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Comparison of Theoretical and Laboratory Permeability for Coarse Grained Soil at Different Ground Conditions

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Abstract. The permeability of soil plays an important role in estimating the quantity of seepage under foundation of hydraulic structures which in turn affect the stability of structures. Empirical correlations such as Hazen, Kozeny-Carman, Breyer, Slitcher, Terzaghi, USBR, Alyamani & Sen are function of grain sizes, porosity/void ratio, coefficient of uniformity (C_u), co-efficient of curvature (Cc) and viscosity of pore fluids etc. These correlations are quite effective for preliminary assessment of permeability during prefeasibility stage. However, at the designing stage, actual measurement of permeability is very important for structural integrity. Soil is not homogeneous and permeability varies from location to location. Actual ground conditions vary from place to place. Moreover, soil profile is not uniform but varies from one section to other. In some places, it may be dense, partially dense, and loose or submerged in water. Depending upon the condition of ground, permeability will also vary from place to place. Keeping in mind the various ground conditions, attempt has been made to determine the coefficient of permeability on the soil samples remoulded at different compactness and moisture conditions. In the present study, attempt has been made to correlate permeability values obtained through different correlations with laboratories values. The study has been carried out with four different types of soils viz. (i) Sind River Sand (MP), (ii) Yamuna River sand, Delhi (iii) Rajasthan Crushed Sand and (iv) Ennore Standard Sand. The paper discusses the value of co-efficient of permeability determined in the laboratory and the values obtained theoretically at different conditions and presents the factors affecting the values.

Keywords: Co-efficient of uniformity; Co-efficient of curvature; co-efficient of permeability; constant head method; relative density

1 Introduction

Permeability is a direct function of average grain size distribution of granular porous media (Freeze and Cherry 1979). The inter relationship are quite effective for preliminary investigation especially at prefeasibility stage. But proper investigation of soil is required during the designing stage, it is important to know the actual response of soil towards permeability for structural integrity by laboratory methods. Several researchers made an effort to calculate the co-efficient of permeability and develop several indirect empirical formulae as laboratory testing sometimes takes considerable time in arriving at meaningful conclusion. Empirical correlations are function of grain sizes, porosity / void ratio, C_u, C_c and viscosity of pore fluids.

There are various empirical correlations available in the literature such as Hazen, Kozeny- Carman, Breyer, Slitcher, Terzaghi, USBR, Alyamani & Sen etc. Several investigators have studied these relationships and modified these formulae based on experimental work. The applicability of these formulae depends on the type of soil and compactness of the soil for which co-efficient of permeability is required to be estimated. As per Vukovic and Soro (1992), the applications of different empirical formulae to the same porous medium material can yield different values of co-efficient of permeability. Again, soil is not homogeneous and permeability varies from location to location. Actual ground conditions vary from place to place. Moreover soil profile is not uniform but varies from one section to other. In some places it may be dense, partially dense, and loose or submerged in water. Depending upon the condition of ground, permeability will also vary from place to place. Keeping in mind the various ground conditions, attempt has been made to determine the coefficient of permeability on the soil samples remoulded at different compactness and moisture conditions. In the present study, attempt has been made to correlate permeability values obtained through different correlations with laboratories values. The study has been carried out with four different types of soils viz. (i) Sind River Sand (MP), (ii) Yamuna River sand, Delhi (iii) Rajasthan Crushed Sand and (iv) Ennore Standard Sand. The paper discusses the value of co-efficient of permeability determined in the laboratory and the values obtained theoretically at different conditions and presents the factors affecting the values.

2 Established Empirical Formulae

Vukovic and Soro (1992) summarized several empirical methods from former studies and presented a general formula:

$$k=g/\nu.C.f(n).d_e^2 \qquad (1)$$

Where, k = co-efficient of permeability; g = acceleration due to gravity; ν = kinematic viscosity; C = sorting coefficient; f(n) = porosity function, and *de* = effective grain diameter. The kinematic viscosity (ν) is related to dynamic viscosity (μ), fluid (water) and density (ρ) as follows:

$$\nu=\mu/\rho \qquad (2)$$

The values of *C*, *n* and *de* are dependent on the different methods used in the grain-size analysis. According to Vukovic and Soro (1992), porosity (*n*) may be derived from the empirical relationship with the co-efficient of grain uniformity C_u as follows:

$$n = 0.255(10.83^{Cu}) \qquad (3)$$

Where C_u is the co-efficient of grain uniformity and is given by

$$C_u = d_{60}/d_{10} \quad (4)$$

Here, d_{60} and d_{10} in the formula represent the grain diameter in (mm) for which 60% and 10% of the sample respectively are finer than d_{60} and d_{10}.

