
0.0	16.6	21.1	6.1	12.8	24.2	18.0	1.2

SIEVE SIZE	PERCENT FINER	SPEC.* PERCENT	PASS? (X=NO)
2.5"	100.0		
2"	98.2		
1.5	95.0		
1	88.7		
.75	83.4		
.5	75.7		
3/8	71.7		
#4	62.3		
#10	56.2		
#20	49.3		
#40	43.4		
#50	39.8		
#60	37.4		
#100	28.6		
#200	19.2		

* (no specification provided)

Material Description

Brown 2.5" max silty sand and gravel
USDA Class I Loamy Sand

Atterberg Limits

PL= NP LL= NV PI= NP

Coefficients

D_{85}= 20.7906 D_{60}= 3.6143 D_{50}= 0.9228
D_{30}= 0.1638 D_{15}= 0.0511 D_{10}= 0.0300
C_u= 120.63 C_c= 0.25

Classification

USCS= SM AASHTO= A-1-b

Remarks

Sample submitted by client on 01/03/24

Sample No.: L-33931 **Source of Sample:** Farm Rd - Sherborn MA **Date:** 1/9/24
Location: S-2 Sample **Elev./Depth:** submitted

YANKEE ENGINEERING & TESTING, INC.

Client: Creative Land & Water Eng., LLC
Project: Creative Land & Water Eng., LLC
Various Sites/Projects
Project No: 15027

Tested By: AK / AH **Checked By:** SMM