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SCALE EFFECTS IN MODELS OF POROUS COASTAL STRUCTURES

by

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Abstract

Physical modelling of most of the hydraulic phenomena in coastal waters can be achieved with considerable accuracy if it were possible to satisfy both Froude and Reynolds laws simultaneously. Gravity and inertia being predominant, coastal hydraulic models are generally designed and operated in accordance with the Froude criterion. Porous coastal structures exhibit further problems when modelling for reflection and transmission. This is mainly because of the probability that flow through the structure may not be turbulent. Using the Froude criterion and scaling the core material geometrically will result in a less permeable core in the model. In order to correct for this dissimilarity it is suggested that the sizes of the core material in certain parts of the model should be larger than that which would be indicated by direct application of the linear scale. This paper refers to detailed investigations both theoretical and experimental, relating to the hydraulic models of porous coastal structures. Results from field and experimental investigations are used to assess the available analytical methods.

1.0 Introduction

Hydraulic modelling frequently involves the simulation of large systems at a substantially reduced scale which usually prevents the attainment of full similitude between model and prototype. Scale effects may be defined as any hydraulic inaccuracy in model performance caused by the reduced size of the model. Such effects may be present to some degree in any model smaller than its prototype.

The forces that may affect a flowing fluid are those of inertia, gravity, pressure, viscosity, elasticity and surface tension. To obtain dynamic similarity between two flow fields when all these forces act, all corresponding force ratios must be the same in model and prototype. In most engineering problems some of the forces may not be involved, may be of negligible magnitude or may oppose other forces in such a way that the effects of both are reduced. In each problem of similitude a proper understanding of the fluid phenomena is necessary to determine how the problem may be satisfactorily simplified by elimination of the irrelevant, negligible or compensating forces.

Most of the hydraulic phenomena that may be met in coastal engineering projects could be simulated with considerable accuracy if it were possible to satisfy both Froude and Reynolds laws simultaneously. Gravity and inertia being predominant, coastal hydraulic models are generally designed and operated in accordance with the Froude criterion. The other forces are assumed to be negligible. However, when the linear scale is too small, viscous forces may become significant and cause inaccuracies in model performance. Therefore, selection of scale for a model involving wave action usually requires a compromise between economy and the degree of accuracy required. In this paper certain aspects related to modelling of wave transmission through a porous breakwater on a natural undistorted scale are presented.

2.0 Modelling for Transmission and Reflection on Undistorted Scale

Breakwaters are usually constructed of rubble with natural rock or concrete armour. In addition to the scale effects discussed earlier, porous structures exhibit further problems when modelling for reflection and transmission. The major problem is largely because of the probability that flow through the structure may not be turbulent. Hudson (1979) observed that generally there is relatively more wave energy reflected and less transmitted in the model structure than in the prototype unless the model scale is large enough to ensure that motion is fully turbulent in the model. Using the Froude criterion and scaling the core material geometrically

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will result in a less permeable core in the model, leading to relatively higher down-rush pressures from inside the structure.

Flow through porous media has to be correctly represented with due regard to the similitude of the hydraulic gradient in model and prototype. For example, hydraulic model tests on breakwaters are normally carried out at small scales such that the flow through various layers of the breakwater is not completely turbulent. Hence in breakwater model tests where transmission is considered critical, it is important to recognise the modelling requirements of both the armour layer and the underlayer. Model design must take these into account and appropriate modifications made in the construction of the model.

It is required that the flow through the main armour layers is properly scaled in order to obtain reliable results with respect to their stability and related factors. Hence for this region the emphasis is on stability and the weight of the armour unit or stone must be accurately reproduced and errors must be avoided in scaling these weights. Breakwater models are normally constructed at scales in the region 1:30 to 1:40. In such models the main armour layer is composed of units which have characteristic dimensions of the order of 5 cm. For typical flow conditions encountered in models the Reynolds number for the main armour will be approximately $5x10^4$ which is an acceptable value for similitude.

However, the condition nearer to the core of the structure is quite different; both the dimensions of the stone and the magnitude of velocities are relatively small. The Reynolds number characterising the flow is below the critical value required for fully turbulent flow. This is of particular importance for wave transmission and will also influence the stability of the main armour layer and the reflection from the breakwater. In order to achieve a correct and more representative hydraulic gradient in the model, some of the interior layers and the core could be made of stones larger than the Froude criterion would demand, satisfying the requirement

$$d_m = k d_p \left[\frac{L_m}{L_p}\right] \quad \ldots\ldots (1)$$

$k(>1)$ is an enlargement factor which should be applied to the linear scale.

$\frac{L_m}{L_p} (= L_r)$ is the linear scale

d_m and d_p are characteristic dimensions of the stones in the cores of the model and prototype.

3.0 Methods of Determining the Scale Ratio for Particle Size

Methods for calculating the enlargement factor k in eq. (1) have been presented by LeMehaute (1965), Keulegan (1973), Jensen and Klinting (1983). Of these studies the first and the last are similar to each other in that an established expression for the hydraulic gradient - velocity relationship was assumed as the initial step. Keulegan (1973) adopted equations arising from a limited experimental study. However, in all these studies attention was not focussed on the relative influence of laminar and turbulent flow coefficients for different media or the influence of porosity.

Although these calculations provide a method of predicting approximate enlargement factors, the correct value is best determined by two dimensional tests. These consist essentially of two series of experiments the first to determine wave transmission and reflection characteristics at prototype scale and the second to determinen the correct size of stone for reproduction of these characteristics in the model. However, due to practical limitations or due to non-existence of the prototype it may not be possible to perform the first investigation. Under such conditions the prototype should be replaced by a model section built on a scale considered sufficiently large to avoid scale effects. Wave transmission characteristics recorded during these experiments may then be considered to be representative of prototype conditions. In the model test series, stone size has to be varied until transmission coefficients are approximately the same. Once the stone size is selected, model breakwaters for three dimensional studies could be constructed. Whalin and Chatham (1974) adopted this technique for a model study of a harbour project at a distorted scale. It is evident that on most occasions this type of detailed experimentation is not feasible on economic considerations. Furthermore exact reproduction is rarely possible because of the variations of transmission coefficients with wave period and height, as an exact correspondence over range of wave periods is unlikely. Hence much reliance is placed on analytical techniques however approximate they may be.

