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Variation in coefficient of permeability of soil with the variation of temperature at prominent locations in India throughout a year

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Abstract: Permeability is a significant property of soil. The coefficient of permeability influences the seepage of water through soil. This coefficient of permeability further depends on the viscosity of water, average particle size, and void ratio of the soil present at the location. Variation of these factors results in the variation of the coefficient of permeability which results in the seepage of water through the earthen structures like earthen dams. In hydraulic structures, seepage of water is one of the major cause for piping failure. This study aims to numerically establish the trend of variation of the coefficient of permeability with the variation of viscosity of water which is caused due to changes in temperature at various prominent locations in India. The locations selected are Delhi, Mumbai, Chennai, Kolkata, Jaipur, and Srinagar. These locations are selected to cover each type of geographical condition, climatic condition (mild and extreme), temperature range, and soil type. The ratio between maximum value of coefficient of permeablity to the minimum value of the same was calculated for each location. It was observed that among the chosen locations, Jaipur showed the maximum variation of permeability while Chennai had the minimum variation. The comparison established may provide an additional source of data for the efficient design of hydraulic structures to be constructed near the selected locations.

Keywords: soil, permeability, temperature, piping, geotechnical failures

Introduction

Soil mechanics could be entirely viewed as the relation of soil particles with water. Water is a major constituent of any soil specimen. Soil and geotechnical engineering would have been incomplete had the water been missing. Both the quantity of water in a soil specimen (technically termed water content) and the virtue of its flow (permeability) are important factors to be studied by any civil engineer. Various other geotechnical properties such as seepage, consolidation, and shear strength are governed by the permeability of soil. A soil mass has typically 3 phases, which are soil solids, voids filled with water and voids filled with air. These voids in a soil permit the flow of water from a point having high head to a point having low head. Permeability is defined as the property of a soil that allows the seepage of fluids (in general cases, water) through the interconnected void spaces present inside the soil mass due to head difference between two points.

The most fundamental mathematical expression for discharge of water from soil, $q = k.i.A$ (Darcy's law) gives us an idea of the laminar flow that will occur because of the hydraulic gradient through the specimen's cross-sectional area. Here, k is the coefficient of permeability, also known as hydraulic conductivity. The units of the coefficient of permeability k is same as the units of velocity, like cm/s or mm/s. The value of k is a measure of the resistance offered by the soil to the flow of water. This coefficient of permeability further depends on the viscosity of water, average particle size, and void ratio of the soil present at the location. The value of hydraulic conductivity varies widely for different soils. Variation of these factors results in the variation of the coefficient of permeability which results in the seepage of water through the earthen structures like earthen dams. In hydraulic structures, seepage is the major cause of failure due to piping actions. This study aims to numerically establish the trend of variation of the coefficient of permeability with the variation of viscosity of water which is caused due to changes in temperature at various prominent locations in India.

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Permeability of soil is a very important aspect for the determination of any geotechnical property of soil and several researchers have devised various methods for the determination of the coefficient of permeability. These can be mainly categorized into:

- Direct methods
- Indirect (Empirical) methods

The direct methods are those methods of permeability determination that require experimental setup and standard operating procedures. They are of two types, laboratory based, and field based methods. The laboratory based methods include constant head permeability test, falling head permeability test, and capillarity permeability test. The field methods include pumping out test, Packer's test, and open end test, etc. On the other hand, indirect methods follow an empirical approach which is pre-established via extensive research works by researchers on vivid soil type and external conditions. Examples of empirical relations include Hazen's equation, Kozeny Carman equation, Casagrande's equation, Samarsinghe's equation, etc.

Out of these many methods, the present study uses the Kozeny-Carman equation (1). This is an empirical relation which is only valid for the laminar nature of flow. The equation was derived by Kozeny and Carman in 1927. For laminar flow through porous media, the discharge can be given as

$$q = C_s (R_h)^2 n A \frac{\gamma_w}{\mu}$$

where, R_h= hydraulic radius for porous medium and is given by

$$R_h = \frac{Area\ of\ flow\ (A_v)}{Wetted\ Perimeter\ (P_v)}.$$

From this, $q = CD^2 \left(\frac{\gamma_\omega}{\mu}\right)\left(\frac{e^3}{1+e}\right) iA.$

And hence, using Darcy's law,

$$k = CD^2 \left(\frac{\gamma_\omega}{\mu}\right)\left(\frac{e^3}{1+e}\right) \qquad (1)$$

where k is the coefficient of permeability, D is the particle size, C is Composite Shape Factor, e is the void ratio of soil, Υ_w is the unit weight of water, and μ is the coefficient of viscosity.