Former studies presented the following formulae which took the general form and presented in equation (1) but with varying *C*, *f(n)* and *de* values and their domains of applicability.

2.1 Hazen formula

It was widely used for the estimation of co-efficient of permeability of uniformly graded soils ranges from fine sand to gravel of diameter 0.1 to 3 mm respectively and uniformity co-efficient less than 5. This formula only depends on the effective size of grains as

$$\kappa = (g/\nu)\times 6\times 10^{-4}[1+10(n-0.26)]d_{10}^2$$

2.2 Kozeny-Carman equation

The KC equation is not appropriate for soil with effective size above 3 mm or clayey soil (Carrier 2003). The KC equation is widely used and accepted for co-efficient of permeability estimation because it depends on both the effective grain size and porosity (number of pores) of the porous media as given below.

$$\kappa = (g/\nu)\times 8.3\times 10^{-3}[n^3/(1-n)^2]\ d_{10}^2$$

2.3 Breyer

This method does not consider porosity and therefore, porosity function takes on value 1. Breyer formula is often considered most useful for materials with heterogeneous distributions and poorly sorted grains with uniformity co-efficient between 1 and 20, and effective grain size between 0.06 mm and 0.6 mm.

$$\kappa = (g/\nu)\times 6\times 10^{-4}\times \log[500/U]d_{10}^2$$

2.4 Slitcher

This formula is most applicable for grain-size between 0.01mm and 5mm.

$$\kappa = (g/\nu)\times 1.0\times 10^{-2}\times n^{3.287}\times d_{10}^2$$

2.5 Terzaghi

$$\kappa = (g/\nu)\times C_t\times[(n-0.13)/\sqrt[3]{(1-n)}]^2\times d_{10}^2$$

where the C_t = sorting coefficient and. In this study, an average value of C_t is used. Terzaghi formula is most applicable for coarse-grain sand (Cheng and Chen 2007.)

2.6 USBR

$$\kappa = (g/\nu)\times4.8\times10^{-4}\times d_{20}^{0.3}\times d_{10}^{2}$$

U.S. Bureau of Reclamation (USBR) formula calculates co-efficient of permeability from the d_{20}, and does not depend on porosity; hence porosity function is a unity. The formula is most suitable for medium-grain sand with uniformity coefficient less than 5 (Cheng and Chen 2007).

2.7 Alyamani & Sen

$$\kappa = 1300\times[I_o+0.025(d_{50} - d_{10})]^2$$

where κ is the co-efficient of permeability (m/day), Io is the intercept (in mm) of the line formed by d_{50} and d_{10} with the grain-size axis, d_{10} is the effective grain diameter (mm), and d_{50} is the median grain diameter (mm). The method considers both sediment grain sizes d_{10} and d_{50} as well as the sorting characteristics. This formula therefore, is exceptionally different from those that take the general form of equation (1) above.

3 Materials and Methods

In order to compare results obtained from these correlations with the laboratory test results, 4 sandy soil samples were selected from different sources for comparing the permeability values and the photographs of samples selected are presented in Fig. 1. The particle size distributions of all 4 samples are presented in Table 1. The grain size distributions indicate that sample 1 and sample 4 have predominance of medium sand. Sample 2 has predominance of fine sand whereas sample 3 has fine to medium sand in equal proportions. The effective size 'd_{10}' value of these samples varies from 0.019 to 0.40. Cu for 3 samples are less than 5, whereas for sample no. 3, it is 28.95. The different grain sizes of the sands are presented in Table 2.

The maximum density, minimum density, required density at 95%, 85%, and 75% of relative density for all selected samples as well as relative density achieved due to wet packing are presented in Table 3. Samples were packed in permeability mould in dry loose packing, wet loose packing, packed at 95% of relative density, packed at 85% of relative density and packed at 75 % of relative density.