4.0 Objectives of the Paper

To obtain complete similitude between model and prototype for flow through porous media it is required that the hydraulic gradient is same for both. In this paper an analytical method is presented, based on the expression for hydraulic gradient under steady flow condition, to evaluate the enlargement factor k. In the initial phase k is expressed in terms of laminar and turbulent resistance terms, velocity and a characteristic dimension as applicable to both model and prototype. Simplifying assumptions are made to express k in terms of parameters applicable only to the prototype and results from steady flow tests are used to assess the validity of such assumptions. Attention is also focused on the sensitivity of k to variations in porosity. Finally, results from experiments pertaining to scale effects on cylindrical lattice structures and spherical lattice structures are presented. The objective is to obtain a clearer understanding of the influence of the key parameters in relation to wave transmission in hydraulic models.

5.0 Analytical Development, its Application and Discussion

5.1 Analytical development

The general expression for the hydraulic gradient (I) for steady flow through porous media is of the form

$$I - au + bu^2 \qquad (2)$$

where u = bulk or macroscopic velocity

where a and b are constants dependent on the void characteristics of the medium, the two terms being interpreted as the laminar and turbulent components respectively.

$$I - I_L - I_T \qquad (3)$$

I = hydraulic gradient

I_L = hydraulic gradient (laminar)

I_T = hydraulic gradient (turbulent)

Of the many expressions developed for flow through porous media, those of Engelund (1953) and LeMehaute (1957) are widely accepted.

A more specific way of presenting the above expressions is as follows,

$$I = f_L \frac{\gamma}{gd^2} u + f_T \frac{1}{gd} u^2 \quad \ldots \quad (4)$$

or

$$I = \left[\frac{2f_L}{Re} + 2f_T\right] \frac{u^2}{2gd} \quad \ldots \quad (5)$$

In which d is the characteristic dimension

Re is the Reynolds number (Re = ud/r)

F and f are liminar and turbulent resistance coefficients

γ is kinematic viscosity

Values of F and f as given by the equations of Engelund (1953) and LeMehaute (1957) are given in Table 1.

The term $$\mathcal{E} = \frac{I_T}{I_L} = \frac{f_T}{f_L} Re \quad \ldots\ldots \quad (6)$$

plays an important role in assessing the degree of turbulence in flow through porous media, including its dependence on Reynolds number.

In evaluating scale effects for laminar and turbulent flow it is observed that for complete similitude between model and prototype it is necessary to consider the total expression for the hydraulic gradient given by eq. 4.

$$I_r = \frac{I_m}{I_p} = \frac{[I_L + I_T]_m}{[I_L + I_T]_p} = 1 \quad \ldots \quad (7)$$

$$I_r = \left[\frac{f_{Lm} \frac{\gamma}{gd_m^2} u_m + f_{Tm} \frac{1}{gd_m} u_m^2}{f_{Lp} \frac{\gamma}{gd_p^2} u_p + f_{Tp} \frac{1}{gd_p} u_p^2}\right] \ldots (8)$$

Using the Froude criterion,

$$u_r = \sqrt{L_r} \quad \ldots\ldots \quad (9)$$

Where Lr is the length scale ratio

$$L_r = \frac{L_m}{L_p}$$

i.e. $$u_m = u_p \sqrt{L_r}$$

Assuming $d_r \neq L_r$ and that dr can be expressed as,

$$d_r = kL_r \quad \ldots . (1)$$

where k (≥1) is an enlargement factor, it is possible to introduce eq. 9 and eq. 1 into eq. 8 in order to obtain an expression for k.

It is observed that k is found from a quadratic equation and is expressed as follows.

$$k = \frac{L_r^{3/2} f_{Tm} Re_p + \sqrt{L_r^3 f_{Tm}^2 Re_p^2 + 4 L_r^{3/2} f_{Lm}(f_{Lp} + f_{Tp} Re_p)}}{2 L_r^{3/2} (f_{Lp} + f_{Tp} Re_p)} \quad \ldots\ldots\ldots (10)$$

However, if it is assumed that

$$f_{Lm} = f_{Lp} = f_L \quad \ldots\ldots (11)$$

$$(\text{i.e } (f_L)_r = 1)$$

and

$$f_{Tm} = f_{Tp} = f_T \quad \ldots\ldots (12)$$

$$(\text{i.e. } (f_T)_r = 1$$

eq. 10 can be simplified to

$$k = \frac{f_T Re_p + f_T^2 Re_p^2 + 4(f_L + f_T Re_p) f_L / L_r^{3/2}}{2(f_L + f_T Re_p)} \quad \ldots\ldots (13)$$

By introducing eq. 6 into eq. 13 k is further simplified to

$$K = \frac{\xi p + \xi p^2 + 4(1 + \xi p)/L_r^{3/2}}{2(1 + \xi p)} \quad (14)$$

where

$$\xi = \frac{I_{Tp}}{I_{Lp}} = \frac{f_{Tp}}{f_{Lp}} Re_p \ldots\ldots (6)$$

subject to conditions specified in eqs. 11 and 12. From the above equation it appears that

as $\xi_p \to 0$ the expression for $k \to 1/L_r^{3/4}$ (i.e. laminar flow) and as $\xi \to \infty$ the expression for $k \to 1$ (i.e. turbulent flow)

Using these two extreme conditions and substituting in eq. 1 then

$$d_r = \sqrt[4]{L_r} \qquad \text{for laminar flow} \quad (15)$$

$$d_r = L_r \qquad \text{for turbulent flow} \quad (16)$$

This indicates that although the turbulent term is correctly represented, the laminar term requires that material should be scaled much larger than the values determined according to the Froude criterion.