From this empirical relation, the dependency of the coefficient of permeability upon temperature can be seen. The temperature at which the soil specimen is present would affect its permeability by bringing changes in the unit weight of water and coefficient of viscosity keeping other factors constant. With the increase in temperature, there would be a decrease in the viscosity of the fluid and thus, an increase in the coefficient of permeability. The temperature change would also have a minimal effect on the unit weight of the fluid, (in this case, water) which is also taken into consideration in this study. The present study focuses on this phenomenon and aims to numerically establish the trend of variation of the coefficient of permeability with the variation of viscosity of water which is caused due to changes in temperature at various prominent locations in India. Eventually, a graphical analysis of the results, for the change in permeability with the temperature would provide the implications of permeability change; on hydraulic structures, seepages in earthen dams, piping failures, consolidation settlements, and effective stresses.

Permeability is an extremely important parameter in the domain of civil and geotechnical engineering. A lot of literature available regarding the permeability, its dependence on various factors like soil grain type, temperature, viscosity, etc, were studied.

Elhakim in 2016 [1] have measured the coefficient of permeability using field falling head at different depths as well as full scale pumping test. The measured values were compared with the empirically obtained values from cone penetration test. It was found that there is no generalized method for estimating soil permeability for all soil types. It is important to calibrate such empirical method using actual field measurements especially for important projects.

Carrier in 2003 [2], have compared the hazen formula and the Kozeny Carman formula for prediction of coefficient of permeability for sand and recommended that the Hazen formula is less accurate than the Kozeny-Carman formula and the Kozeny Carman equation should be preferred.

Understanding the variation of water properties was equally important for this study and various literatures studying the water temperature effect on infiltrartion rate, and the effect of temperature on physical properties of soil were studied. Levy et al. (2013) [3] studied the hydraulic conductivity of soil columns subjected to rain of two different intensities with 3 cases of water temperature (8°C, 21°C, and 45°C). It was found that the higher water temperature led to higher hydraulic conductivity of soil.

Joshaghani et al. in 2018 [4], performed experimental investigation of the sandy soild to study the ffects of temperature. The parameters studied were intrinsic permeability and void ratio. They found that the soil hydraulic conductivity increases with temperature but the intrinsic permeability, which is the property of medium alone and does not depend upon the fluid, decreases as the temperature increases because of the changed void ratio of the soil due to thermal effects.

The study on viscosity of water at different temperatures by Korson et al. (1968) [5] provided the relevant data of temperature and corresponding values of viscosity, which was required for the present study.

A deep understanding of other parameters like composite shape factor and grain size was also important. These factors are location dependent and cannot be generalized for other soil types. Khanikar and Goswami (2016) [6] studied the dependence of hydraulic conductivity on effective grain size values for Golaghat district in Assam. Their findings indicate that there is a significant variance in hydraulic conductivities of distinct aquifer zones within the aquifer system in the area due to the presence of fine sands.

Chapuis (2004) [7] worked on prediction of saturated hydraulic conductivity of sand and gravel using effective diameter and void ratio using Hazen's equation and the Naval Facilities Engineering Command (NAVFAC) method and proposed a new equation having lesser standard deviation.

To obtain the region specific idea about the soil property and behaviour, studies of Annual Report on Soil and Land Use Survey of India, Govt. of India (2018-19) [8], Chennai's seismic hazard assement by Boominathan et al. in 2008 [9], deterministic seismic microzonation of Kolkata city by Shiuly anad Narayan in 2012 [10], and dynamic soil properties for microzonation of Delhi by Hanumantharao and Ramana in 2008 [11] were done. These literarture helped in providing the in situ soil properties at the selected locations.

