# CHAPTER 112

## Permeability characteristics of rubble material - New formulae

Robert W K Shih[1]

## 1 Introduction

Rubble mould structures have been used extensively to protect coastal areas of human interest. These include breakwaters, seawalls and related structures. To be successful, a rubble mould structure should absorb most of the energy from the incident waves and be able to withstand the pore pressures generated during the process. These are determined by the geometry of the structure and the hydraulic properties of rubble.

Advances in computer resources enable the interaction between waves and rubble structures to be simulated numerically (Ref 1, 2 and 7). The general approach is to describe the porous medium as a continuum, having properties of dimension, porosity and permeability. The flow of water into and through such a porous continuum may then be described, depending upon the velocities and pore pressures induced. In physical hydraulic modelling of coastal structures various researchers (Ref 5) have considered the importance of permeability characteristics on the scaling of porous rubble core material. Similitude is usually achieved by selecting a model material, of prototype porosity, which yields a comparable hydraulic gradient to the prototype when subjected to an equivalent Froude scaled flow velocity. Both the numerical and physical methods of modelling, however, require a good description of the energy dissipation process which is related to the permeability of the structure. At present, most modellers use formulae which were originally developed for flows in sand. That proposed by Engelund (Ref 4) has been most widely used.

Engelund's formula is expressed in the Forchheimer form which describes the hydraulic gradient (i) in laminar, transitional and turbulent conditions by: $i = au + bu^2$ (Eqn 1) where u is the superficial velocity. The dimensional coefficients a and b are generally referred as the laminar and turbulent coefficients respectively, and are given in terms of particle diameter (D) and

---

[1]Engineer, Coastal Structures Section, Hydraulics Research, Wallingford, Oxfordshire, OX10 8BA, UK

sample porosity (n):

$$a = \alpha_o \, (1-n)^3 \, \frac{\upsilon}{gn^2 D^2} \, , \quad b = \beta_o \, \frac{(1-n)}{gn^3 D} \qquad \text{(Eqn 2)}$$

with appropriate coefficient values:

(i) uniform spherical particles $\alpha_o = 780$, $\beta_o = 1.8$;
(ii) uniform rounded sand grains $\alpha_o = 1000$, $\beta_o = 2.8$;
(iii) irregular angular grains $\alpha_o$ up to 1500 or more, $\beta_o$ up to 3.6 or more

It should be noted values have been derived for $\alpha_o$ and $\beta_o$ for materials with diameters much less than 10mm. Large uncertainties are involved when applying these values to rubble materials which have diameters up to or greater than 1m.

The research work presented in this paper is part of a comprehensive study on the hydrogeotechnical performance of rubble mound breakwater. It aims at providing a better insight into the permeability properties of porous media, particularly as they influence the wave/structure interactions. Extensive literature review on previous experimental works and methods of analysis and implementation has been carried out and presented in Ref 8. Based on the review, a new permeameter has been designed, and used to test samples with wide ranges of size and grading under a wide range of flow conditions. Analysis on the results have indicated the inadequacy of the existing formulae and new formulae are proposed in this paper. Results from this study will be implemented in the numerical models which are being developed in parallel.

## 2 Permeameter design

During the design of the permeameter which was constructed especially for the present study, the following points were considered:

(i) The main body should be sufficiently large to test material of characteristic diameters up to 50mm. It has been suggested that the permeameter diameter should be at least ten times the diameter of the largest material to be tested (Ref 3).
(ii) The design should minimise the potential of air entrainment in the material sample.
(iii) The water supply should be capable of generating a flow velocity through the sample of at least 0.1 m/s.
(iv) The measured pressure head loss should be representative of the complete sample cross-section.
(v) The sample should be constrained to retain constant porosity throughout a test without significant dilation or loss of fines.
(vi) The inflow velocity should be measured precisely.
(vii) The system should be capable of reproducing and measuring hydraulic gradients in the range 0.01 to 5.

