Permeability calculation based on grain size analysis for hydrogeological-geotechnical investigation of Van Cao - Hoa Lac metro line

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Abstract: Permeability (K) is a fundamental parameter governing the design, construction, and operation of underground projects. Various methods have been developed to determine K; among them, estimation from grain size distribution is widely regarded as a simple and cost-effective approach. This study aims to estimate K from grain-size data using several empirical formulas applied to 14 samples collected during the hydrogeological-geotechnical investigations of the Van Cao-Hoa Lac metro project. The estimated K values were subsequently validated through two field pumping tests conducted at the corresponding boreholes with the purpose of identifying the most appropriate method for determining K. The mean K values obtained from different empirical methods varied by several orders of magnitude, with the Hazen method showing the closest agreement with those derived from pumping tests. The results indicate that grain-size-based formulas provide a reliable approach for evaluating aquifer permeability and offer valuable support during the preliminary design stage of the metro project.

Keywords: Permeability, grain size distribution, pumping test, hydrogeological-geotechnical investigation, Van Cao - Hoa Lac metro.

1. Introduction

Permeability (K) quantifies the ability of soil or rock to transmit water. In underground engineering projects, it represents a fundamental parameter for design and risk assessment. Accurate estimation of K is essential for predicting seepage behavior, evaluating hydrogeological risks, and developing effective groundwater control strategies. Moreover, it plays a vital role in managing groundwater levels during excavation and construction, selecting appropriate dewatering and waterproofing techniques, and conducting slope stability analyses. Permeability can be calculated directly from laboratory test such as constant head and falling head permeability test, or field tests such as field permeameter test, pumping test, slug test, infiltration test, and borehole dilution test. However, the directly measuring this parameter are both time-consuming and expensive.

Grain size analysis is a simple and basis laboratory test for any site geotechnical investigation. Calculate K based on grain size distribution has increasingly applied in practice within the last decades (Aguila et al., 2023). The first formula for estimation of K from grain size is introduced by Seelhim in 1988, since then a number of formulas have been established by works of Hazen, Kozeny, Beyer, Slitcher. et.al (Thomas. V, Peter. D, 2011). Each empirical formula for estimating permeability reflects specific soil conditions and provides a certain level of accuracy. Therefore, it is essential to evaluate how commonly used grain-size-based formulas perform when applied to the wide range of sediment types present in heterogeneous soil layers, and how well they predict K. Numerous studies have examined methods for determining permeability from grain-size analyses. However, many of these evaluations rely on reference methods with support volumes that differ significantly from those of grain-size measurements (Aguila et al., 2023) in which pumping test is most commonly used as it provides a high accuracy of K calculation.

To date, Vietnam has implemented only a modest number of underground construction projects. Nevertheless, ongoing infrastructure development has led to a marked increase in such works, particularly within major urban centers such as Hanoi and Ho Chi Minh City. Underground construction can induce substantial alterations to the aquifer system, while aquifer hydrogeological parameters, in turn, exert critical control over project design, construction methodologies, and operational performance. Despite this growing demand, lack number studies have been published in Vietnam that specifically address the determination of aquifer system parameters-particularly permeability (K)-for underground construction applications. The objective of this study is to estimate permeability (K) using several empirical formulations and to evaluate their applicability by comparing the estimated values with those obtained from pumping test data, with the aim of identifying the most suitable method for calculating K. Soil sampling and pumping tests were carried out along the Van Cao–Hoa Lac metro alignment, the fifth urban railway line in Hanoi. The outcomes of this investigation are expected to provide valuable insights into the hydrogeological conditions of the project area and to support the preliminary design phase of the metro line, thereby enhancing overall time and cost efficiency.

2. Methodology

2.1. Site investigation

The Hanoi urban railway line No. 5 (Van Cao-Hoa Lac) is designed as a double-track system with a standard gauge of 1,435 mm and a total length of approximately 39 km. The alignment includes about 6.5 km of underground section, 2 km of elevated track, and nearly 30 km is at ground level. Soil sampling and pumping tests were conducted at two boreholes (DYGA14 and DYGA17) as seen in Fig. 1. The total drilling depths of boreholes DYGA14 and DYGA17 were 44 m and 52 m, respectively. Soil samples were collected at 2 m intervals, comprising disturbed samples from sandy soil layers and undisturbed samples from clayey soil layers. After being sealed and properly labeled, the samples were transported to the laboratory for grain size analysis and other relevant tests.
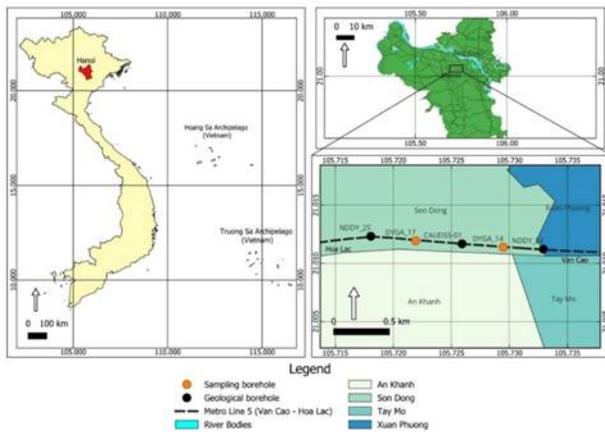