This study focuses on the variation of coefficient of permeability with the change in temperature. Hence, a selective collection of the maximum and minimum weekly temperature of each of the 52 weeks of the year 2019 for each of the six cities was done. For the collection of this data; a reliable source was needed and thus the data of ACCUWEATHER (www.accuweather.com) was used for this process. The maximum and minimum temperature values were compiled for each location. The data of viscosity and unit weight for the different temperature that the soil specimen will be experiencing in these cities were also tabulated from the available literature [5].

Eventually a graphical analysis of the results was done through graphs and a pictorial angle of the change in permeability v/s the temperature was documented. Since permeability is majorly affected by the fluid properties, the variation of γ/μ is considered to be equivalent to the variation of coefficient of permeability from equation (1).

Data Collection and Analysis

The Table 1 provides a concise overview of the extensive weekly data (tabulated in Appendix section of this report), concerning only the minimum and maximum variations in permeability.

Table 1: Minimum and Maximum Variation in Permeability

Week. of max temp	Week of min temp	T_{max} °C	T_{min} °C	Viscosity for T_{max} μ (kg/ms)	Viscosity for T_{min} μ (kg/ms)	Unit wt. for T_{max} (N/m^3)	Unit wt. for T_{min} (N/m^3)	γ/μ for T_{max} (ms)$^{-1}$ in 10^6	γ/μ for T_{min} (ms)$^{-1}$ in 10^6
				New Delhi					
06/04 - 06/10	12/24 - 12/31	46	2	0.000586	0.001674	9709.938	9810.000	16.5698	5.8602
				Mumbai					
03/26 - 04/01	02/05 - 02/11	40	11	0.000653	0.001271	9733.482	9806.076	14.9057	7.7152
				Kolkata					
05/07 - 05/13	01/01 - 01/07	40	11	0.000653	0.001271	9733.482	9806.076	14.9057	7.7152
				Chennai					
04/30 - 05/06	01/01 - 01/07	43	18	0.000618	0.001054	9722.691	9796.266	15.7325	9.2943
				Jaipur					
06/04 - 06/10	12/24 - 12/31	46	1	0.000586	0.001731	9709.938	9809.019	16.5698	5.6667
				Srinagar					
07/23 - 07/29	01/08 - 01/14	34	0	0.000734	0.001792	9755.064	9809.019	13.2902	5.4737

Each of the six cities presented its unique set of permeability range. Therefore, this huge sample space of 52 weeks of permeability variation required graphical representation to analyse the data in a better way.