It should be noted that the expression for k as given by eq. 14 is valid on the assumption that the respective resistance coefficients for the model and prototype are equal. It is observed that the enlargement factor is a function of the Reynolds number of the prototype (Re_p), the scale ratio of length (L_r) and the ratio of turbulent/laminar resistance coefficients (fr/f_L).

However, it should be appreciated that it is difficult in practice to determine the Reynolds number of the prototype by measuring the velocity within a porous structure. The largest uncertainty in the use of the above evaluation for model studies of breakwaters is that concerning the magnitude and characteristics of the velocity field in the prototype structure. Under such circumstances it is convenient to replace the Reynolds number by a related parameter whose value could either be measured or evaluated from existing field data. For this purpose it is possible to use the hydraulic gradient ($I = \Delta H/\Delta L$) and relate it to field measurements on wave transmission.

Eq. 5 can be expressed as a quadratic equation in terms of the Reynolds number

$$Re^2 + \frac{f_L}{f_T} Re - \frac{I g d^3}{f_T \nu^3} = 0 \quad \ldots\ldots (17)$$

the solution being

$$R_e = \frac{-f_L \pm f_L^2 + 4 I g d^3 f_T/\nu^2}{2 f_T} \quad \ldots (18)$$

in which

$$I = \frac{\Delta H}{\Delta L} \quad \ldots\ldots (19)$$

5.2 Evaluation of hydraulic gradient

When applying eq. 18 to a practical case, it is necessary to estimate the head loss of a rubble mound breakwater and this has to be obtained from reported values of wave transmission. An analysis of this type is appropriate to successive quasi-steady flows such as long wave interaction with breakwaters. As an initial approximation, ΔH can be taken as the amplitude at the loop in front of the breakwater and ΔL as the average width of the core. $\Delta H / \Delta L$ is the gradient of the head loss through the voids in the core of the breakwater section. The influence of k is more significant if the crest of the core material section is relatively high with respect to the total structure. With reference to the properties of prototype material, LeMehaute (1965) suggests the use of an effective diameter which is taken to be the "10 percent smaller than" quarry stone from the core material grading curve.

Results from field studies on wave transmission provide further information which is of use for this type of computation. Fig. 1 relates to the work of Thornton and Calhoun (1972). For a given wave steepness it is possible to evaluate Kt from which the extreme values of ΔH can be computed as

$$\Delta H = (1 \pm K_t) H_i \quad \ldots\ldots (20)$$

It is evident that the problem is more complicated if it is required to determine the conditions for similitude and scale effects in the case of a breakwater which is subjected to overtopping. Simple relationships cannot be obtained for the combination of overtopping and permeability.

5.3 Influence of laminar and turbulent resistance coefficients

On the basis of the above analytical developments, it is possible to assess the influence of some of the important parameters.

The requirement that the respective resistance coefficients are the same for the model and prototype (eq. 11 and 12) is not fully justified and is assumed valid in the absence of experimental data covering a wide range of materials. Until steady flow tests are performed on a wider spectrum of materials used for breakwater construction the influence of these parameters will remain unclear. The conditions under which Engelund's equation was derived have been already presented.

In this paper the results from tests on cylindrical lattice structures can be used to illustrate this point. Given in Table 2, are the resistance coefficients of three structures in which the porosity, the shape of void and the tortuosity remain unchanged. The varying parameter is the size of the void characterised by its dimension which is also equal to the diameter of the cylindrical member.

It is evident that the values of f_L and f_T for these structures vary quite significantly indicating the influence of the void dimension. Since all parameters except the void dimension (d) are constant it can be assumed that the turbulent parameter is proportional to a certain power of the diameter (d) of the cylinder (i.e. $b \times d^m$) and m was found to be equal to -1.98 with a correlation coefficient of 0.96, indicating the existence of an inverse square law. Although this value was determined, only on three sets of data it is evident that the overall results do not support the simplifying assumptions made, eqs. 11, 12 i.e. $(f_L)_r \neq (f_T)_r \neq 1$.

5.4 Influence of porosity on the enlargement factor

The analytical development presented earlier can be used to assess the influence of porosity on the modelling of transmission. For this purpose, Engelund's equation is assumed to be valid and ξ_p represented by

$$\xi_p = \frac{\beta_0}{\kappa_0} \frac{1}{n(1-n)^2} Re_p \quad \ldots\ldots (21)$$

with $\alpha_0 = 15000.00$ and $\beta_0 = 3.6$ being used for computations. This expression is now substituted in eq. 14 to calculate the enlargement factor, k.

Fig. 2 is a plot of the enlargement factor, k, versus porosity (n) for various L_r at a prototype Reynolds number, $Re_p = 1000$. Since the influence of k is important for low flow rates, a Re_p value of 1000 was used for the illustration. Varying Reynolds numbers will be considered in a separate plot. From Fig. 2 it is observed that for a given scale ratio, k reaches a maximum at n = 0.35 and for small models the curvature of the plots is pronounced. A reasonable value of porosity for quarry-run core material is in the range 0.35 to 0.40, depending on the grading. In this region the respective curves are reasonably flat and therefore a variation in porosity will not have a significant influence on the value of k. However, in other regions the curves have considerable slope and a difference of 0.1 in porosity can change the value of k by approximately 20% or more. This plot clearly illustrates the sensitivity of k to changes in porosity and the importance of assessing the value of the porosity of the prototype in order to obtain an appropriate value of k for correct similitude.

Fig. 3 is a plot of the enlargement factor (k) versus porosity (n) for varying prototype Reynolds number at scale ratio Lr = 1.30. Two-dimensional studies on breakwaters are typically constructed at scales around this value. It is evident that as flow changes from laminar to turbulent the enlargement factor reduces in magnitude and approaches unity.

Fig. 4 is a plot of the enlargement factor (k) versus scale ratio (Lr) for varying prototype Reynolds number at a porosity of 0.4, the latter being a representative value with regard to breakwater studies. The advantage of working with a large model at high Reynolds numbers is clearly evident.