It was decided that a bottom water entry would be most appropriate. This would allow the majority of air entrained in voids between particles to be eliminated by running water through the system for a few minutes before commencement of the test.

The final design solution is presented in Figure 1. The permeameter is cylindrical in shape with overall height and internal diameter equal to 1.45m and 0.6m respectively. Flexible PVC tubes 9mm in diameter were used to allow measurement of a representative pressure head loss at a separation of 0.5m across the entire sample cross-section. Rigid perforated steel plates were incorporated to contain the sample at top and bottom. Water was pumped through the permeameter, initially through a 0.3 metre baffled inlet section, and allowed to flow freely over the upper rim. The system was operated up to a flow velocity of approximately 0.1 m/s. The pumped water was flow gauged using an orifice plate meter in the supply pipe. The discharge water from the permeameter was allowed to drain back freely into the reservoir, within which the pump intake was located, thus providing continuous water cycling.

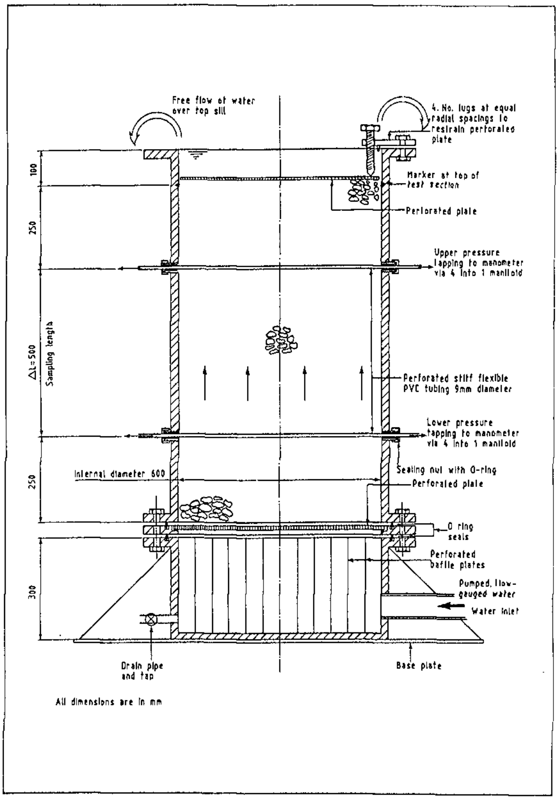



Fig.1 Schematic sectional plan of the present permeameter

## 3 Testing procedure

The testing procedure is represented by a flow chart in Figure 2. Details of each process are given below.

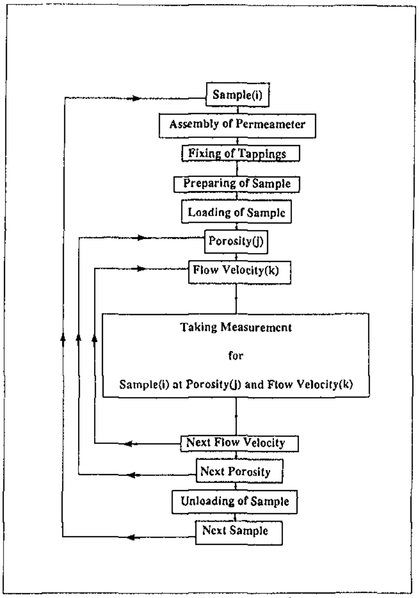



Fig.2 Flow chart for the test procedures

### Assembly of the permeameter

Before the permeameter was assembled, it was necessary to ensure that areas such as the flanges, gaskets and bolt holes at the interfaces among the chamber, the perforated base plate, and the base stand, were free from particles.