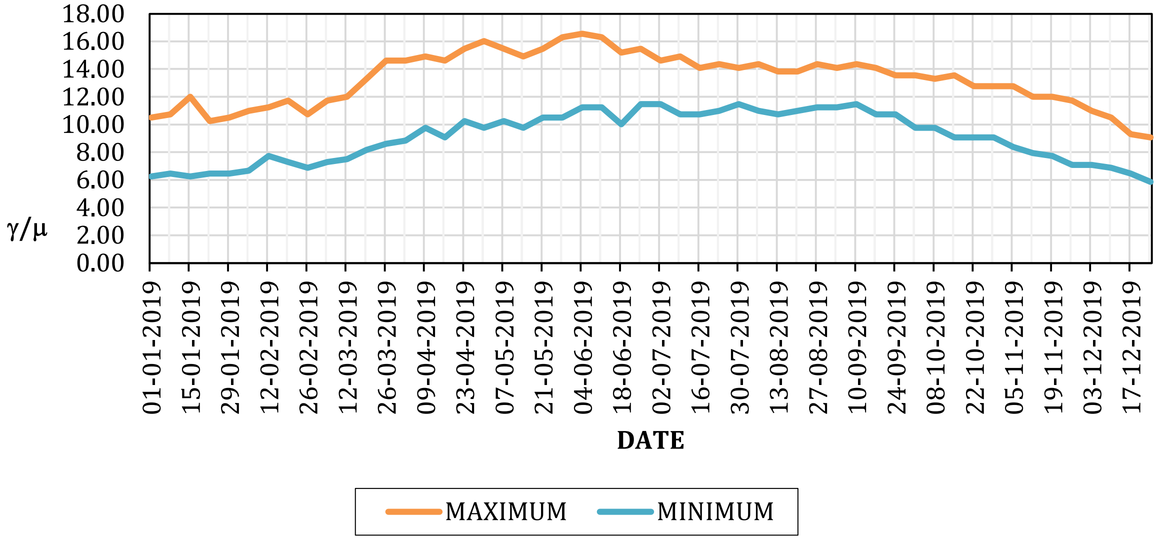

Figure 1: Variation of Coefficient of Permeability in New Delhi

Figure 1 represents the variation of γ/μ with the weeks in the year 2019 for the city of New Delhi. The orange curve shows the variation with respect to maximum temperatures for each of the 52 weeks of the year whereas the blue one signifies the minimum temperature. It is clearly observed that there is almost a constant difference in the magnitude of γ/μ for the two curves which would ultimately result in the difference in the permeability when incorporated with the values of C, D and e according to the Kozeny Carman equation. A ratio of $16.5698/5.8602 = 2.8275$ is observed for the maximum and the minimum values of orange and blue curves respectively which ultimately means that for the year 2019, the maximum permeability of the soil in New Delhi was 2.8275 times the minimum value of permeability. Through this analysis one can also judge the time for conduction and a basic outcome for any soil experiment related to permeability based on the above data.