Figure 1. Location of study site and field works

As illustrated in Figure 2, the soil profile comprises Quaternary unconsolidated sediments subdivided into four distinct layers. In both boreholes, the uppermost layer consists of approximately 5 m of fill material, underlain by a medium silty clay layer extending to a depth of about 10 m. The third layer consists of fine sand in borehole DYGA14 and medium sand in borehole DYGA17, extending from depths of 10.6 m to 44.0 m and 10.4 m to 48.7 m, respectively. The bottom layer comprises a gravelly sand deposit encountered at the termination depth of both boreholes. Standard Penetration Tests (SPT) were conducted at 2 m intervals within the sand layers, with recorded SPT-N values ranging from 12 to 40, indicating loose to dense fine sand in DYGA14 and loose to dense medium sand in DYGA17.

The determination of K values from grain size analyses and pumping tests in this study was conducted for the third layer, identified as the confined aquifer. According to the drilling log descriptions, this aquifer is heterogeneous, with thin interbedded silty clay layers occurring at various depths within the sand sequence.

Grain size analyses were performed on a total of 14 samples, comprising eight samples from borehole DYGA14 and six samples from borehole DYGA17. The grain size distribution curves of representative specimens from the two boreholes are presented in Figure 4. According to the Unified Soil Classification System (ASTM D2487-11, 2011), the tested samples predominantly consist of sand, accounting for 65.6–91.1% of the total composition. The proportion of fines (passing the No. 200 sieve) ranges from 8.9% to 34.4%. Based on these results, the soils are classified as fine sand in borehole DYGA14 and medium sand in borehole DYGA17.
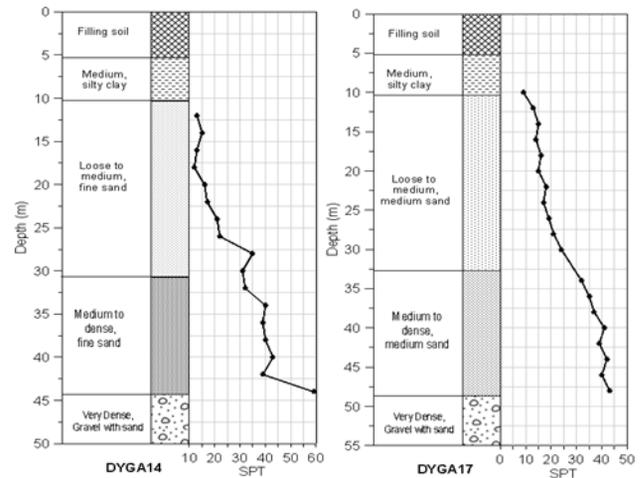

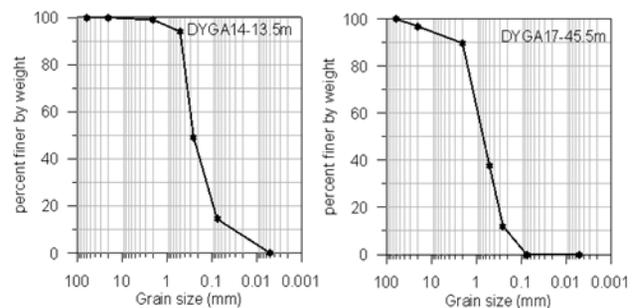**Figure 2.** Soil profile at borehole DYGA14 and DYGA17

Figure 3. Grain size distribution curves of the samples taken from DYGA14 and DYGA17

2.2. Estimation of permeability using grain size data

A general formula to calculate K based on grain size distribution is written as follow: $K = \frac{g}{v} \cdot C \cdot f(n) \cdot d_e^2$

Where:

K is permeability; g is gravity; υ is kinematic viscosity of water

C is an empirical coefficient; f(n) is porosity factor (n); d_e is the effective grain size

Based on this general formula, seven different empirical formulas for estimating K were proposed by

proposed by Hazen, Kozeny, Slitcher, Terzaghi, Breyer, the U.S. Bureau of Reclamation (USBR), and Alyamani and Sen. These formulas are applicable under specific soil conditions, as summarized in Table 1.

