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OKUSA, S., Faculty of Marine Science and Technology, Tokai University, Shimizu, Japan
UEOKA, T., Tone River Dam Administrative Office, Ministry of Construction, Maebashi, Japan
SAKATA, Y., Hirose and Com. Ltd., Osaka, Japan

PERMEABILITY OF POROUS MEDIA AN GEOTEXTILES FOR OSCILLATORY FLOW

PERMEABILITE DE MILIEUX POREUX ET DE GEOTEXTILES POUR UN ECOULEMENT OSCILLATOIRE

WASSERDURCHLÄSSIGKEIT PORÖSER MEDIEN UND GEOTEXTILIEN BEI OSZILLIERENDEM DURCHFLUSS

A porous medium is placed in the central part of a U-tube filled with water. When water on one side of the porous medium is forced to oscillate, the output oscillation is damped with an associated time lag. The output oscillation is described by a second order linear differential equation. The solution shows that the damping and time lag in a steady state depend on the permeability, length, and porosity of the medium set in the U-tube. On the basis of this theory a series of experiments on the permeabilities of porous media, geotextiles, and porous media placed between geotextiles was carried out using the forced oscillation of water in a U-tube. The permeabilities were almost constant for oscillation periods of 6-25s.

A porous medium with a higher permeability than that of the geotextile placed between sheets of the geotextile showed a decrease in permeability, but the degree of the decrease depended on the geotextile type. Relationships between the Reynolds numbers of the oscillatory flow, seepage velocities and permeabilities, and permeabilities by this method and constant-head method are also discussed.

Ein poröses Medium ist im Mittelbereich eines mit Wasser gefüllten U-Rohrs angelegt. Wenn das poröse Medium dabei an einer Kante von dem schwingengenden Wasserfluss beaufschlagt wird, läßt sich die Schwingung des Wasserflusses mit dem entsprechenden zeitlichen Verzug abdämpfen. Ausgehend von Theorie wurde eine Reihe von experimentellen Untersuchungen zur Ermittlung der Wasserdurchlässigkeit von porösen Medien, Geotextilien und zwischen Geotextilien vorliegenden porösen Medien unter Verwendung eines schwingengendem Wasserflusses im U-Rohr durchgeführt. Es zeigte sich, daß die Wasserdurchlässigkeit im Laufe von 6-25s unter Beaufschlagung des Wasserflusses nahezu unverändert blieb.
Ein poröses Medium mit einer höheren Wasserdurchlässigkeit als die der zwischen den Geotextblättern angesetzten Geotextilien, zeigte eine Verringerung der Wasserdurchlässigkeit, wobei der Abfall der Wasserdurchlässigkeit von dem Typ der Geotextilien abhängig ist. Zusammenhänge zwischen der Reynolds-Nummer des schwingengendem Wasserflusses, Wasserdurchlässigkeit, etc. werden besprochen.

INTRODUCTION

One of the most important functions of geotextiles is the filtering action in a one-directional drainage application. For this application geotextiles are used as replacements for graded granular filters because of their comparable performance, improved economy, consistent properties and ease of replacement (1).

In the case of geotextiles used as filters in offshore and coastal constructions, the water flow is oscillatory instead of the one-directional drainage flow encountered on land because of oscillatory wave actions (tide waves and wind waves) in the ocean (2).

One of the authors developed a new technique for measuring the permeability of porous media for oscillatory flow by use of water oscillation in a U-tube filled with a porous medium (3). Using this technique, we measured the permeabilities of several porous media, geotextiles and porous media sandwiched by sheets of a geotextile for 4 to 24 second period waves. It was found that the permeabilities of the porous media, geotextiles and porous media sandwiched by geotextiles were nearly constant irrespective of the wave period for usual ocean wave period. The permeability of the sandwiched porous media is mainly controlled by the lower permeability of the two materials, but the influence of a geotextile on the permeability of a porous medium depends on the combination of the type of a geotextile and porous medium.