The perforated base plate was first connected to the chamber hoisted by a gantry. This was done with four 15mm diameter bolts passing from the bottom flange of the chamber into threaded holes in the base plate. This partly assembled permeameter was then hoisted over the top of the base stand. It was lowered down such that the four prefabricated holes on the flange of the chamber, the base plate, and the base stand all lined up with one another. Four 15mm diameters bolts were used to pass through these holes and tighten the three different parts together. The permeameter was then filled with water to check for leakage.

### Fixing the tappings

Pressures were measured at two levels, 0.5m apart, inside the permeameter. At each level, the measurement arrangement consisted of a pair of tapping tubes running perpendicularly across the inside diameters of the permeameter. These tubes were made of flexible PVC tubes 9mm in diameter, with perforations at 40mm intervals. The open ends of these two tapping tubes were connected outside the permeameter via a looped PVC tube. The single outlet from this looped tube was connected to a manometer to provide a representative measurement of pressure at that particular level.

Preparing of samples

The main samples used in the tests were generally limestone with density equal to 2.76 gm/cm$^3$. Before use each samples was sieved to produce the required size bands. They were then washed to eliminate fine material which might be washed away during the test, and hence affect the porosity.

Loading of samples

Samples, in small quantities, were carefully loaded into the permeameter. The weight of each sack was recorded so that the total quantity in the permeameter could be determined.

Porosity of the test specimen

Before starting a new series of tests, water was pumped through the sample for 10 minutes at the highest discharge to allow natural settlement to take place. The porosity obtained at the end of this period was defined as the highest porosity that the sample could achieve.

Lower porosities were obtained by compacting the sample with a vibrating poker. This was done by following the procedure below.

(i) The permeameter was filled with water up to the top surface of the sample.
(ii) A fixed amount of material was added onto the surface and smoothed by hand.
(iii) The vibrating poker was used until the water surface just covered the samples.

In cases of high porosities, the poker was only required to be inserted to a depth of about 150mm at two locations. As the samples became more compact, the poker had to be inserted to a greater depth and at more locations. In general, six to eight different porosities were achieved in a series of tests.

Porosity measurements

Porosity was calculated from the weight of the samples loaded, the gross volume of the samples when stabilised, and the specific gravity of the samples.

Flow conditions

For each porosity, up to nine different flow rates were used, increasing regularly from approximately 0.01 m/s to 0.10 m/s.

## 4 Test conducted

The test samples were produced as a range of single size classes and mixtures derived from them. Each single size class was initially referred to by its nominal upper sieve size, generally significantly greater than either $D_{15}$ or $D_{50}$ which are the diameters of the sample that 15% and 50% of the sample exceed (see Table 1).

| Nominal Size (mm) | $D_{15}$ (mm) | $D_{50}$ (mm) | $D_{85}$ (mm) |
|---|---|---|---|
| 4 | 1.49 | 2.13 | 2.76 |
| 6 | 4.94 | 5.42 | 6.26 |
| 10 | 7.22 | 8.65 | 9.74 |
| 14 | 9.35 | 10.87 | 12.40 |
| 20 | 12.72 | 14.65 | 17.39 |
| 28 | 19.28 | 21.77 | 24.58 |
| 40 | 27.61 | 33.23 | 37.77 |
| 61 | 54.50 | 63.00 | 73.80 |

Table 1 Single size samples

As quarried rock is more likely to exhibit a "gradual" size grading curve. This is illustrated by Kobayashi et al based on available field data (Ref 6) who describe prototype gradings falling in:

$1.24 < (D_{50}/D_{15}) < 2.0$
$1.24 < (D_{85}/D_{50}) < 1.8$
$1.54 < (D_{85}/D_{15}) < 3.6$

To study the effect due to both the 'size' and 'distribution' of samples within the mixture, a series of tests were carried out on graded samples (see Table 2).