Table 1. Empirical formulas used to estimate permeability from grain size analysis (Aguila et al., 2023)

Method	C	f(n)	de	Application range
Hazen	$\frac{g}{\vartheta} \cdot (6.10^{-4})$	$1+10(n-0.26)$	d_{10}	0.01mm<de<3mm
Kozeny	$\frac{g}{\vartheta} \cdot (8.3.10^{-3})$	$\frac{n^3}{(1-n)^2}$	d_{10}	Large-grain sands
Slitcher	$\frac{g}{\vartheta} \cdot (10^{-2})$	$n^{3.287}$	d_{10}	0.01mm<de<5mm
Terzaghi	$\frac{g}{\vartheta} \cdot (8.4.10^{-3})$	$\left(\frac{n-0.13}{\sqrt[3]{1-n}}\right)^2$	d_{10}	Large-grain sands
Breyer	$\frac{g}{\vartheta} \cdot (6.10^{-4})\log(\frac{500}{C_u})$	1	d_{10}	0.06 mm<de<0.6mm, 1<Cu<20
USBR	$\frac{g}{\vartheta} \cdot (4.810^{-4})d_e^{0.3}$	1	d_{20}	Medium grain sands
Alyamani and Sen	0.015	1	$I_0^g + 0.025(d_{50}-d_{10})$	Well-graded sand (Cu<4)

C_u (= d_{60}/d_{10}) is the uniformity coefficient of the soil.

The grain size distribution of the soil samples was determined using sieve analysis for particles larger than 0.075 mm in diameter (sand and gravel fractions) and hydrometer analysis for particles smaller than 0.075 mm in diameter (silt and clay fractions). The grain size distribution curve was developed by plotting the cumulative percentage finer by weight on a logarithmic scale against particle size on an arithmetic scale (see Figure 3). The effective grain size (d_{10}) corresponds to the particle diameter at which 10% of the sample's weight is finer (Fetter.Jr, C.W, 2000). Similarly, d_{50} and d_{60} represent the grain sizes at 50% and 60% passing, respectively, and are obtained from the same curve. The porosity of each sample was calculated using the empirical relationship proposed by Vuković and Soro (Vukovic. M and Soro.A. 1992), as expressed below:

$$\phi = 0.255(1 + 0.83^U)$$

Where: ϕ is porosity; U (= d_{60}/d_{10}) is the uniformity coefficient.

2.3. Calculation of permeability from field pumping tests

Field pumping tests provide a good measurement for the permeability of an aquifer. When water is pumped from a well, the water level is lowered within the well thus creating a hydraulic gradient which causes the water to flow to the well lowering the water level in the aquifer which results in a cone of depression forming around the well. The hydraulic properties of the aquifer affect the drop in water depth and its lateral extent. Thus, the soil permeability of the aquifer is calculated using the field pumping measurements. In this study, four (02) field single pumping tests were conducted in accordance with TCVN 9148:2021 standard (TCVN 9148, 2021). A constant-rate pumping test and three multiple stage step-drawdown tests were conducted to determine aquifer parameters. Each step of pumping test carried out over 480 min and recover time 70 min. The constant-rate pumping test was carried out pumping 214.27 m³/d for the first step and 206.84 m³/d and 203.41 m³/d for the second and third stage, respectively. Water level variations were automatically measured using the CTD loggers installed in pumping wells.

The permeability (K) was calculated under the assumption that the pumping tests were conducted in confined aquifer conditions using a partially penetrating well, as described below:

$$K = \left[\frac{Q}{2\pi sM}\right]\left[ln\left(\frac{R}{r}\right) + \left(\frac{M-L}{L}\right)ln\left(1 + 0.2\frac{M}{r}\right)\right]$$

Where:
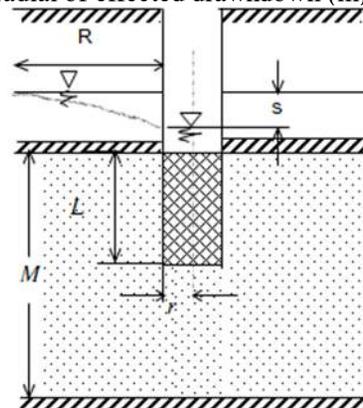K is permeability (m/d)
s is drawdown (m);
Q is flow rate of discharge pumping well (m³/d);
M is thickness of the confined aquifer (m);
L is screen length (m);
r is radial of screen (m);
R is radial of effected drawdown (m)