Figs. 2, 3 and 4 illustrate some of the problems associated with modelling flow through porous media with particular attention being focused on the occurrence of laminar flow and varying porosity. In the absence of extensive experimentation it is necessary to use this type of analytical method to evaluate model properties required to compensate for scale effects. Sufficient care should be taken in evaluating prototype properties which are required for this purpose.

When using an enlargement factor it is important to ensure that it is uniformly applied to the regions concerned and precautionary measures should be adopted in grading the model material and in the construction of the model. It is also very difficult to adjust or to duplicate the voids ratio for a scale model of a breakwater. The relatively large variation of the permeability with a small variation of the void coefficient is the main source of error in this kind of study.

This aspect can be further investigated by analysing the hydraulic characteristics of randomly packed spheres of diameters 19 and 25 mm which are in the ratio 1:1.32. Table 3, given below, illustrates the relevant parameters. Both media consist of spherical elements of different diameter packed in a similar way. The use of this type of element ensures that the voids matrix is uninfluenced by the irregularities in shape of the constituent element. Information pertaining to rounded stones is also included for comparison.

In the case of the spheres it is observed that f_T is approximately the same whereas f_L differs significantly. This illustrates the point that by using material which are slightly different, in this case a change in diameter by a factor 1.32, it is possible to obtain flow coefficients which are different. For example, if the required enlargement factor obtained by using the flow coefficients of the 19 mm spheres is 1.32, this necessitates the use of 25 mm spheres which have different permeability coefficients. This demonstrates some of the limitations of the analytical procedure and further developments can be achieved by detailed experiments on flow through porous media.

6.0 Scale Effect Tests on Wave Transmission and Reflection

Experimental investigations on scale effects pertaining to wave transmission are important to obtain information on the reliability of using models to predict prototype performance. Although a given experimental result relates to a certain state of flow, it does not necessarily represent prototype condition nor can it be used to predict prototype behaviour. Hence care must be exercised when interpreting transmission coefficients obtained under laboratory conditions for application in prototype conditions.

Tests to determine the scale effects of wave transmission through porous structures have been reported by Johnson, Kondo and Wallihan (1966). Wilson and Cross (1972) for rubble, Delmonte (1972) for closely packed uniform spheres and Kondo and Toma (1972) for cylindrical lattice structures. In all cases they have used the Froude criterion for scaling and considered the largest structure to be the control model.

In this paper results from tests performed on three cylindrical lattice structures and two spherical lattice structures are presented. The details of the investigation are reported in Table 4. Using the Froude criterion for scaling and considering the largest structure to be the control model with the smaller units as models, the conditions specified in the Table were used for the five structures. At the selected wave period and depth, transmission and reflection coefficients were obtained for different incident wave heights. It is noted that water depths ranging from 15 cm to 30 cm and wave periods ranging from 1.0 to 1.5 seconds were used for this study.

Figs. 5a to 5c show the results from cylindrical lattice structures. From these plots it is observed that scale effects are not particularly dominant for the three structures tested. In the case of K_t and K_d the results can be presented by a single curve with a good degree of correlation. The same cannot be said for the variation of K_r and this is attributed to an inherent deficiency in the method of measurement known as the loop-node technique. This problem has been encountered by all who have performed similar studies.

Fig. 6 presents the results for the spherical lattice structure. Unlike the cylindrical lattice structures, the presence of scale effects is clearly observed. The smaller structures exhibited higher transmission, higher reflection and lower loss coefficients in comparison with the control model. A single curve cannot be used to represent either transmission or reflection for both structures.

It is a point of interest to note that a cross-comparison with the work of Delmonte (1972) indicated that higher transmission coefficients are obtained for larger structures and this trend is not observed in the present study. This may be due to the fact that the wave period range used by Delmonte varied from 1.90 secs to 0.95 secs, whereas the corresponding range for this study varied from 1.16 secs to 1.00 secs. At shorter periods the energy dissipation is more effective and it increases with the length of the structure resulting in minimum transmission. Hence it is important to realise that due consideration should be given to the wave period range when comparing the results of scale-effect studies. It is recommended that for a given set of structures, teststo investigate scale effects be performed for different ranges of wave period and water depth to assess their influence on the phenomenon.

The objectives of this test programme were to investigate the influence of scale effects and their relative magnitude. From the foregoing discussion, it is evident that the results obtained cannot be generalised over a wide range of wave period and their interpretation is strictly limited to the test conditions. It is observed that the experiments are not really representative of typical model-to-prototype relationships. A more detailed study would need to cover scale ratios ranging from 1/10 to 1/100 for different ranges of wave period. For the selected test conditions in the present study, scale effects were less evident in cylindrical lattice structures than in spherical lattice structures.

7.0 Closure

This paper identifies important aspects pertaining to the hydraulic modelling of porous coastal structures. In particular it concentrates on the modelling technique of enlarging the size of the core material in the model than would be indicated by direct application of the linear scale. For this purpose an analytical method is presented and its relative merits and demerits are discussed. The influence of important parameters such as the overall porosity, scale and the flow conditions (Reynolds Number) are illustrated. Results from steady flow tests are presented in order to assess the importance of the resistance coefficients of both model and prototype material. Results from wave transmission and reflection tests are presented to assess the influence of scale effects. A cross comparison is also performed with previous investigations. The outcome of this study is applicable directly in the design and application of hydraulic model investigations of wave action through porous structures.