The photographs of the samples are presented in Fig. 1.


Sample-1 Sind River Sand (MP)
Sample-2 Yamuna River sand
Sample-3 Rajasthan Crushed Sand
Sample-4 Ennore Standard Sand

Fig. 1. Types of sand selected

The particle size distributions of all 4 samples are presented in Table 1

Table 1. Particle size distribution

Sample	Mechanical Analysis						Soil Type (IS:1498)	Remarks
	0.002mm & less	0.002 to 0.075mm	0.075 to 0.425mm	0.425 to 2.0mm	2.0 to 4.75mm	4.75mm & above		
	Clay	Silt	Fine Sand	Medium Sand	Coarse Sand	Gravel		
1	0.0	1.0	10.7	74.5	11.9	1.9	SP	Medium Sand
2	0.0	7.4	75.8	7.9	7.7	1.2	SP-SM	Fine Sand
3	0.9	17.9	35.5	37.2	8.5	0.0	SM	Fine Sand
4	0.0	1.7	26.5	70.7	1.1	0.0	SP	Medium Sand

The different grain sizes of samples are presented in Table 2

Table 2. Different grain sizes of samples

Parameters	Sind River Sand (MP)	Yamuna River sand	Rajasthan Crushed Sand	Ennore Standard Sand
d_{10}	0.40	0.09	0.019	0.19
d_{20}	0.55	0.13	0.085	0.32
d_{30}	0.69	0.17	0.16	0.47
d_{50}	1.00	0.22	0.35	0.72
d_{60}	1.30	0.26	0.55	0.90
C_u	3.25	2.89	28.95	4.74

The relative density of the soil samples were determined according to IS 2720 (Part 14) 1986.

Here, for calculation of required density γ_d at which samples are packed, relative density (I_d) were considered as 95 %, 85 % & 75 %. Moreover the maximum density, minimum density, required density at 95%, 85%, and 75 % of relative density for all selected samples as well as relative density achieved due to wet packing are presented in Table 3.

Table 3. Calculated values of minimum, maximum and required density

Type of Soil	Sind River Sand (MP)	Yamuna River Sand	Crushed Sand Rajasthan	Ennore Standard Sand
Min density, γ_{min} (g/cc)	1.57	1.37	1.32	1.55
Max density, γ_{max} (g/cc)	1.99	1.76	1.66	1.79
Required density @ 95% of relative density, γ_d (g/cc)	1.96	1.74	1.64	1.78
Required density @ 85% of relative density, γ_d (g/cc)	1.91	1.69	1.60	1.75
Required density @ 85% of relative density, γ_d (g/cc)	1.87	1.64	1.56	1.72
Relative Density Achieved due to wet Packing (%)	32.3	47.2	58.6	36.2

4 Preparation of Test Sample

In the present study, the theoretical values of co-efficient of permeability's are to be compared with laboratory co-efficient of permeability's compacted at different ground conditions like i) 95% relative density, ii) 85 % relative density, iii) 75 % relative density iv) dry loose packing i.e. at minimum density and v) wet loose packing . These ground conditions can be achieved by compacting by rodding, dry pouring and placing under water as par Head (1994). The methods of compaction are given below:

4.1 Compacting by rodding

For achieving compactness closer to 95 %, 85% & 75% of maximum relative densities, compacting by rodding are used.

4.2 Dry pouring

When the sample is to be packed at minimum/low density, dry pouring of sample is used. Here a funnel fitted with a length of flexible tubing, long enough to reach the bottom of the permeameter cell is used for pouring the sample The pouring is to be continued until the surface of the sand is at the correct level. The surface is to be levelled carefully with the minimum disturbance. The jolting of the cell or agitating the sample is to be avoided for packing the sample in low density.

4.3 Placing under Water

Here, the valve on the base of the permeameter cell to be connected to the de-aired water supply and then valve to be opened to allow water to enter the cell to about 15mm above the porous disc. Now a large funnel fitted with a bung attached to a string or wire is to be supported over the cell, so that tubing reaches to the surface of water in the cell. Sample is now poured into the funnel. Now the funnel is to be raised so that the end of tubing is just at the water surface. The water surface is to be maintained at about 15 mm above the surface of the placed soil by admitting more water through the base valve. The process is to be continued until the required amount of soil has been deposited in the cell, and water added.