A TECHNIQUE OF MEASURING PERMEABILITY OF POROUS MEDIA FOR OSCILLATORY FLOW

When the water in a U-tube filled with a porous medium having a sectional area A and a length l (Fig.1) is forced to oscillate, we assume that the water flow through the porous medium experiences resistance 2α from the porous skeleton in proportion to the flow velocity v per unit mass of water. The equation of motion of the water in the small element is expressed by,

$$\frac{Dv}{Dt}An\rho ds = -\frac{\partial p}{\partial s}Ands - g\frac{\partial z}{\partial s}An\rho ds - 2\alpha vAn\rho ds \quad (1)$$

where p is the water pressure at s, n is the porosity of the medium, ρ is the density of water, g is the acceleration of gravity, t is the time, $-\partial z/\partial s$ is the

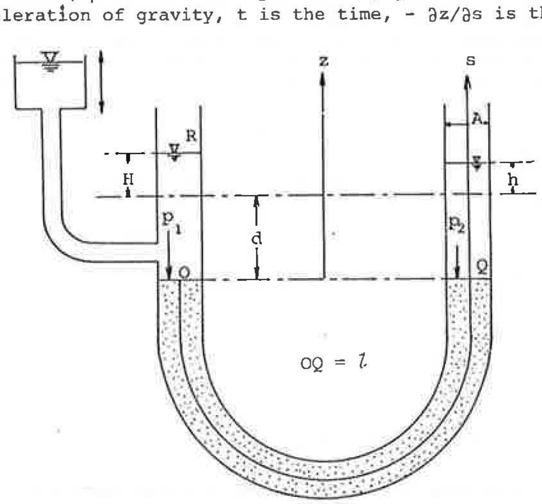

Figure 1 Oscillatory flow of water in a U-tube filled with a porous material

gradient of the tube relative to the z axis and $Dv/Dt = (v\,\partial v/\partial s + \partial v/\partial t)$, s is the axis along the U-tube, and z is the vertical axis (positive upward). If we assume that the flow through the U-tube is uniform along the s axis ($\partial v/\partial s = 0$) and take into account the fact that $h = p/\rho g + z$ is the piezometric head in the tube, for a stationary flow, i.e., $\partial v/\partial t = 0$, we obtain Darcy's law and the coefficient of permeability k as,

$$v' = nv = -k\,\partial h/\partial s \quad \text{and} \quad k = ng/2\alpha \tag{2}$$

The equation of motion (1) can be represented in terms of k by,

$$\frac{\partial v}{\partial t} + \frac{ng}{k} v = -g\frac{\partial}{\partial s}\left(\frac{p}{\rho g} + z\right) \tag{3}$$

When the water on the left side of the U-tube in Fig.1 is periodically forced to oscillate with an amplitude H_0 and a period T as given by

$$H = H_0 \sin\omega t = H_0 \sin 2\pi t/T$$

the pressures on the surfaces of the porous medium are given by

$$\begin{aligned} p_1 &= p_0 + \rho g(d + H) \quad \text{at point O in Fig.1} \\ p_2 &= p_0 + \rho g(d + h) \quad \text{at point Q in Fig.1} \end{aligned} \tag{4}$$

where p_0 is the atmospheric pressure, d is the mean water depth to the surface of a porous medium, h is the amplitude of the output oscillation in the opposite side of the tube, and the influence of the inertia of motion of the water column RO in Fig.1 is neglected. Integrating (3) along the s axis from O to Q under the boundary conditions of (4) and using $nAv = Av' = Adh/dt$, we get

$$(D^2 + 2\alpha D + \omega_0^2)h = R\exp(i\omega t) \tag{5}$$

where $\omega_0^2 = \sqrt{ng/l}$ is the angular velocity of the water oscillation without the resistance of the porous skeleton against the water flow, $R = ngH_0/l = \omega_0^2 H_0$, $D = d/dt$ and the imaginary part of (5) expresses the motion, h. The general solution of (5) is expressed by (4),

$$h = C_1\exp(\beta_1 t) + C_2\exp(\beta_2 t) + \frac{R\sin(\omega t - \theta)}{\sqrt{(\omega_0^2 - \omega^2)^2 + (2\alpha\omega)^2}} \tag{6}$$

where C_1 and C_2 are integral constants, respectively, and

$$\beta_1 = -\alpha + \sqrt{(\alpha^2 - \omega_0^2)}$$
$$\beta_2 = -\alpha - \sqrt{(\alpha^2 - \omega_0^2)}$$
$$\tan\theta = 2\alpha\omega/(\omega_0^2 - \omega^2)$$