| Mixtures (Nominal dia. in mm) | $D_{15}$ (mm) | $D_{50}$ (mm) | $D_{85}$ (mm) | $D_{50}/D_{15}$ | $D_{85}/D_{50}$ | $D_{85}/D_{15}$ |
|---|---|---|---|---|---|---|
| 6,10,14 | 4.09 | 8.20 | 11.77 | 2.00 | 1.44 | 2.88 |
| 6,10,14,20 | 4.43 | 9.77 | 16.70 | 2.21 | 1.71 | 3.77 |
| 6,10,14,20,28 | 4.76 | 11.59 | 22.50 | 2.43 | 1.94 | 4.73 |
| 6,10,14,20,28,40 | 5.70 | 14.02 | 29.24 | 2.46 | 2.09 | 5.13 |
| 10,14,20 | 8.04 | 11.59 | 17.60 | 1.44 | 1.52 | 2.19 |
| 10,14,20,28 | 8.50 | 14.02 | 23.62 | 1.65 | 1.68 | 2.78 |
| 10,14,20,28,40 | 8.97 | 17.29 | 30.17 | 1.93 | 1.75 | 3.36 |
| 14,20,28 | 10.66 | 17.29 | 24.75 | 1.62 | 1.43 | 2.32 |
| 14,20,28,40 | 11.51 | 20.59 | 31.10 | 1.79 | 1.51 | 2.70 |
| 20,28,40 | 16.99 | 24.38 | 32.10 | 1.43 | 1.32 | 1.89 |

Table 2 Wide graded samples

The gradings of the graded sample were chosen based on the following criteria.

(i) Each mixture should contain at least three different sizes of materials.
(ii) Sizes of materials should be increased gradually.
(iii) Ratios of $(D_{50}/D_{15})$, $(D_{85}/D_{50})$ and $(D_{85}/D_{15})$ should cover the ranges observed in the field data.

## 5 Analysis of test results

### 5.1 Single size samples

In considering the large amounts of data produced, it proved to be convenient to describe the flow/resistance relationship for each test in terms of the Forchheimer equation (Eqn 1) with coefficients a and b initially represented by the expressions proposed by Engelund (Eqn 2). A simple assessment of the dependence of coefficients $\alpha_o$ and $\beta_o$ on the particle sizes was carried out. Regression analysis was performed depending on the particle sizes (Eqn 3).

$$\frac{i}{u}\,\frac{gD_{15}^2}{\upsilon}\,\frac{n^2}{(1-n)^3} = \alpha_o + \beta_o\,\frac{1}{n(1-n)^2}\left(\frac{uD_{15}}{\upsilon}\right) \qquad \text{(Eqn 3)}$$

Good linear relation was observed (see Figs 3a to 3g).

The laminar constant $(\alpha_o)$ was found to increase in proportion to $D_{15}^2$. Its lower limit coincided with the upper limit suggested by Engelund (see Fig 4a). The turbulent constant $(\beta_o)$ was found to decrease exponentially with $D_{15}$ (see Fig 4b). These results suggest that Engelund's expressions for a and b will need to be modified to represent flow in material larger than 10mm. At its simplest this may be given for formulae for $\alpha_o$ and $\beta_o$.

The permeability relationship for <u>single size materials</u> is therefore given by $i = au + bu^2$, where i = hydraulic gradient, u = superficial velocity and

$$\boxed{\begin{aligned} a &= \left[\alpha_1 + \alpha_2 \left(\frac{g}{\upsilon^2}\right)^{2/3} D_{15}^2\right] \frac{(1-n^3)}{n^2}\,\frac{\upsilon}{g}\,\frac{1}{D_{15}^2} \\ b &= \left\{\beta_1 + \beta_2 \exp\left[\beta_3 \left(\frac{g}{\upsilon^2}\right)^{1/3} D_{15}\right]\right\} \frac{(1-n)}{n^3}\,\frac{1}{gD_{15}} \end{aligned}}$$

where (Eqn 4)

n = porosity
$\alpha_1$ = 1683.71, $\alpha_2 = 3.12 \times 10^{-3}$
$\beta_1$ = 1.72, $\beta_2$ = 1.57, $\beta_3 = -5.10 \times 10^{-3}$
$\upsilon$ = kinematic viscosity of water = $1.14 \times 10^{-6}$ m²/s
g = gravitational acceleration = 9.81 m/s²

Good agreement was obtained between observed and predicted hydraulic gradients, Fig 5.