The laboratory permeability were determined by constant head method as described in IS 2720 (Part 17) – 1986 and results are presented in Table No. 4

Table 4. Result of Constant head permeability test

S. No.	Type of Sand	'k'(cm/sec) 95% Max. RD	'k'(cm/sec) 85% Max. RD	'k'(cm/sec) 75% Max. RD	'k'(cm/sec) Dry Packing, Mini. RD	'k'(cm/sec) Wet Packing
1	Sind River Sand (MP)	0.40 x10^{-04}	0.59 x10^{-04}	1.06 x10^{-04}	2.2 x10^{-04}	0.79 x10^{-04}
2	Yamuna River sand	0.31 x10^{-04}	0.53 x10^{-04}	0.99 x10^{-04}	1.96 x10^{-04}	0.57 x10^{-04}
3	Rajasthan Crushed Sand	0.10 x10^{-04}	0.18 x10^{-04}	0.37 x10^{-04}	0.67 x10^{-04}	0.18 x10^{-04}
4	Ennore Standard Sand	0.78 x10^{-04}	1.15 x10^{-04}	1.75 x10^{-04}	3.77 x10^{-04}	1.2 x10^{-04}

The co-efficient of permeability calculated from grain-size analysis using empirical formulae are presented in Table 5

Table 5. Co-efficient of permeability based on empirical equations

Type of Sand	Hazen 'k' (cm/sec)	Kozeny-Carman 'k' (cm/sec)	Breyer 'k' (cm/sec)	Sitcher 'k' (cm/sec)	Terzaghi 'k' (cm/sec)	USBR 'k' (cm/sec)	Alyamani & Sen 'k' (cm/sec)
Sind River Sand (MP)	2.19 x10^{-01}	9.43 x10^{-02}	2.05 x10^{-01}	7.32 x10^{-02}	NA	1.49 x10^{-02}	1.49 x10^{-01}

Yamuna River sand	1.16 x10^{-02}	5.17 x10^{-03}	1.06 x10^{-02}	4.03 x10^{-03}	NA	NA	6.02 x10^{-03}
Rajasthan Crushed Sand	NA	5.21 x10^{-05}	2.66 x10^{-04}	4.05 x10^{-05}	NA	NA	2.26 x10^{-04}
Ennore Standard Sand	4.23 x10^{-02}	1.57 x10^{-02}	4.28 x10^{-02}	1.23 x10^{-02}	NA	4.29 x10^{-03}	4.01 x10^{-02}

5 Result and Discussions

5.1 Theoretical permeability

The comparison of results of permeability values obtained through existing correlations and laboratory permeability values calculated at different ground conditions are presented in Table 4 and Table 5 respectively. The basic reason for this divergence is due to applicability of these formulae under restrictive conditions. Further, depending upon gradations of different type of sand applicability of these formulae are questionable as explained below.

The Hazen and USBR methods is applicable in soil where C_u <5. However for Rajasthan crushed sand (sample no 3) the C_u value is 28.7 therefore this formula is not applicable sample no. 3. Further, Terzaghi method is suitable for coarse sand only therefore this empirical correlation cannot be correctly used for medium and fine sand. USBR method is applicable to medium sand, so it cannot be used for coarse and fine sand.

Overall results showed that the co-efficient of permeability calculated by the USBR and Slitcher methods are giving lower values as compared to other methods as presented in Table 5. These values are in consistent with the conclusions by (Vukovic and Soro 1992) and (Cheng and Chen 2007) method. Breyer method is most useful for analyzing heterogeneous sample with well-graded grain (Pinder and Ceila 2006). It is the best estimator for sample no.3. However, for less heterogeneous sample i.e. sample no. 1, 2 and 4, this method underestimates the values. Hazen formula which is based only on the d_{10} particle size is less accurate than Kozney-Carman formula, which is based on entire particle size distribution and particle shape (Carrier 2003). Therefore, the estimations by Kozney-Carman for sample no. (1, 2 & 4) are more accurate than Hazen, and possibly the best estimation in the study. Alyamani and Sen Method is very sensitive to the shape of the grading curve and more accurate for well-graded sample.