The first two terms of (6) diminish in an oscillating or steady manner according to $\alpha = ng/2k \gtrless \omega_0$ given a sufficiently long time, t. In a steady state, the water surface motion of the right side of the U-tube becomes a forced harmonic oscillation represented by the third term,

$$h = \frac{R}{\sqrt{(\omega_0^2 - \omega^2)^2 + (2\alpha\omega)^2}}\sin(\omega t - \theta)$$

By measuring the amplitude $h_0 = R/\sqrt{(\omega_0^2 - \omega^2)^2 + (2\alpha\omega)^2}$ or the phase lag θ at a steady state in the U-tube, we can obtain the coefficient of permeability of the porous medium in the tube for each value of the oscillation period as (3),

$$k = \frac{2\pi l}{T\sqrt{(H_0/h_0)^2 - [1 - l(2\pi/T)^2/ng]^2}} \tag{7}$$

$$k = \frac{2\pi l}{T[1 - l(2\pi/T)^2/ng]\tan\theta}$$

Because the measurement accuracy is better for the amplitude than for the time lag, (7) was used for determination of the coefficient of permeability in the following section.

MATERIALS AND APPARATUS

Five types of porous media and three types of geotextiles were used for the experiment. Their physical properties are shown in Tables 1 and 2.

Fig.2 shows the U-tube used for the experiment and its dimension. The U-tube was made of transparent acryl plastic.

The experimental material was first placed in a cassette 15 cm in length and of the same cross sectional area as the U-tube. The cassette was then set in the central part of the bottom of the U-tube. Great care was taken with the seal between the cassette and the U-tube body.

The input oscillation was generated by moving a bucket connected with a flexible vinyl hose 3.5 cm in diameter to the side of U-tube up and down as shown in Fig.2. The reading of the input and output wave amplitudes were made by volume strain-gauge wave meters or with the naked eye

Table 1 Physical properties of porous material

Material Range of Diameter (mm)	Specific Gravity	D_{10} (mm)	D_{50} (mm)	D_{60} (mm)	Uniformity Coefficient	Porosity (%)
Glass Ball 13.75-12.20	2.54	12.20	12.80	13.00	1.07	37.9
Medium Gravel 9.52-4.76	2.68	5.00	6.60	7.05	1.41	33.1
Fine Gravel 9.52-4.76	2.69	2.20	3.07	3.35	1.52	34.6
Coarse sand 2.00-0.84	2.66	0.92	1.30	1.40	1.52	33.1
Medium Sand 0.84-0.56	2.67	0.45	0.60	0.64	1.42	32.6

Table 2 Physical properties of geotextiles

Geotextile	Thickness of a Sheet (mm)	Range of Porosity (%)	Average Porosity (%)
Teram 1000	0.7	70.4-80.0	75.0
VNB 600	2.7	90.0-93.0	91.5
VN 420	2.5	90.0-93.0	91.5

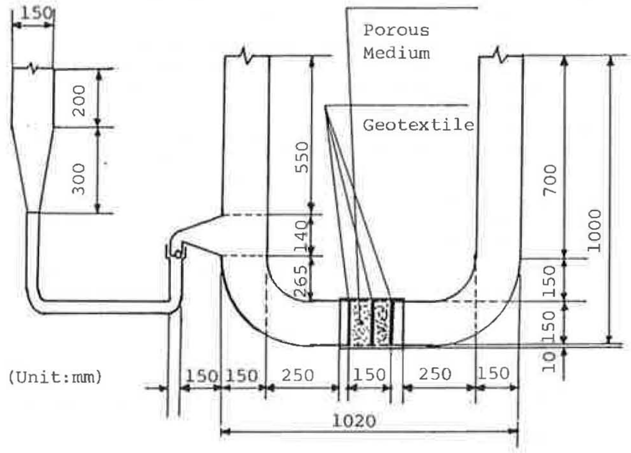

Figure 2 U-tube for measuring permeability of a porous medium during oscillatory flow

and the scales fixed to either side of U-tube.