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	f_L	f_T	f_T/f_L	I_T/I_L
Engelund (1953)	$\alpha_o(1-n)^3/n^2$	$\beta_o(1-n)/n^3$	$\beta_o/\alpha_o n(1-n)^2$	$\dfrac{\beta_o Re}{\alpha_o n(1-n)^2}$
LeMehaute (1957)	$c_2/2n^5$	$c_3/2n^5$	c_3/c_2	$c_3 Re/c_2$

TABLE 1 STEADY FLOW LAMINAR AND TURBULENT COEFFICIENTS

n = 0.607 Diameter	a and b in $I = au + bu^2$		f_L and f_T in $I = f_L \frac{\nu}{gd^2} u + f_T \frac{1}{gd} u^2$	
	a (sec/m)	b (sec/m)^2	f_L	f_T
15 mm	0.612	3.051	1210.9	0.449
20 mm	0.682	1.338	2400.1	0.263
30 mm	0.642	0.751	5083.5	0.221

TABLE 2 STEADY FLOW COEFFICIENTS FOR CYLINDRICAL LATTICE STRUCTURES

	a and b in $I = au + bu^2$		f_L and f_T in $I = f_L \frac{\gamma}{gd^2} u + f_T \frac{1}{gd} u^2$	
	a (sec/m)	b (sec/m)²	f_L	f_T
Spheres D = 19 mm n = 0.350	1.707	14.632	5420.6	2.727
Spheres D = 25 mm n = 0.394	1.454	11.558	7995.7	2.835
Rounded stone D = 34.8 mm n = 0.362	1.120	14.085	11932.2	4.808

TABLE 3 STEADY FLOW COEFFICIENTS FOR SPHERES AND ROUNDED STONES

Properties of porous media				Conditions specified for scale effect tests		
Details of structures used for the investigation		Dimension (Diameter in mm)	Porosity	Structure length (cm)	Water depth (cm)	Wave period (sec)
Cylindrical lattice structure	control model 1:1.5 model 1:2 model	30.0 20.0 15.0	0.607 0.607 0.607	45.0 30.0 22.5	30.00 20.00 15.00	1.50 1.23 1.06
Spherical lattice structure	control model 1:1.34	51.0 38.0	0.476 0.476	40.8 30.4	26.84 20.00	1.16 1.00