Therefore, the most suitable formulae for estimation of co-efficient of permeability in the studies are as follows:

Sample 1 (Kozney-Carman formula) = 9.43x10^{-02} cm/sec, Sample 2 (Kozney-Carman formula) = 5.17x10^{-03} cm/sec, Sample 3 (Breyer formula) = 2.66x10^{-04} cm/sec, with value of constant head parameter acceptable and Sample 4 (Kozney-Carman formula) = 1.57x10^{-02} cm/sec.

The results are also compared with Odong (2007) and same indicate close resemblance in terms of applicability of correlation for assessment of permeability of different type of sands.

Moreover from empirical equations:

$$k_{\text{Sind River Sand (MP)}} > k_{\text{Ennore Standard Sand}} > k_{\text{Yamuna River sand}} > k_{\text{Rajasthan Crushed Sand}}$$

5.2 Results of comparison of laboratory co-efficient of permeability determined at different conditions

Soil is not homogeneous and permeability varies from location to location. An actual ground condition varies from place to place. Moreover soil profile is not uniform but varies from one section to other. In some places it may be dense, partially dense, and loose or submerged in water. Depending upon the condition of ground, permeability will also vary from place to place. Keeping in mind the various ground conditions, attempt has been made to determine the coefficient of permeability on the soil samples remoulded at different compactness and moisture conditions. In the present study sands are compacted at different conditions:

Dry packing, loose condition, minimum relative density. In case of dry packing, loose condition, the general sequence of laboratory values of co-efficient of permeability in decreasing order as follows:

$$k_{\text{Ennore Standard Sand}} > k_{\text{Sind River Sand (MP)}} > k_{\text{Yamuna River sand}} > k_{\text{Rajasthan Crushed Sand}}$$

From the above equation, it is clear that permeability values are more for medium grained sand, however sand containing 17.9 % silt is having lowest value. Silt helps in filling the voids in between sands, thus reducing permeability value.

In comparison with theoretical permeability values, it is seen that laboratory values of co-efficient of permeability (from Table No. 4 & Table No. 5) of all the sand compacted in dry and loose condition are far lesser than theoretical values. The basic reason for this divergence is due to applicability of these formulae under restrictive conditions. Further, depending upon gradations of different type of sand applicability of these formulae are questionable as explained above.

Wet packing, loose condition. In case of wet packing, loose condition, the general sequence of laboratory values of co-efficient of permeability in decreasing order as follows:

$$k_{\text{Ennore Standard Sand}} > k_{\text{Sind River Sand (MP)}} > k_{\text{Yamuna River sand}} > k_{\text{Rajasthan Crushed Sand}}$$

In comparison with theoretical values, laboratory values of co-efficient of permeability of all the sand samples compacted in wet loose condition are much lesser than theoretical vales.

When compared with the samples packed in dry and loose condition, it is seen that sand samples packed dry but in presence of water, the co-efficient of permeability values reduced approximately to $(1/3)^{rd}$ to $(1/4)^{th}$ of the values of co-efficient of permeability of dry packing, loose condition. It is also seen that due to packing in presence of water, relative density of samples have increased to 32.3 % for Sand sample of Sind River, MP, 47.2 % for Yamuna river sand, 58.6 % for Rajasthan Crushed sand and 36.2 % for Ennore standard sand. Generally larger grains have higher settling velocity than small grains. So when grains settle through fluids the larger grains will impact substrate with larger momentum, possibly jolting the grains into tighter packing, therefore with lower porosity and thus increased relative density. Out of all the samples, one with larger silt percentage (17.9%) i.e. Rajasthan crushed sand gained highest relative density and Sind river Sand, MP with 1 % silt content gained lowest relative density . the sequence is as follows:

$$RD_{\text{Rajasthan crushed sand (17.9 \% silt)}} > RD_{\text{Yamuna river sand (7.4 \% silt)}} >$$
$$RD_{\text{Standard sand (1.7 \% silt)}} > RD_{\text{Sind river MP (1.0 \% silt)}}$$

So, increase in RD values due to wet packing varies from 32. 3 % to 58.6 %, which indicates loose packing in presence of water has improved compactness to medium compactness.