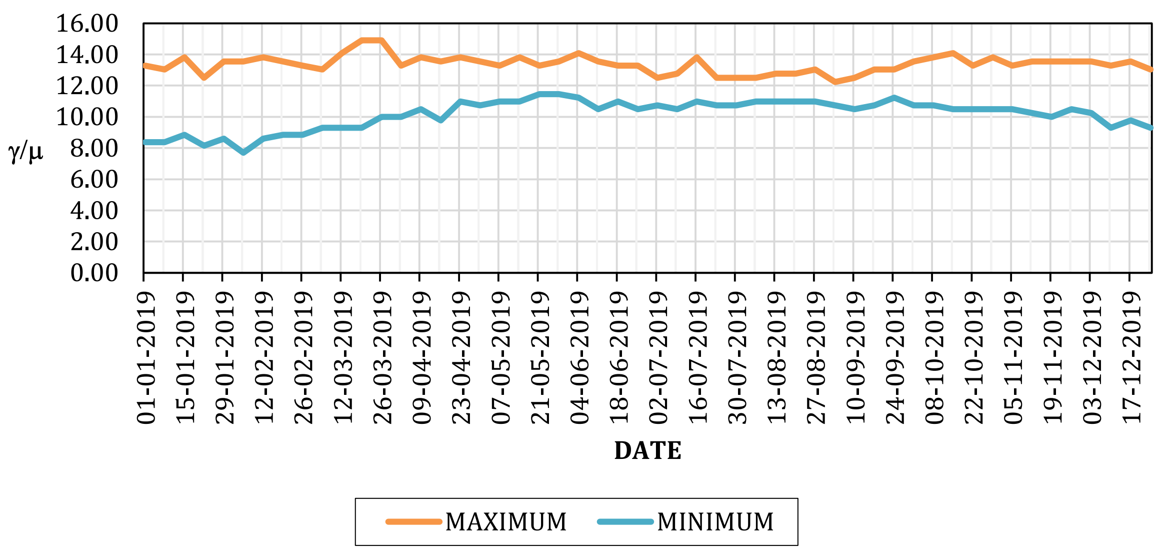

Figure 2: Variation of Coefficient of Permeability in Mumbai

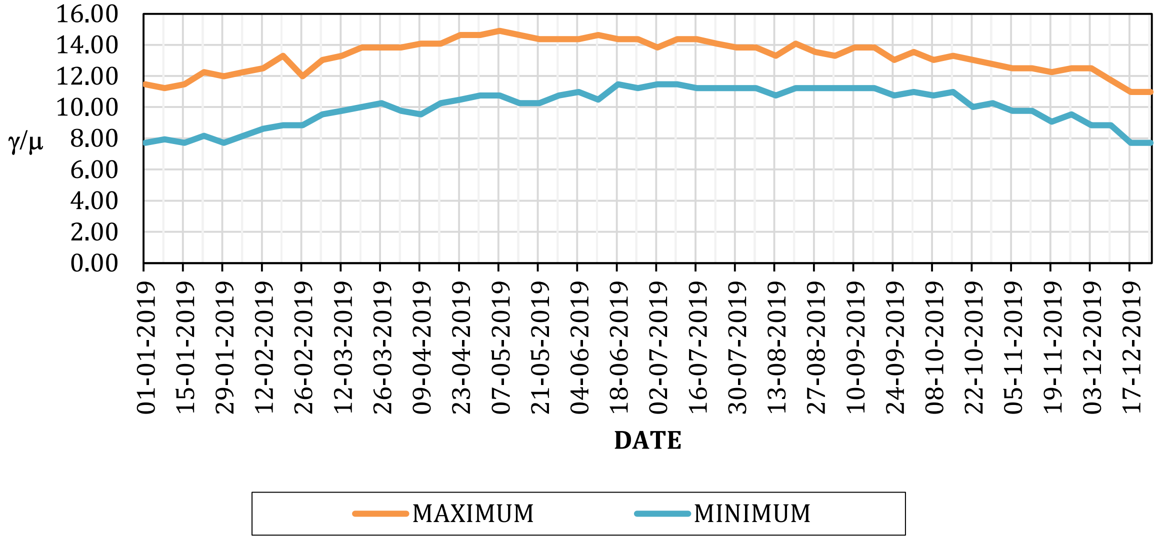

Figure 3:Variation of Coefficient of Permeability in Kolkata

Figure 2 and Figure 3 represent the variation of γ/μ with the weeks in the year 2019 for the city of Mumbai and Kolkata respectively. The orange and blue curves have the same meaning as discussed earlier. Owing to the fact that Mumbai has moderate weather throughout the year a very close gap between the curves for quite some range of weeks can be seen. Both the cities are situated close to the sea and as a result, a similar temperature range in both the cities are observed. Another interesting observation is that the ratio of $14.9057/7.7152 = 1.932$ is observed for the maximum and the minimum values of orange and blue curves respectively which ultimately means that for the year 2019, the maximum permeability of the soil for both Mumbai and Kolkata was 1.932 times the minimum value of permeability. However the absolute values of permeabilities for both the cities would differ and would depend upon the corresponding values of C,D and e.