TABLE 4 DETAILS OF THE PRESENT STUDY ON THE INFLUENCE OF SCALE EFFECTS ON WAVE TRANSMISSION AND REFLECTION

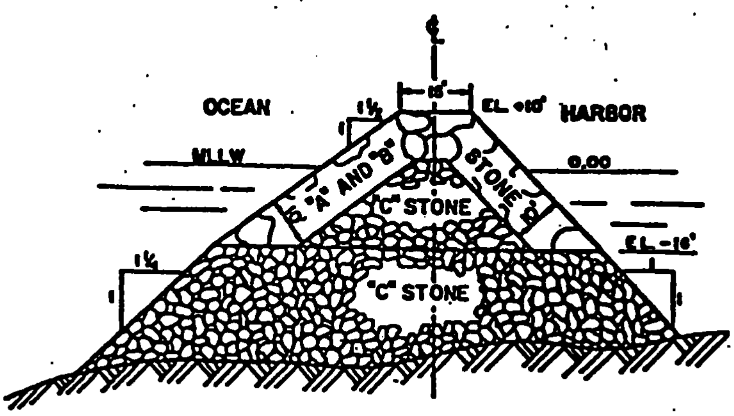

Fig. 1a Monterey breakwater cross section

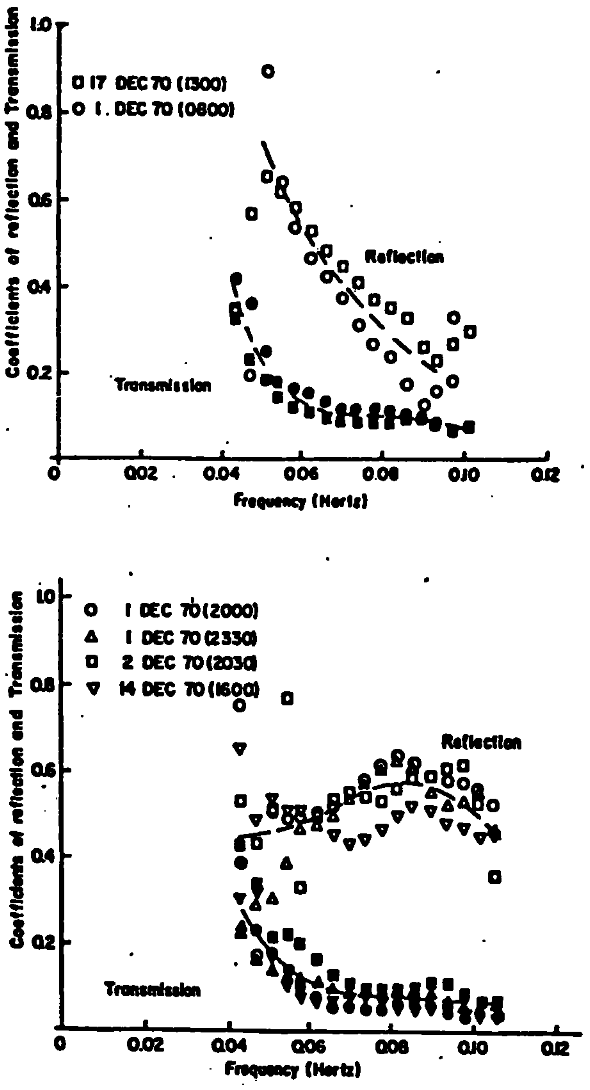

Fig. 1b Reflection and Transmission coefficients vs Frequency

Fig. 1 Field investigations on porous coastal structures

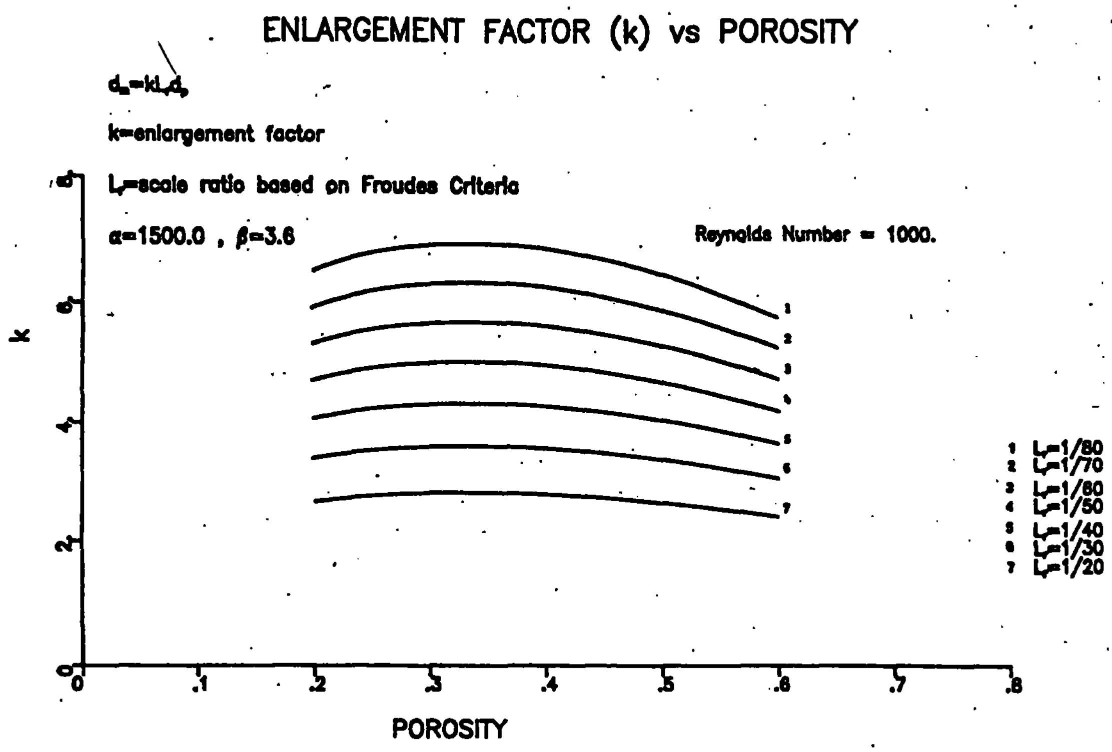