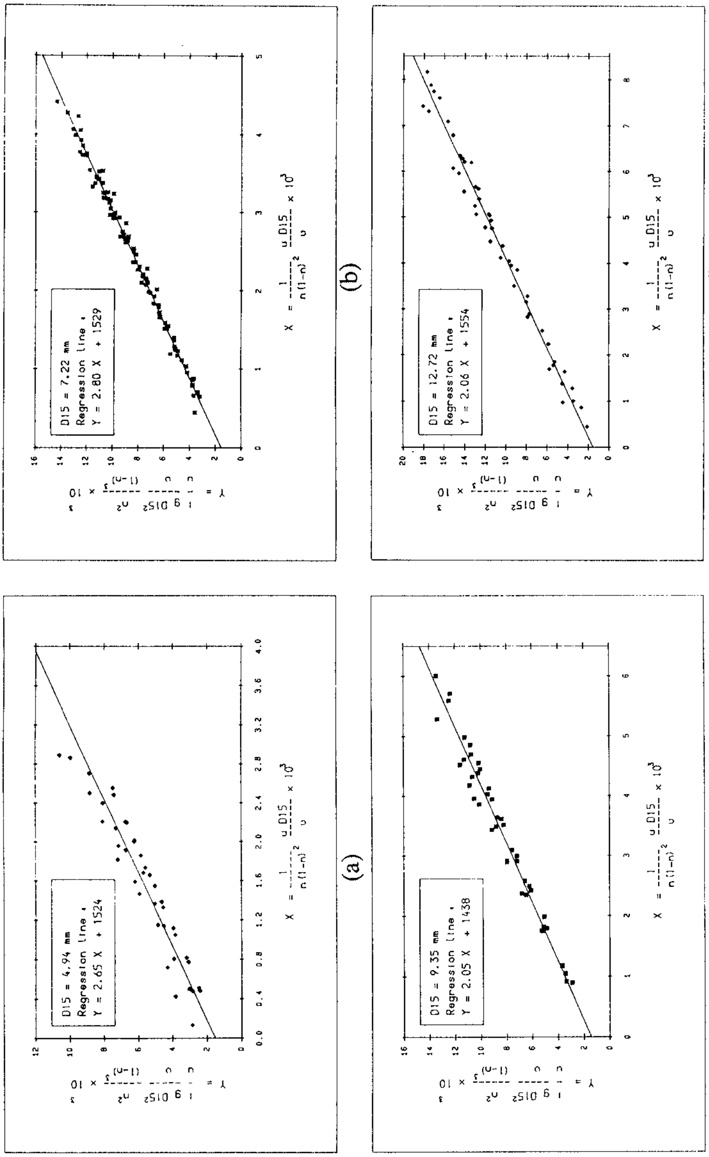



Fig.3 Regression analysis on results of single size materials

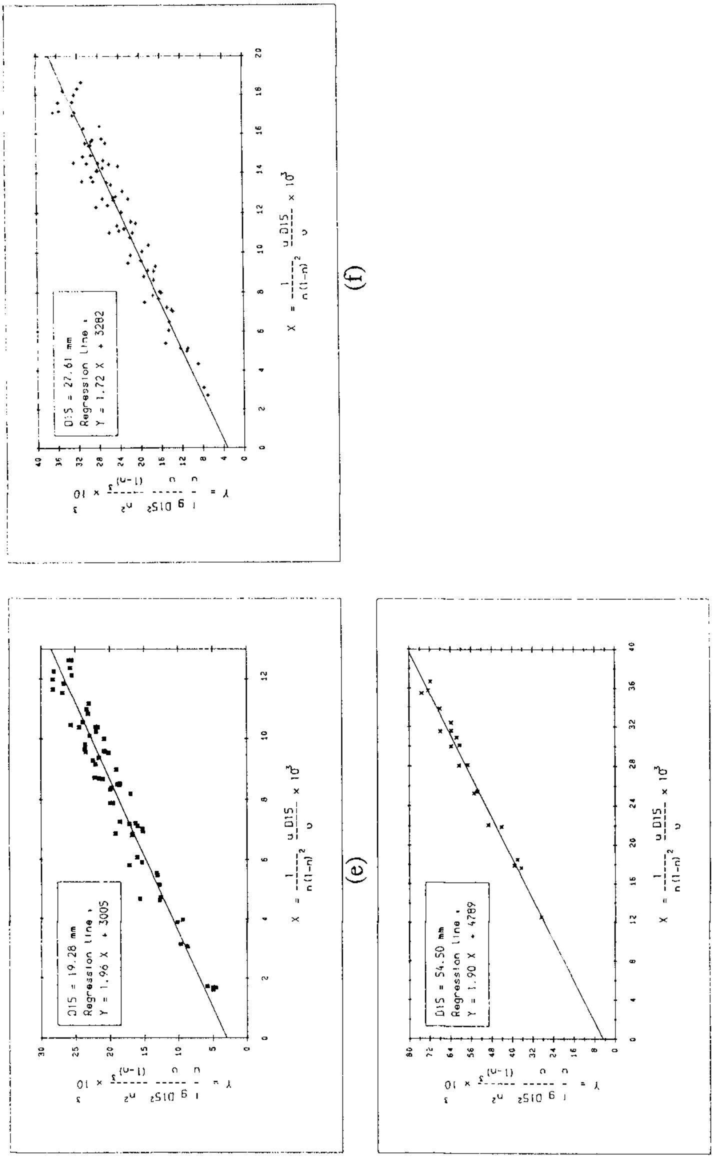
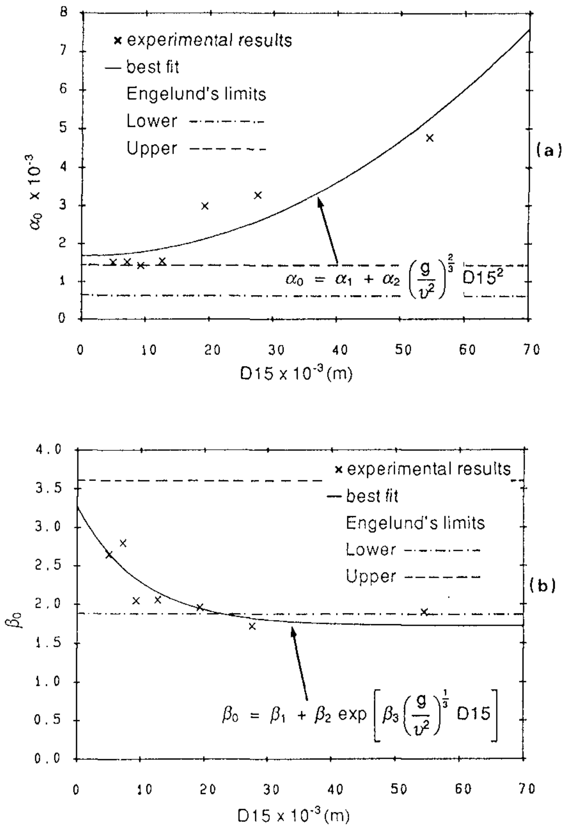

(e)
D15 = 19.28 mm
Regression line ,
Y = 1.96 X + 3005
(f)
D15 = 27.61 mm
Regression line ,
Y = 1.72 X + 3282
(g)
D15 = 54.50 mm
Regression line ,
Y = 1.90 X + 4789

Fig.3 cont.