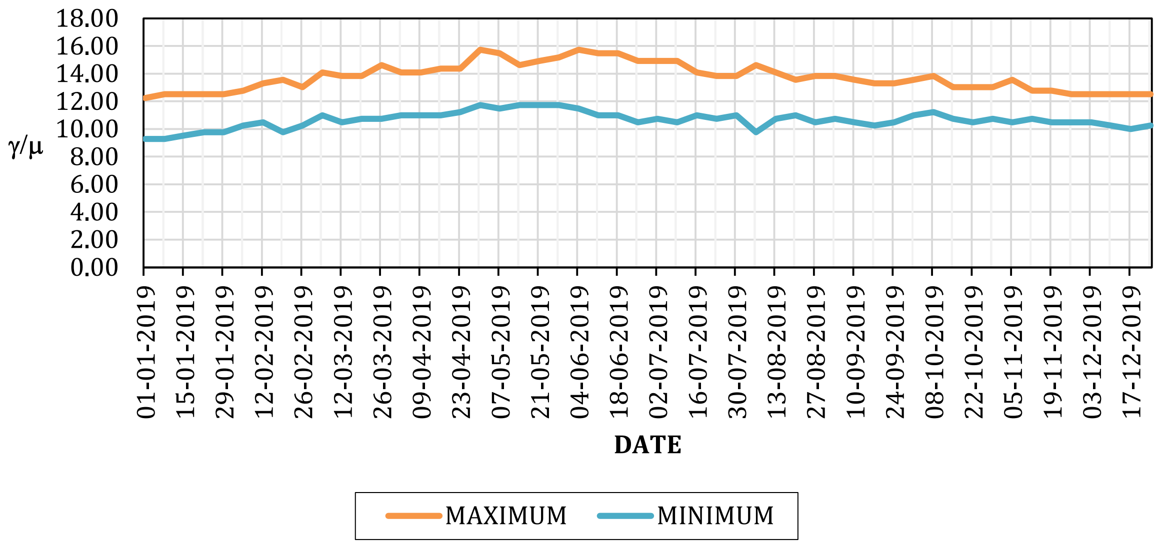

Figure 4: Variation of Coefficient of Permeability in Chennai

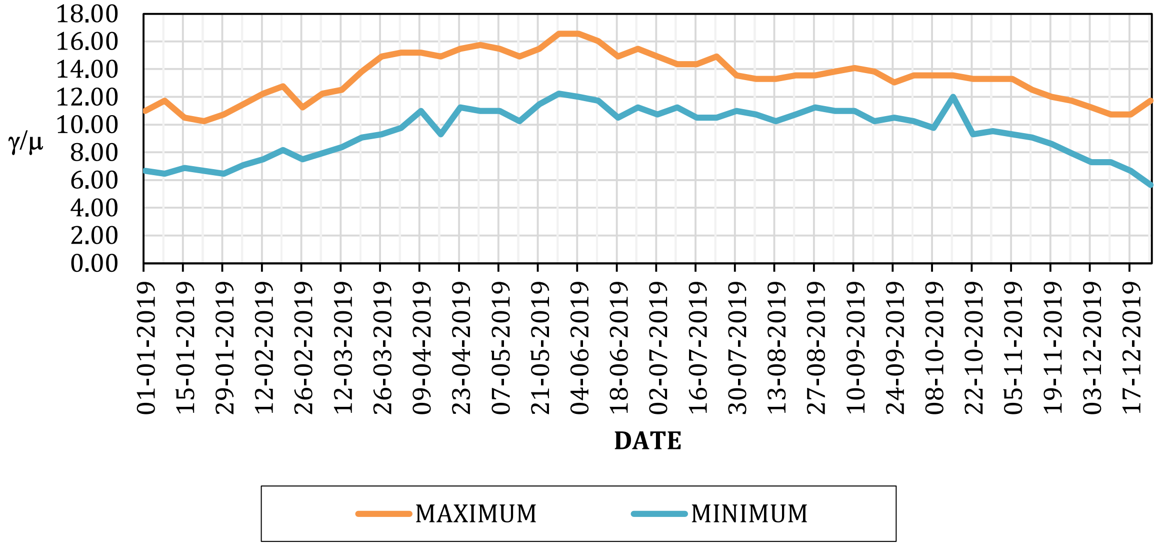

Figure 5: Variation of Coefficient of Permeability in Jaipur

These graphs represent the variation of division of unit weight by viscosity of water; with the weeks in the year 2019 for the city of Chennai and Jaipur respectively. The orange and blue curves have the same meaning as discussed earlier. As it is clearly observable, Chennai has a very tropical climatic condition and it is hot and humid throughout the year. There is small yet a nearly constant difference in the magnitudes of the orange and blue curves. The ratio of max to min value of orange and blue curve is $15.7325/9.2943 = 1.6927$ which is relatively low when compared to the other cities. Jaipur on the other hand is the polar opposite of Chennai and has a very extreme climate. Low temperatures in the winter and an extremely hot summer thus result in the ratio of max to min value of orange and blue curve to be as high as $16.5698/5.6667 = 2.924$. This shows that the maximum permeability of soil for the year 2019, in Jaipur would be almost three times the lowest value for that area. Because of the uneven weather pattern, it is also observed that the orange and blue curves are separated by very fine margins at some instances in the year.