3. Results

3.1. Permeability estimation from grain size analysis

Based on the grain size distribution curves, the mean effective grain diameters (d_{10}) were determined to be 0.06 mm and 0.10 mm for boreholes DYGA14 and DYGA17, respectively (see Table 2). The soil samples obtained from boreholes DYGA14 and DYGA17 were classified as fine sand and medium sand, respectively, as described in Section 2.1. All samples exhibit a coefficient of uniformity (Cu) greater than 4, indicating poorly graded sand. Based on the applicability criteria of the various permeability (K) estimation methods (Table 1, Column 4), the Kozeny and Terzaghi formulas-typically applied to large grain sands-and the Alyamani and Sen formula-recommended for well-graded sands-are not suitable for the soil conditions encountered in this study. The samples satisfy the requirements for estimating K using the four empirical relationships proposed by Hazen, Breyer, Slitcher, and USBR.

The (K) values derived from grain size analyses are summarized in Table 2. For borehole DYGA17, the highest average K value was obtained using the USBR method (9.34 m/d), whereas the lowest was calculated using the Slitcher method (1.65 m/d). The average K values estimated using the Hazen and Breyer equations were 7.23 m/d and 8.97 m/d, respectively. As shown in Table 2, K values generally decrease with increasing depth for all methods, except for samples collected near the upper portion of the sand layer (at depths of 13.5 m and 45.5 m). Similarly, for borehole DYGA14, the highest average K value was obtained using the USBR method (3.83 m/d), while the lowest value (0.99 m/d) was derived from the Slitcher method. The Hazen and Breyer equations yielded average K values of 3.56 m/d and 3.75 m/d, respectively. However, the K values estimated for borehole DYGA14 show irregular variation with depth, reflecting the heterogeneity in soil composition within this layer.

Table 2. Calculated K values based on the results of the grain size analyses

Borehole code	Sample depth (m)	d_{10} (mm)	d_{20} (mm)	d_{60} (mm)	Cu	n	Permeability, K (m/d)			
							Hazen	Breyer	Slitcher	USBR
DYGA - 14	13.5	0.05	0.10	0.31	5.80	0.34	2.64	2.82	0.71	2.19
	17.5	0.02	0.06	0.32	14.13	0.27	0.29	0.40	0.06	0.63
	21.5	0.08	0.15	0.35	4.29	0.37	7.19	7.09	2.17	5.05
	25.5	0.05	0.09	0.28	5.74	0.34	2.27	2.42	0.61	1.78
	29.5	0.08	0.15	0.36	4.49	0.37	6.50	6.48	1.93	4.90
	33.5	0.07	0.14	0.36	5.29	0.35	4.46	4.64	1.24	4.71
	37.5	0.07	0.19	1.57	24.06	0.26	2.12	2.85	0.42	8.50
	41.5	0.06	0.12	0.39	6.61	0.33	3.01	3.34	0.77	2.88
	Average	0.06	0.12	0.49	8.80	0.33	3.56	3.75	0.99	3.83
DYGA - 17	13.5	0.13	0.24	0.97	7.33	0.32	14.19	16.25	3.49	14.97
	17.5	0.10	0.16	1.25	12.71	0.28	5.79	7.77	1.22	6.01
	25.5	0.08	0.20	1.09	14.53	0.27	3.19	4.38	0.66	10.00
	33.5	0.09	0.16	1.25	13.56	0.28	4.93	6.69	1.03	5.70
	37.5	0.10	0.20	0.92	8.78	0.30	8.03	9.74	1.86	10.03
	45.5	0.22	0.33	1.15	5.19	0.35	8.03	8.03	8.03	8.03
	Average	0.10	0.19	1.09	11.38	0.29	7.36	8.97	1.65	9.34

According to Thomas and Peter (2011), discrepancies in estimated permeability (K) among different methods may arise from the temperature-dependent assumptions embedded in each formula, which influence the kinematic viscosity of water. In addition, the porosity functions used in several empirical formulas were derived from laboratory measurements that may not accurately represent natural geological conditions (Thomas. V, Peter. D, 2011). Therefore, it is essential to validate K values obtained from empirical approaches using field-based observations. In this study, pumping tests were conducted to provide such validation.