After the oscillation in the U-tube became steady, reading of the oscillation commenced. A steady state was attained after several wave periods. The lag time was read on the recording sheet or measured by stopwatch. Readings with the naked eye and stopwatch were found to be more accurate.

Figs.3 and 4 show examples of the reading of amplitude ratio H_0/h_0 and phase lag $\tan\theta$.

In addition to the measurements with the U-tube method, the permeability of the fine gravel and two sands was measured by the constant head test method. The permeability of the gravel medium and the glass balls could not be measured by the constant head test.

RESULTS

Porous Media Fig. 5 shows the relation between permeability and oscillation period from 4 through 24 seconds. The figure maintains that the permeability of granular porous media is almost independent of the oscillatory flow period usually encountered in ocean waves. The same can be said for geotextiles. Therefore, the U-tube oscillatory method can be used for the determination of the permeability of porous media. For oscillation shorter than 5 seconds, however, the permeability was reported to become very low (3).

For the gravel materials the average discharge velocity expressed by $\bar{v} = \sqrt{2}\,\pi h_0/T$ was about $(3\text{-}8)\times10^{-1}$ cm/s in a range of periods shorter than 10 seconds, and increased slowly to $(5\text{-}10)\times10^{-1}$cm/s from 10 through 15 second periods. It decreased slowly again. For the the sandy material the average velocity was very small (around 10^{-1}cm/s) and independent of the periods.

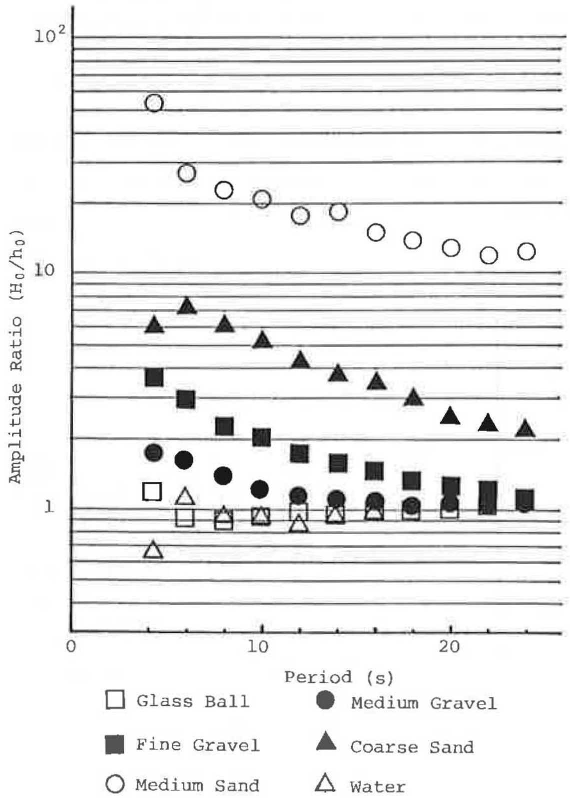

Figure 3 Relation between amplitude and period

The average Reynolds number of the water flow through a porous medium is represented by

$$R_e = \frac{vD_{50}}{\nu}$$

where D_{50} is mean diameter and ν is kinematic viscosity. Since the mean diameter is the same for one material and the kinematic viscosity can be assumed to be almost