Fig.2 Enlargement factor vs Porosity for different scale ratios

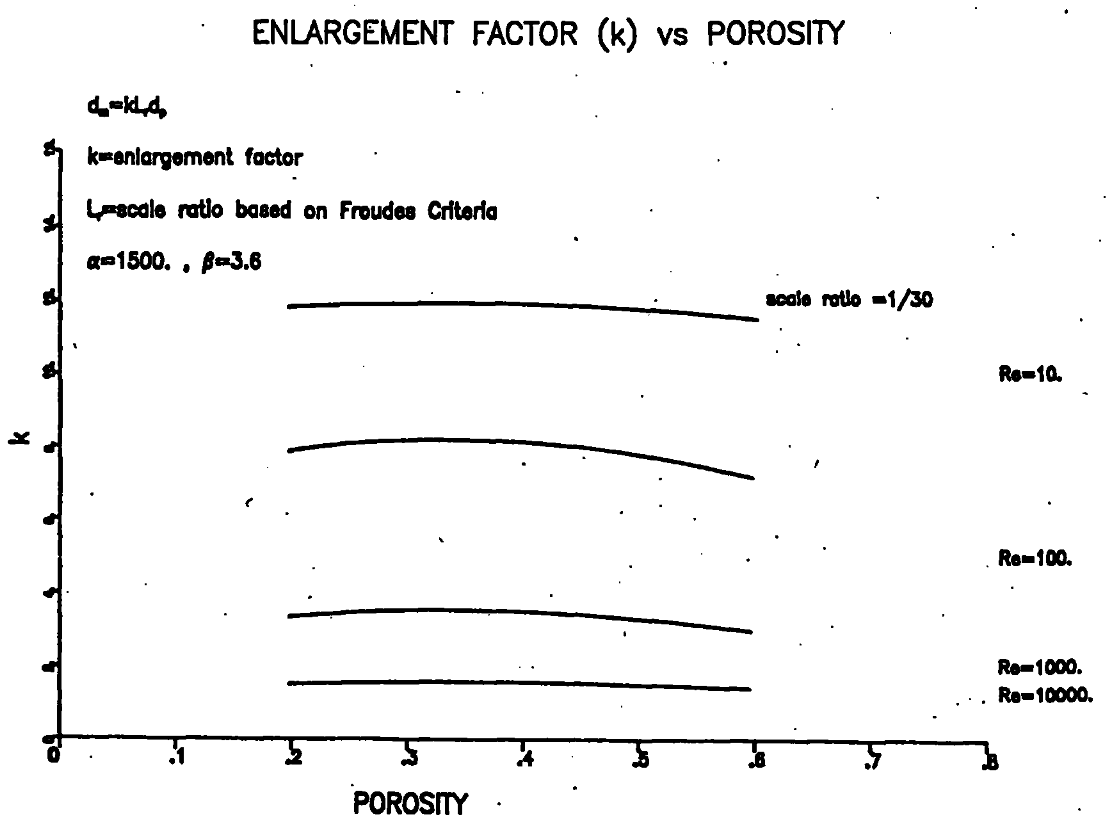

Fig.3 Enlargement factor vs Porosity for varying prototype Reynolds number

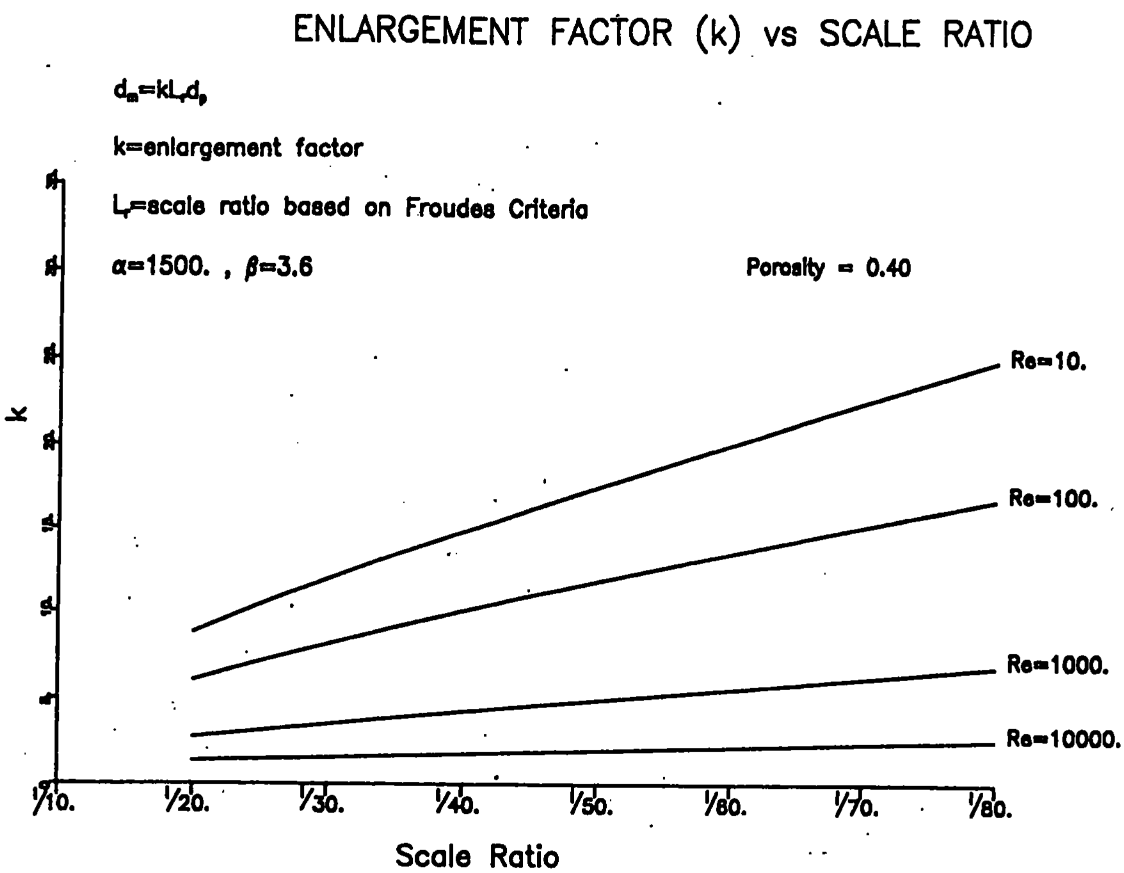

Fig.4 Enlargement factor vs Scale ratio for varying prototype Reynolds number

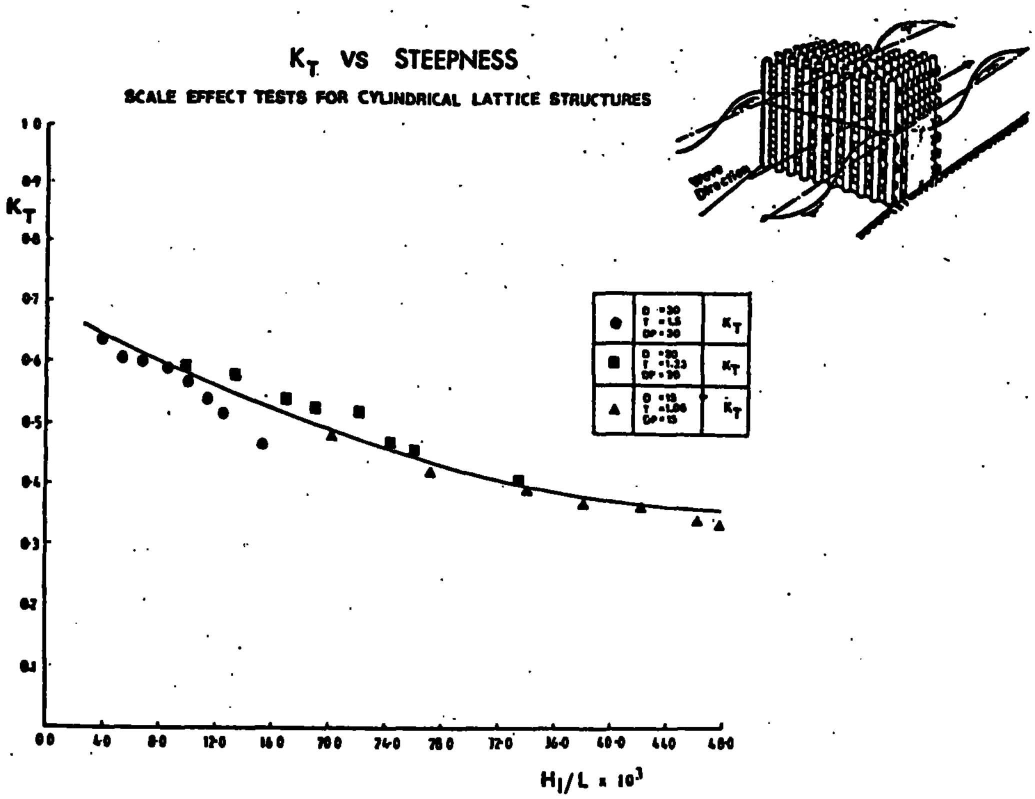

Fig.5a Transmission coefficients vs Steepness for cylindrical lattice structures