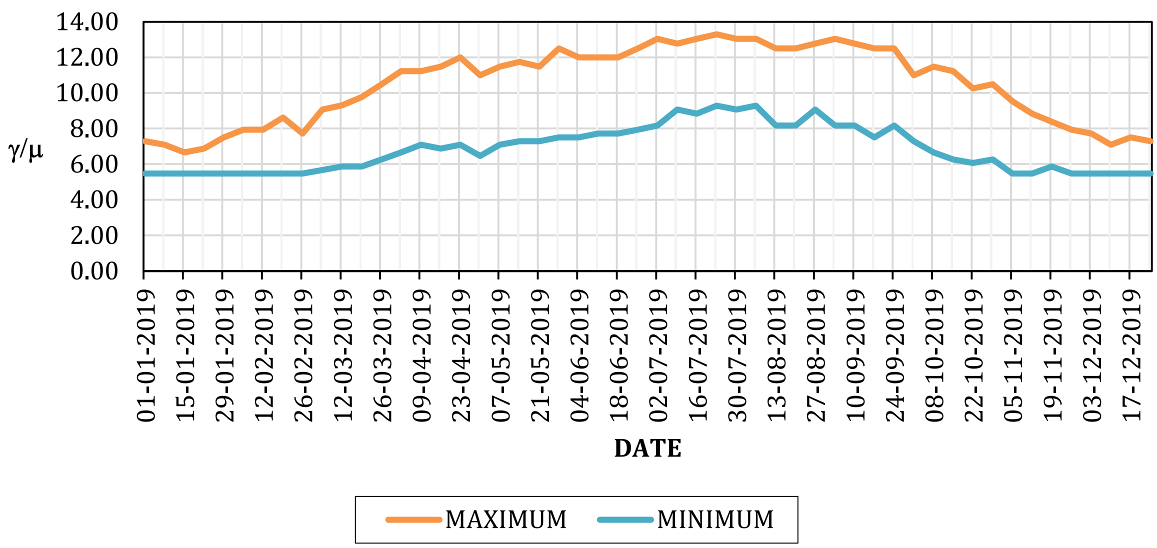

Figure 6: Variation of Coefficient of Permeability in Srinagar

Figure 6 represent the variation of γ/μ with the weeks in the year 2019 for the city of Srinagar in J&K. The orange and blue curves have the same meaning as discussed earlier. This city lies at a high altitude in a mountainous terrain as a result of which it has cold weather throughout the year. Since permeability is inversely proportional to temperature, it is clearly evident that the absolute permeability of this city would be lower than the cities discussed earlier. Another interesting aspect of discussion for this city in particular is the temperature below 0 °C. Since water freezes at this temperature, no flow of water could take place because of its change in state; the scope of viscosity and unit weight is restricted to temperatures of and above 0 °C. The ratio of the maximum and the minimum value of the orange and blue curve is $13.2902/5.4737 = 2.428$. it is also observe that the margin of gap between the two curves is quite low which shows the invariancy in temperature.

In this way a complete analytical and graphical measure and comparison of permeability parameter γ/μ is established for each of the six cities which when incorporated with the parameters such as C, D and e in the Kozeny Carman equation would provide us an absolute difference in permeability values. This has several practical implications that go hand in hand with these results and are discussed in the following section.

Practical Implications

The concept of permeability is very significant in the area of soil mechanics and geotechnical engineering. Most of the properties of soils are a point of study because of the presense of water in the voids of the soil. Being a porous medium, its permeability has a lot of practical significance.

The phenomena of seepage of soil which can happen under hydraulic structures like dams, weirs, etc. requires a knowledge of permeability through the soil. Larger permeability will lead to larger amount of seepage loss through a soil strata per unit time. Construction of a reservoir will also be feasible only when the soil beneath loses very less amount of water through permeability. Moreover, uplift pressures act on the base of the hydraulic structures and if the seepage is high due to higher permeabilities, higher uplift forces may be experienced by the structures. So high variation of such an important and significant factor like permeability, which affects a lot of design criterias for a structure can lead to uneconomical structures. Moreover, safety of a structure can also be compromised if appropriate considerations of the variation of permeability is not done. Failures of hydraulic structures due to seepage problems are very common. Seepage water, especially in earthen dams, can cause erosion, and piping failures. It may further lead to instability and an increased possibility of the complete overturning of the structure. So, a proper analysis of the variation of permeability needs to be done before the initiation of these types of projects.In order to establish a magnitude based variation rather than just a factor based variation, there needs to be an accurate calculation backed by experimental data. Permeability factors like C, D and e are definitely different for each city and soil condition but in order to quantitatively analyze the results, these are assumed to be same for all the six cities. The given table represents the magnitude of permeability differences in each of these cities. The factorial effect on the coefficient of consolidation and rate of seepage can also be established for each of the six cities.