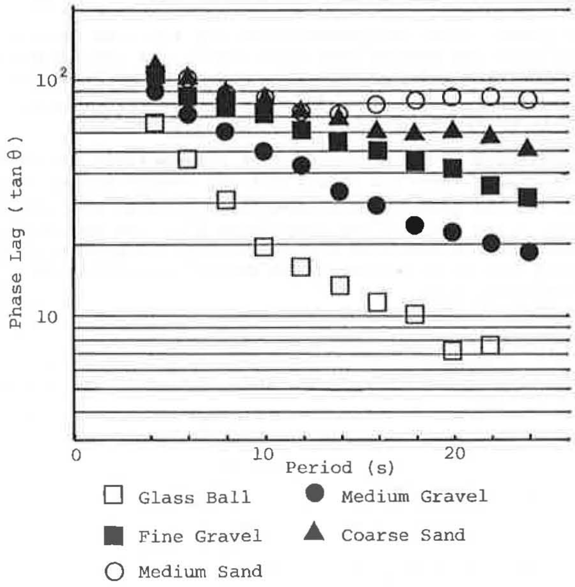

Figure 4 Relation between phase lag and period

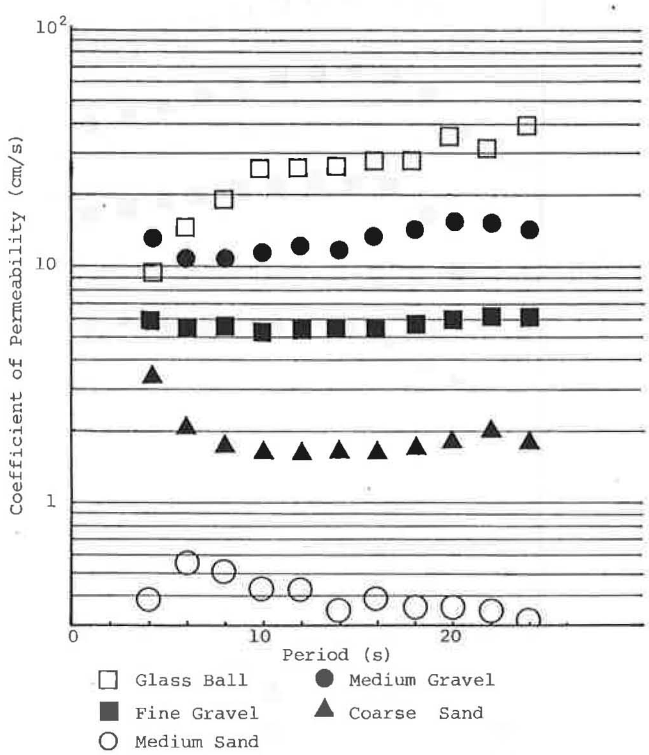

Figure 5 Coefficients of permeability of five porous media for oscillatory flow

constant in laboratory temperatures, the Reynolds number has the same tendency as the average velocity. The relation between the Reynolds number and the period for each material is shown in Fig.6. It has been considered that Daracy's law holds for the Reynolds numbers smaller than 4 (5). In many cases of the experiments the Reynolds number exceeded 4. The coefficient of permeability, however, was nearly constant. This might be explained by the fact that in a higher range of Reynolds numbers (greater than 4), the flow would be still laminar (5).

The coefficients of permeability for the fine gravel, coarse sand and medium sand have nearly the same order as those obtained from the constant head method (Table 3), although the coefficients from the former method were a little higher than those from the latter method.

Geotextiles The coefficients of permeability are shown in Fig.7 as a function of the periods. Those values are almost of the same order of magnitude in a given range of period. It is interesting that Teram 1000 has the greatest permeability in spite of its relatively low porosity. The permeability of a geotextile is mainly controlled by its infrastructure.

Table 3 Comparison of coefficients of permeability obtained from U-tube and constant head methods

Material	D_{50}	Coefficient of Permeability U-Tube (cm/s)	Coefficient of Permeability Constant Head (cm/s)
Fine Gravel	3.07	5.70	4.00
Coarse Sand	1.30	1.79	0.70
Medium Sand	0.60	0.37	0.25