3.2. Verification of estimated permeability using field pumping tests

Figure 4 illustrates the variation of groundwater levels with time until stabilization (steady-state condition) was achieved during the three pumping tests. At borehole DYGA14, steady state was reached approximately 450 minutes after the start of pumping in Tests 1 and 2, and about 50 minutes in Test 3. At borehole DYGA17, stabilization occurred after

approximately 420, 120, and 50 minutes for Tests 1, 2, and 3, respectively. The shorter stabilization times observed at DYGA17 indicate a higher permeability and a more responsive aquifer system compared to DYGA14, reflecting local variations in soil texture and permeability within the studied layer.
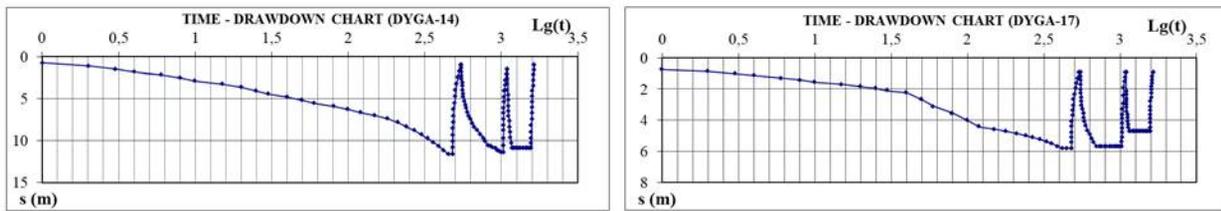

Figure 4. Variation of ground water level with time in borehole DYGA14 and DYGA17

The (K) values obtained from the pumping tests at borehole DYGA14 ranged from 3.35 to 3.43 m/d, with an average of 3.39 m/d. At borehole DYGA17, K values varied between 6.71 and 7.95 m/d, averaging 7.16 m/d (Table 3). Overall, the results indicate that the aquifer at DYGA17 exhibits approximately twice the permeability of DYGA14, consistent with the predominance of medium sand at DYGA17 and fine sand at DYGA14, as confirmed by the grain size analyses.

Table 3. K values obtained from the pumping tests

Borehole	Pumping test	r (m)	s (m)	Q (m³/d)	L (m)	M (m)	R (m)	K (m/d)
DYGA - 14	I	0.06	11.63	214.27	4	13.60	50	3.41
	II	0.06	11.42	206.84	4	13.60	50	3.35
	III	0.06	10.96	203.41	4	13.60	50	3.43
	Average							3.39
DYGA - 17	I	0.06	5.81	214.27	4	13.60	50	6.82
	II	0.06	5.70	206.84	4	13.60	50	6.71
	III	0.06	4.73	203.41	4	13.60	50	7.95
	Average							7.16

Comparison of permeability (K) values derived from grain size analyses (Table 2) and pumping tests (Table 3) shows the closest agreement between the Hazen-based estimates and the field-measured values. The Slitcher method yielded considerably lower K values, while the Breyer and USBR equations produced slightly higher estimates than those obtained from the pumping tests. These results indicate that the Hazen equation provides the most reliable estimation of K for the fine- to medium-sand materials investigated. The discrepancies between laboratory- and field-derived permeability (K) values likely reflect natural heterogeneity and scale effects within the aquifer. Grain-size analyses provide depth-specific estimates, whereas pumping tests yield effective horizontal K values for the broader aquifer. Because sedimentary processes create substantial vertical and horizontal variability-especially in deltaic environments such as Hanoi-the reliability of grain-size-based estimates can be limited. Nevertheless, due to their time and cost efficiency, grain-size-based formulas remain useful during the preliminary design stage of the Van Cao–Hoa Lac metro line.

4. Conclusion

The objective of this study was to compare commonly used empirical formulas for estimating permeability (K) from grain size data and to assess their predictive accuracy in sandy aquifer deposits. Given that the studied formation consists primarily of fine- to medium-grained sand, four empirical methods-Hazen, Breyer, Slitcher, and USBR-were applied to estimate K from grain size distributions. The K values derived from the Hazen equation closely matched those obtained from pumping tests (3.39 m/d vs. 3.59 m/d for DYGA14, and 7.36 m/d vs. 7.16 m/d for DYGA17). In contrast, the Slitcher method produced the lowest K estimates, while the Breyer and USBR methods yielded slightly higher values than the field results. The discrepancies between laboratory- and field-derived K values highlight the influence of natural heterogeneity and scale effects within the aquifer system. Overall, the findings demonstrate that the Hazen equation provides the most reliable estimates for fine- to medium-sand deposits, and that combining empirical and field-based approaches is essential for obtaining representative permeability values in similar geological settings along metro line and as well as other regions in Vietnam.

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