The values of the different parameters take for this purpose are:

- C = 1
- D = 0.15 mm
- e = 0.5

Table 2: Seepage and Consolidation Ratio

City	k for T_{max} (cm/s)	k for T_{min} (cm/s)	Seepage ratio	Consolidation ratio
Delhi	20.711	7.325	2.8275	2.828
Mumbai	18.625	9.637	1.932	1.932
Kolkata	18.625	9.637	1.932	1.932
Chennai	19.662	11.612	1.6927	1.693
Jaipur	20.700	7.075	2.924	2.924

Srinagar	16.612	6.837	2.428	2.428

In this way a noticeable and highly impactful change in the coefficient of permeability and the factors that are measured using it are observed. Although all of the factors are location specific; and factors for the determination of seepage would depend on the flow net parameters (N_f, N_d) and the available head of water (H), and consolidation would depend upon the coefficient of volume change; still a clear idea can be drawn that temperature change would bring severe hazards if neglected and thus engineers should perform precise temperature analysis before going ahead on any construction activity.

Conclusion

To conclude, with the help of this study, the differences and variations in coefficient of permeability for various locations can be estimated by using the weather reports for those locations.

For the same soil types compacted under the same void ratio, the permeabilities of different locations can be compared. Here, the locations taken were New Delhi, Mumbai, Kolkata, Chennai, Jaipur, and Srinagar. This selection was done to incorporate different weather patterns in the study.

The Ratio of $\frac{\gamma}{\mu}$ will also give the ratio of $\frac{K_{max}}{K_{min}}$ for a given value of Composite Shape Factor, void Ratio, and effective grain size. Therefore, the ratio of maximum coefficient of permeability and minimum coefficient of permeability can be determined.

Table 3: Ratio of K_{max} and K_{min}

S. No.	Location	$\frac{K_{max}}{K_{min}}$	Remarks
1.	Jaipur	2.924	High Ratio due to high maximum temperature and low minimum temperature in Extreme Climate
2.	New Delhi	2.828	High Ratio due to high maximum temperature and low minimum temperature in Extreme Climate (but lesser variations if compared to Jaipur)
3.	Srinagar	2.428	Despite being a location with colder climate, relatively high ratio due to extremely low minimum temperature and moderate value of maximum temperature
4.	Mumbai	1.932	Location close to sea, and hence, being a moderate climate area, higher value of minimum temperature was observed, which caused the decrease in the ratio.
5.	Kolkata	1.932	Location close to sea, and hence, being a moderate climate area, higher value of minimum temperature was observed, which caused the decrease in the ratio.
6.	Chennai	1.693	Location close to sea, and hence, being a moderate climate area, comparatively higher value of minimum temperature was observed, which caused more decrease in the ratio.

A similar study can be performed to eastimate these ratios for any other location where the assessment of the variation of permeability is required.

Limitations

This study of variation of permeability reveals a lot of information about the changes in permeability of soil at different temperature changes in the selected locations. However, there are few limitations and sources of errors in the study, which limits the applicability of this form of study. Some of the areas which cause the limitations are discussed below.

First of all, such analysis of permeability using the Kozeny Carman Equation is valid only for Granular, or Coarse Grained Soils. The Kozeny Carman equation works well for studying the permeabilitiy of coarse-grained soils such as sand and silts empirically and for only coarse grained non plastic soils, the coefficient permeability comes with a linear relation with the term $\frac{e^3}{1+e}$. However, Kozney Carman equation does not give good results when applied to clayey soils. Therefore, permeability of only non plastic soils can be studied with the help of Kozeney Carman Equation.

Also, this study will be applicable only up to a small depth below the ground as at lower strata, there will be other heating effects from the earth's core and the permeability's variation might not be significant.Apart from this, it is assumed that the temperature equilibrium between the atmosphere, ground, and ground water, is attained in negligible time. But, in reality, this may not happen as the specific heat capacities of different materials will be differeing and such quick variations of the permeability of the soil may not take place.However, at a larger time scale, say in 1 to 2 months, the variation of maximum and minimum permeability with maximum and minimum temperature will be more or less similar to that found in this study. More conclusive remarks can be made only after the experimental verification of the study.

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