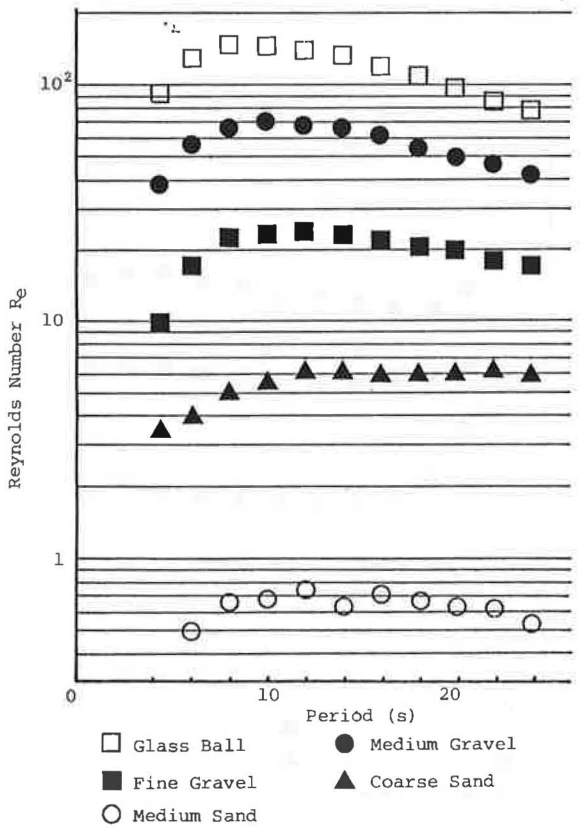

Figure 6 Relation between Reynolds number and period

When entrapped air bubbles appeared on the surface of Teram 1000 during the U-tube test, the oscillatory water flow was impeded, causing lowering of permeability. The entrapped air bubbles in VNB 600 and VN 420 had little influence on the permeability (Table 4). The influence of the entrapped air bubbles in a geotextile again depends on the infrastructure of the geotextile, i.e., the ease of squeezing the entrapped air bubbles out of the pores.

Porous Medium Sandwiched by Geotextile Two types of sandwiched samples were prepared for each porous medium. One type was a porous medium 15 cm in length sandwiched between two sheets of geotextile. This is called the one-layer sample. The other type was a one-layer sample divided by another sheet of the geotextile at the mid section, as shown in Fig.2.

Fig.8 shows an example of the relation between coefficients of permeability and period. Fig.9 shows an example of the comparison of U-tube test results for the three types of samples (porous medium, one-layer and two-layer samples) of the fine gravel.

It is clear that the coefficient of permeability of one-layer and two layer samples are almost independent of the periods. The average value of coefficients between 10 s and 24 s is therefore used for the representative value for each sample in the following analysis. Table 5 shows the comparison of the coefficients of permeability for all samples. The table disclosed the following facts: 1) The decrease in the coefficient of permeability is greater for samples sandwiched by VNB 600 and VN 420 than for those sandwiched by Teram 1000, although Teram 1000 has a smaller permeability than the other two (Fig.10); 2) For the samples sandwiched by VNB 600 and VN 420 the difference of coefficients of permeability between one-layer and two-layer samples is very small, while the coefficients of permeability sandwiched by Teram 1000 decreases greatly from one-layer samples to two-layer

Table 4 Influence of entrapped air bubbles on permeability of geotextiles

		Teram 1000	VNB 600	VN 420
Permeability having entrapped air	k_1	4.8×10^{-3}	2.76×10^{-1}	1.6×10^{-1}
Saturated	k_2	9.0×10^{-2}	2.84×10^{-1}	2.0×10^{-1}
k_1/k_2		0.053	0.97	0.77

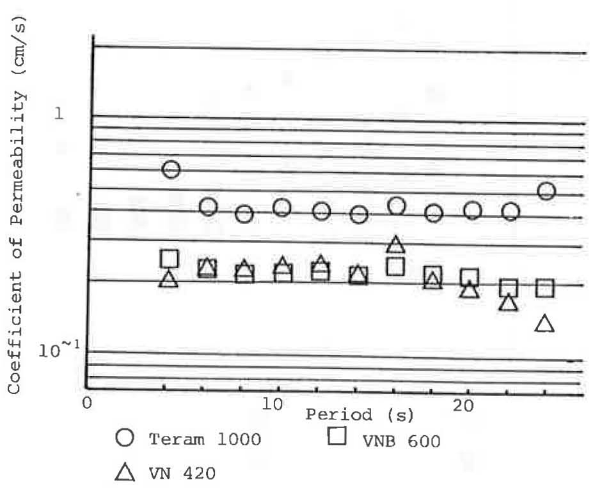

Figure 7 Coefficients of permeability of three geotextiles for oscillatory flow

samples; 3) The influence of geotextiles on the permeability of porous media is greater for large diameter porous media than for small diameter media (Fig.10).