$\alpha_1 = 1683.71$

$\alpha_2 = 3.12 \times 10^{-3}$

$\beta_1 = 1.72$

$\beta_2 = 1.57$

$\beta_3 = -5.10 \times 10^{-3}$

$\upsilon$ = kinematic viscosity of water
= $1.14 \times 10^{-6}$ m²/s

g = gravitational acceleration = 9.81 m/s²

Fig.4 Dependence of $\alpha_0$ and $\beta_0$ on particle diameter $D_{15}$ for single size materials

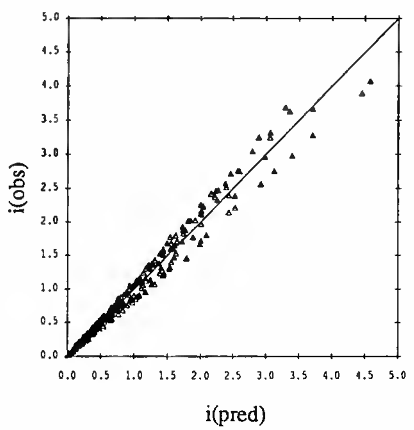



Fig.5 Comparison between i(obs) and i(pred) for single size materials

Number of data points = 392

## 5.2 Wide graded samples

For wide graded samples, same permeability relationship for single size samples was adopted with $D_{15}$ replaced by $D_*$ where

$$D_* = D_{15} \left(\frac{D_{15}}{D_{50}}\right)^{c1} \left(\frac{D_{50}}{D_{85}}\right)^{c2} \qquad \text{(Eqn 5)}$$

so as to include the effect due to the grading of the material. Coefficients c1 and c2 were determined such that the total square errors in hydraulic gradient, $(i_{predicted} - i_{observed})^2$, was minimum. This gave c1 = -1.11 and c2 = 0.52 (see Fig 6).

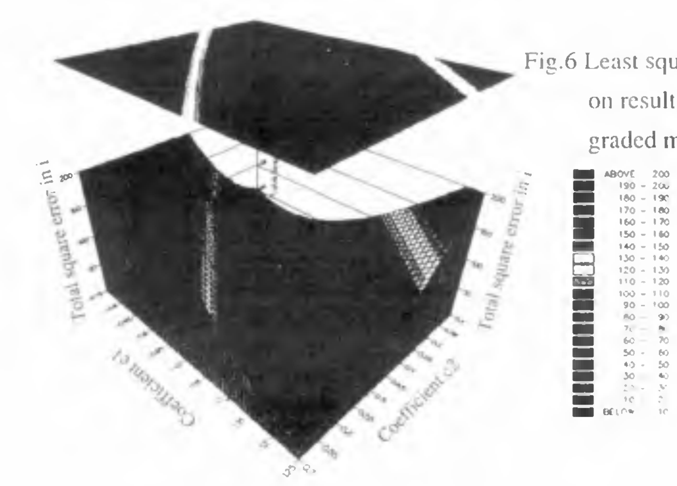



Fig.6 Least square analysis on results of wide graded materials

The permeability relationship for wide graded materials is therefore given by:

$$i = au + bu^2$$

where

i = hydraulic gradient, u = superficial velocity

and

$$a = \left[ \alpha_1 + \alpha_2 \left( \frac{g}{\nu^2} \right)^{2/3} D_*^2 \right] \frac{(1-n^3)}{n^2} \, \frac{\nu}{g} \, \frac{1}{D_*^2}$$

$$b = \left\{ \beta_1 + \beta_2 \exp\left[ \beta_3 \left( \frac{g}{\nu^2} \right)^{1/3} D_* \right] \right\} \frac{(1-n)}{n^3} \, \frac{1}{gD_*}$$

$$D_* = D_{15} \left( \frac{D_{15}}{D_{50}} \right)^{-1.11} \left( \frac{D_{50}}{D_{85}} \right)^{0.52} \quad \text{(Eqn 6)}$$

where

$n$ = porosity
$\alpha_1$ = 1683.71, $\alpha_2$ = $3.12 \times 10^{-3}$
$\beta_1$ = 1.72, $\beta_2$ = 1.57, $\beta_3$ = $-5.10 \times 10^{-3}$
$\nu$ = kinematic viscosity of water = $1.14 \times 10^{-6}$ m²/s
$g$ = gravitational acceleration = 9.81 m/s²

Good agreement was obtained between observed and predicted hydraulic gradients Figure 7.