Again, when we compared co-efficient of permeability values due to wet packing with laboratory co-efficient values of dry packing compacted at 75% and 85% of relative density respectively, it is theoretically understood that RD values should have increased to approximately 80% due to wet packing , but in actual it increased only up to values varies from 32.3% to 58.6%. This may be because, probability of presence of any air voids or air bubbles might have replaced with water thus further reducing the co-efficient of permeability. Packing in presence of water helped in removing entrapped bubbles of air present between sand particles as well as water acts as lubricating agents for particles to come close to each other and thus reducing permeability values of all four type of sand significantly.

Dry packing, packed at 95 %, 85 % and 75 % of maximum relative density. In case of dry packing, packed at 95%, 85% and 75% of maximum relative density the general sequence of laboratory values of co-efficient of permeability in decreasing order as follows:

$$k_{\text{Ennore Standard Sand}} > k_{\text{Sind River Sand (MP)}} > k_{\text{Yamuna River sand}} > k_{\text{Rajasthan Crushed Sand}}$$

In comparison with theoretical values, laboratory values of co-efficient of permeability of all the sand samples compacted as dry packing packed at 95%, 85% and 75% of maximum relative density are much lesser than theoretical values.

Moreover as the relative density of sand samples increases, co-efficient of permeability of sand decreases and vice-versa.

Overall comparison. It is seen that for all the conditions, the general sequence of co-efficient of permeability values are:

$$k_{\text{theoretical values}} > k_{\text{dry packing}} > k_{\text{packed at 75 \% relative density}} > k_{\text{wet packing}} > k_{\text{packed at 85 \% relative density}} > k_{\text{packed at 95 \% relative density}}$$

From the above equation it is generally clear that, as the relative density of samples increases, co-efficient of permeability values decreases and vice versa. It is because as relative density increases voids between the sand particles decreases and thus reduces the values of co-efficient of permeability. However co-efficient of permeability values due to wet packing come in between the values compacted at 75% & 85% relative density respectively.

Further co-efficient of permeability of the samples packed at 95% of maximum relative density reduced to approximately half when compared with samples packed in presence of water.

6 Conclusions

Based on the present study, the following conclusions can be drawn

1. Empirical equations used for estimating the co efficient of permeability of soils can relatively lead to underestimation or overestimation unless the appropriate method is used.
2. Compare to empirical values in most of the samples (except sample no.3), laboratory constant head methods yields very lower values of co-efficient of permeability. The correlations of grain-size analyses with laboratory constant head methods are generally much weaker, when samples are compacted at 95% of relative density.
3. Kozney-Carman's formula followed by Hazen formula is the best empirical equations, used for wide range of soil sample. However, Breyer formula is the best for estimation of highly heterogeneous soil sample.
4. Slitcher, Terzaghi and USBR formulae grossly underestimated the coefficient of permeability in comparison to other evaluated formulae.
5. For all the four types of sand, co-efficient of permeability comes out highest for dry packing condition and lowest for samples packed at 95% of maximum relative density.
6. As the relative density of samples increases, co-efficient of permeability values decreases and vice versa.
7. It is also seen that due to packing in presence of water, relative density of samples have increased to 32.3% for Sand sample of Sind River, MP, 47.2% for Yamuna river sand, 58.6% for Rajasthan Crushed sand and 36.2% for Ennore standard sand.
8. Co-efficient of permeability of samples packed in loose condition but in presence of water is approximately to 1/3rd to ¼th of the values of co-efficient of permeability of samples which is dry packed & in loose condition.

9. Co-efficient of permeability of the samples packed at 95% of maximum relative density reduced to approximately half when samples are packed in presence of water & in loose condition.
10. It is seen that for all the conditions, the general sequence of co-efficient of permeability values are:

$$k_{\text{theoretical values}} > k_{\text{dry packing}} > k_{\text{packed at 75 \% relative density}} > k_{\text{wet packing}} >$$
$$k_{\text{packed at 85 \% relative density}} > k_{\text{packed at 95 \% relative density}}$$

11. Irrespective of types of packing , the general sequence of co-efficient of permeability values are :

$$k_{\text{Ennore Standard Sand}} > k_{\text{Sind River Sand (MP)}} > k_{\text{Yamuna River Sand}} > k_{\text{Rajasthan Crushed Sand}}$$

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