CONCLUSIONS

(1) The coefficient of permeability of a large-grained porous medium having a coefficient of permeability greater than 10^{-1} cm/s is determined by measuring the forced harmonic oscillatory flow with the period of 4 s through 25 s in a U-tube filled with the medium.

(2) The coefficient of permeability for oscillatory flow determined by the U-tube method is a little greater than that determined by the constant head method.

(3) The permeability of a geotextile for oscillatory flow is controlled by the infrastructure of the geotxtile, and is in the range of 10^{-1} to 10^{-2} cm/s.

(4) The air bubbles entrapped in a geotextile can influence the permeability of it, but the degree of influence differs from one geotextile to the next.

(5) The influence of geotextiles on the permeability for oscillatory flow depends on the combination of the type of geotextile and the porous medium. However, the larger the diameter of the porous medium, the greater the influence is.

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Table 5 All values of coefficients of permeability obtained by U-tube method (unit:cm/s)

Material (D_{50}:mm)	Medium only	Sandwiched by geotextile: Teram 1000 ($k = 9.0\times10^{-2}$) one-layer	two-layer	VNB 600 ($k = 2.8\times10^{-1}$) one-layer	two-layer	VN 420 ($k = 2.0\times10^{-1}$) one-layer	two-layer
Glass Ball (12.80)	33.20	13.01	8.05	5.00	3.19	4.95	3.37
Medium Gravel (6.60)	13.94	7.37	4.73	4.10	3.16	4.08	2.93
Fine Gravel (3.07)	5.70	3.61	2.90	2.62	1.54	2.58	1.96
Coarse Sand (1.30)	1.79	1.40	0.944	0.890	1.04	1.05	0.880
Medium Sand (0.64)	0.374						

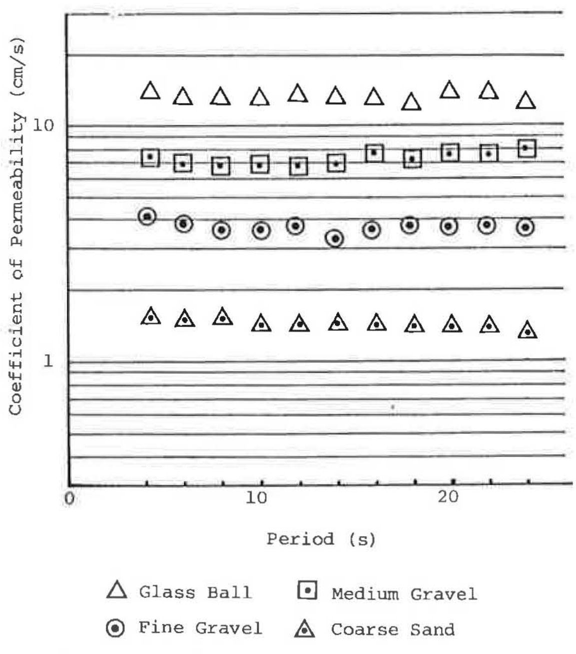

Figure 8 Relation between coefficients of permeability of one-layer samples sandwiched by Teram 1000 and period