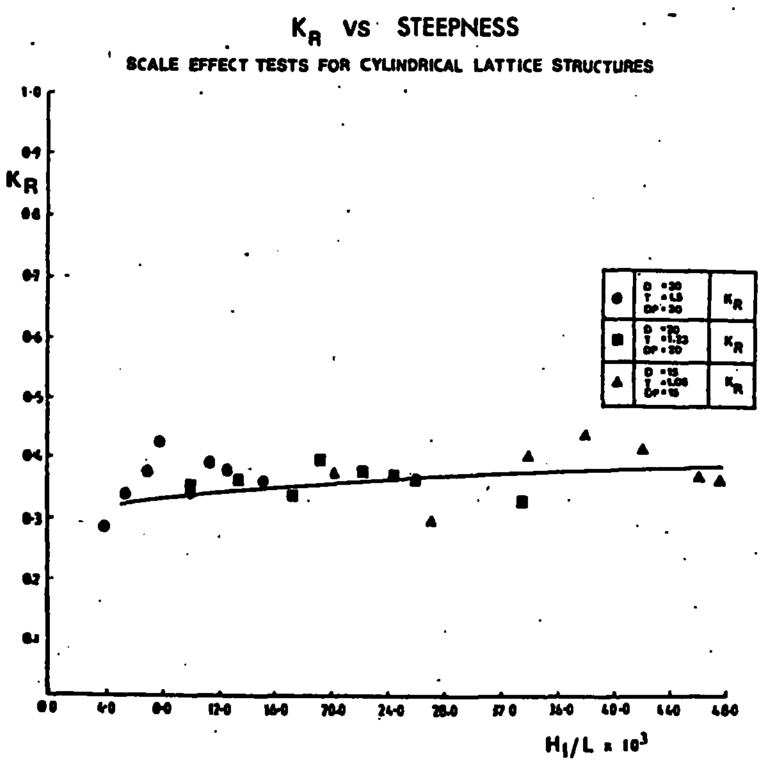

Fig.5b Reflection coefficients vs Steepness for cylindrical lattice structures

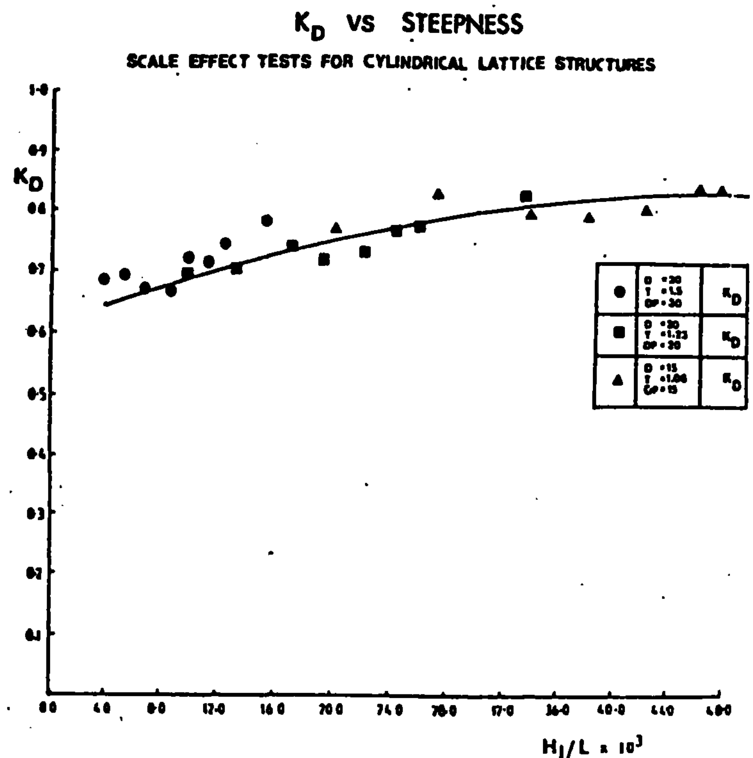

Fig.5c Loss coefficients vs Steepness for cylindrical lattice structures

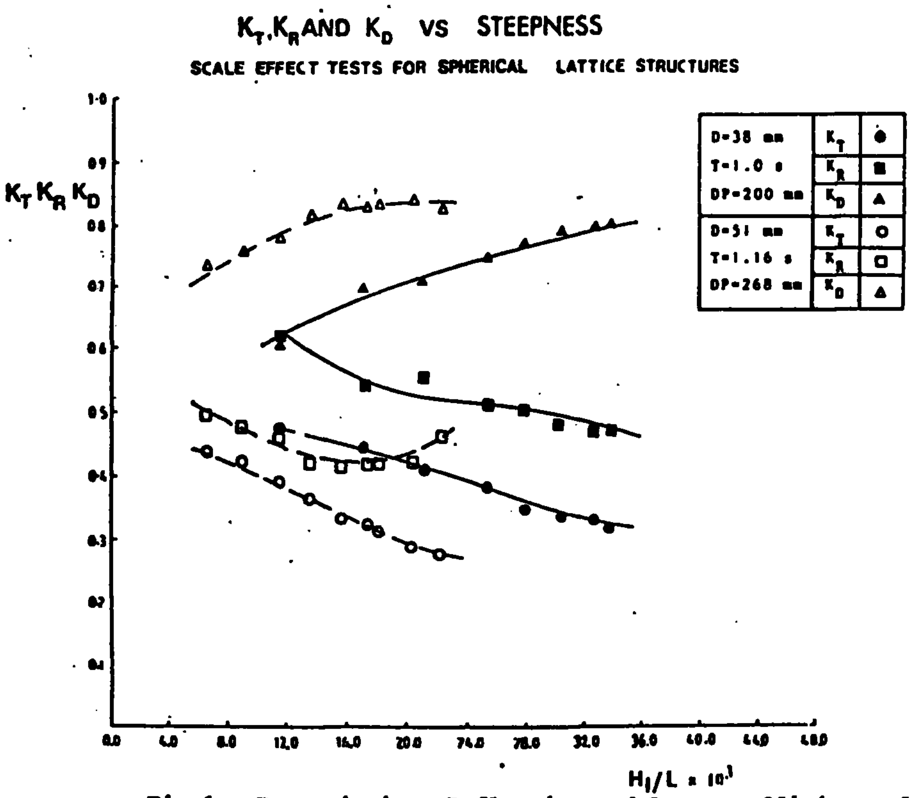

Fig.6 Transmission, Reflection and Loss coefficients for spherical lattice structures