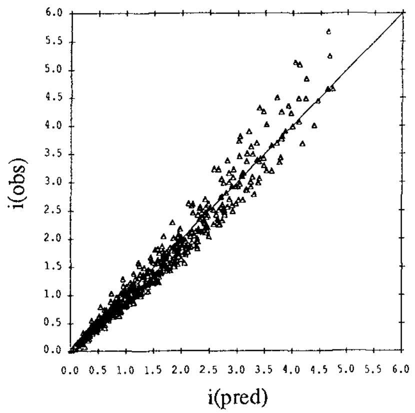



Fig.7 Comparison between i(obs) and i(pred) for wide graded materials

Number of data points = 641

## 6 Conclusions and recommendations for future work

### 6.1 Conclusions

A permeameter (Fig 8) with diameter equal to 0.6m was used in the present study. Materials with size varying from 2 mm to 61 mm were tested as single size and wide graded samples. Hydraulic gradients varying from 0.1 to 5.0 were used. New formulae (Eqn 4) and (Eqn 6) for the permeability of rubble materials were proposed to update the existing formulae proposed by Englelund which were originally derived for sand. It should be noted that the newly proposed formulae were based on experimental results carried out in steady state.

### 6.2 Recommendations for future work

It is recommended that future work should cover the following areas:

(i) Unsteady/cyclic flows
 - Influence on inertia forces

(ii) Air entrainment effects
 - External and internal waves breaking

(iii) Interface loss between different rubble layers
 - Real breakwater composition

## 7 Acknowledgements

The work on which this paper is based has been funded by the Department of the Environment.

The permeability tests were designed primarily by R V Stephens and conducted by A R Channel. The work was carried out in the Coastal Structures Section managed by N W H Allsop, in the Maritime Engineering Department of Hydraulics Research Limited, Wallingford.

Fig.8 Permeameter in operation

## 8 References

1. Allsop N W H and Shih R W K. "Permeability of rubble mound coastal structures to wave action: Laboratory and numerical modelling." Proc. of Wave Research and Coastal Engineering, Hannover, 1988.

2. Barends F B J and Holscher P. "Modelling interior processes in a breakwater." Proc. Conf. Breakwaters 88, ICE, Eastbourne, May 1988.

3. Dudgeon C R. "Wall effects in permeameters." Proc. ASCE Journal Hyd. Div, HY5 : 137-148. Paper No 5433, Sept 1967.

4. Engelund F. "On the laminar and turbulent flows of ground water through homogeneous sand." Trans. Danish Academy of Technical Sciences, Volume 3, No 4, 1953.

5. Jensen O J and Klinting P. "Evaluation of scale effects in hydraulic models of laminar and turbulent flows." Coastal Eng 7, 1983, pp 319-329.

6. Kobayashi M, Terashi M and Takahashi K. "Bearing capacity of a rubble mound supporting a gravity structure." Report of the Port and Harbour Research Institute, Vol 26, No 5, pp 215-252. 1987.

7. Madsen O S and White S M. "Reflection and transmission characteristics of porous rubble mound breakwaters." Technical Report No 207, RA M Parsons Laboratory, Dept Civil Eng, MIT, 1975.

8. Stephens R V, Shih R W K and Allsop N W H. "Permeability characteristics of rock fill materials in rubble mound coastal structures." Report IT 340, Hydraulics Research, Wallingford.