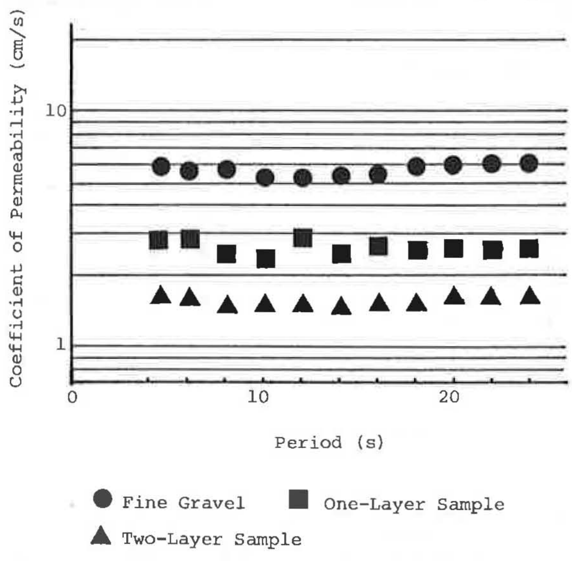

Figure 9 Comparison of U-tube permeability test results for a porous medium, one-layer and two-layer samples of fine gravel sandwiched by VN 420

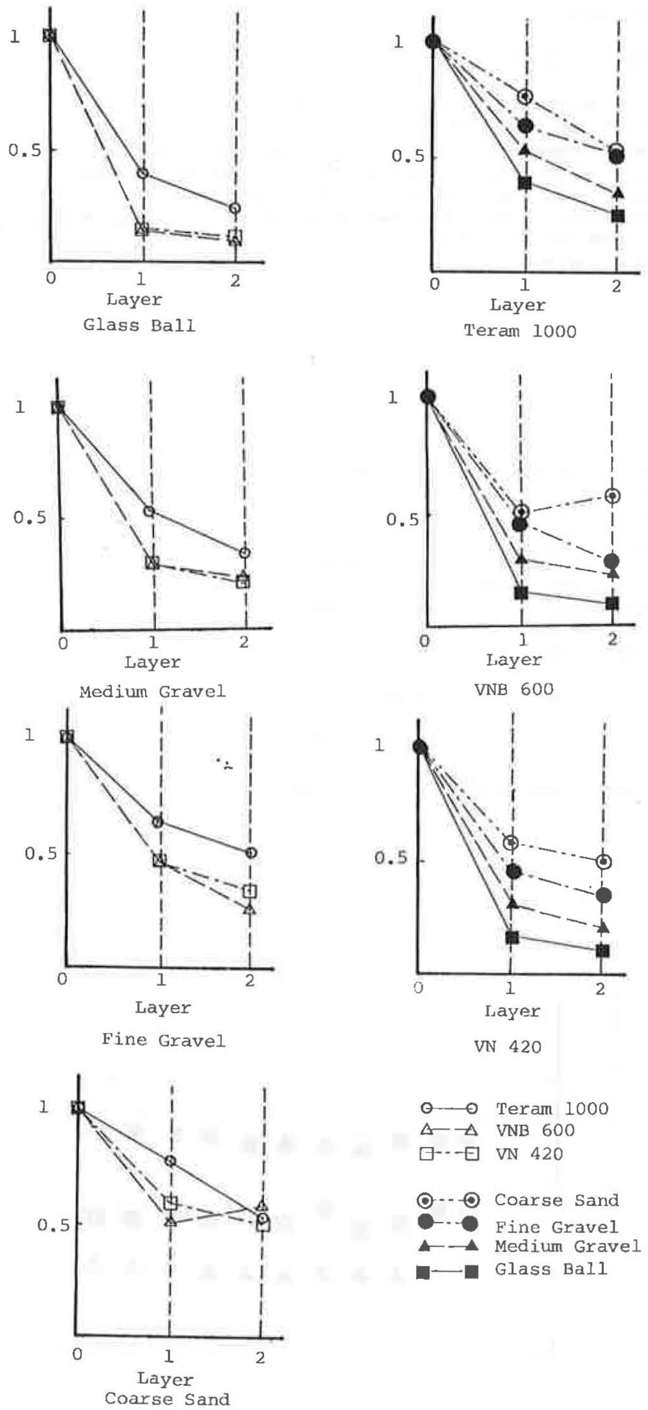

Fig. 10 Decrease in coefficients of permeability normalized by the coefficient of permeability of each porous medium due to sandwiching by geotextile

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