CHAPTER ONE HUNDRED SEVENTY FIVE

Stability of Armour Units in Flow Through a Layer

Alex C. Thompson *
Hans F. Burcharth **

Abstract

As part of a program to study the hydraulics of wave attack on rubble mound breakwaters tests were made on model armour units in a steady flow through a layer laid on a slope. The flow angle has little effect on stability for dolosse or rock layers. The head drop at failure across each type of layer is similar but the dolosse layer is more permeable and fails as a whole. There was no viscous scale effect. These results and earlier tests in oscillating flow suggest a 'reservoir' effect is important in the stability in steep waves.

Introduction

Many types of concrete unit for armouring rubble mound breakwaters have been designed to try and achieve a good stability to weight ratio and low costs of production. The designer of a breakwater often finds it difficult to choose between these different units as no systematic information on their stability exists. The physics behind the differences in stability of slender and bulky units is still poorly understood despite the large number of model tests and investigations of flow in rubble mound structures that have been performed.

Generally for units of the same weight and density, slender ones like dolosse exhibit a better hydraulic stability than bulky ones like cubes. However the different types of armour do not respond in the same way to changes in wave characteristics. Whillock and Price (7) for example, showed that oblique wave attack can dislodge dollose much more easily than waves approaching at right angles and Burcharth (3) has demonstrated that the stability of a dolosse slope decreases as the wave period increases. Both effects are in contrast to the behaviour of slopes made of rocks.

It is thought that the explanation for this is the 'reservoir effect' by which the greater volume of voids in a dolosse pack can absorb a larger fraction of the uprushing wave than a rock slope. This idea emerged from work by the present authors (4) on oscillating flow over the surface of dolosse and rock layers. They found that the dolosse were only slightly more stable than stones of the same weight in this fully submerged flow, a similar result to that of Brebner (2) who tested dolosse and rocks in steady flow. The present work investigated the stability of dolosse and rocks on a slope in flow from underneath at various angles to the layer. The flow is uni-directional and through the

* Lecturer, University of Sheffield, England
** Professor of Marine Civil Engineering, Aalborg University, Denmark

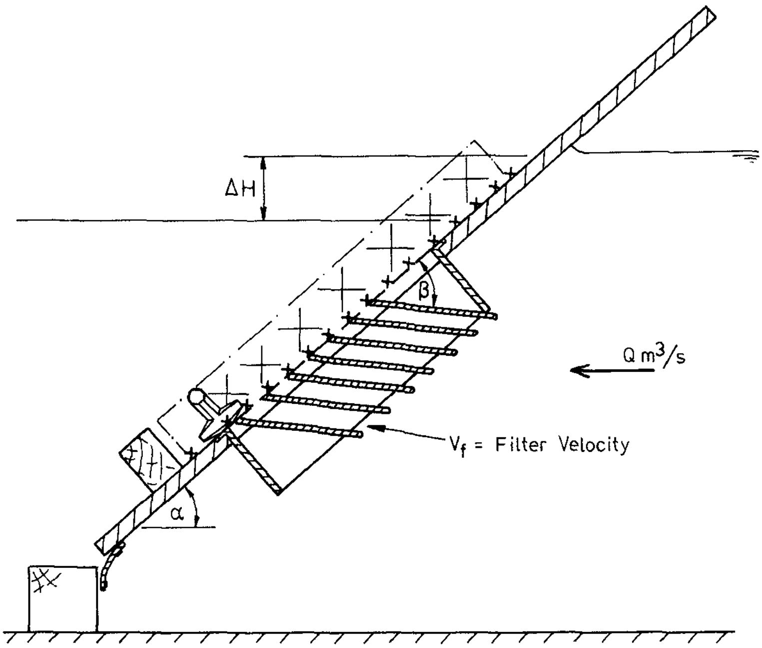

Figure 1 Throughflow Test Rig

layer. The object was to see if the differences in stability of slender and bulky units could be due to a difference in their response to flow through the cover layer, rather than to flow parallel to the surface. It was thought that at some instants of the wave motion on a breakwater the flow emerging through the slope may have a similar effect to the test flow.

A secondary object was to examine a further scale effect which might arise in models of rubble mound breakwaters, if flow through the layers was important as well as flow over the surface. To this end a scale model of the relevant parts of the main rig was made and tested.

Experimental Method

Layers of dolosse and rocks laid on a slope were subjected to flow through the slope, and through the layer. The head drop and flow rate at which the layer failed, as defined below, were found for different slope angles, α and flow angles, β. A sketch of the apparatus is shown in fig. 1.

The test rig consisted of a plywood board thickness 20mm, width 0.9m and height 1.2m which formed the test slope. This was mounted so that its slope could be varied between 15^{o} and 45^{o} in the high head flume at the Hydraulics Research Station, Wallingford. This is a glass sided flume with a wooden floor and cross-section of 0.9 x 0.9m. Rubber seals were arranged round the edge of the board so that flow took place only through a hole of dimensions 0.6m wide by 0.34m deep in the lower half of the board, under the area covered by the armour units. The bottom units rested on a wooden ledge running the width of the board, and all units lay on an expanded metal mesh covering the board and the flow opening. In the flow opening one of three sets of vanes fixed at angles of 20^{o}, 45^{o} and 90^{o} to the slope could be mounted. These were made from aluminium plates of thickness 3mm and length 150mm mounted with a gap of 20mm between each in a rigid frame made from 12mm plastic plates. The flume was supplied with water from a large sump via a pump feeding a constant head tank. The water then flowed through a control valve into the inlet tank of the flume, over a 'V' notch where the discharge was measured, into a settling section through various screens and into the working section of the flume. The slope was mounted halfway along the 10m working length and at the end of the flume an adjustable over-shot tailgate allowed the water level downstream of the test slope to be varied.

The armour units used for the test were plastic dolosse with metal bars embedded in the limbs to give a weight of 130 gms, a height of 70cm and an average density of 2.40 gm/cm^3. The rock was selected from a supply of crushed rock by eye to match a number of individually weighed rocks and to have a reasonably cube-like shape. The average weight of the rocks was then found to be 124 gm and the density 3.0 gm/cm^3.

The number of dolosse used was 297 and the same number of rocks were employed in building a test layer. A single layer of units was used, placed by hand starting from the bottom of the slope but with no overall system of laying other than to get all the units in an area of 0.9m x 0.5m and to fill any obvious holes. This area was chosen so that the flow opening was covered, the full width of the channel occupied by units and because initial trials with the units showed that the number used filled this area naturally. The photographs 1 and 2 show views of the layers as completed.

The procedure for each test was to set the slope at the desired angle using a protractor in the form of an adjustable set square with a spirit level attached to it The layer of units was then laid as described above above and the flume filled using a slow rate of flow to avoid a large head drop across the slope before the flume downstream of the slope filled up. The rate of flow was then increases slightly and the water levels immediately upstream and downstream of the slope measured, while the slope was observed closely for signs of failure. The water levels were measured with point gauges attached to metre rules. The rules were held against the metal rails at the top of the flume, which had been accurately levelled, and read from the top edge of the rails. This system was adopted to follow the fast change in water levels which occurred after increasing the flow, so that the levels at the point of failure could be measured. As soon as holes appeared in

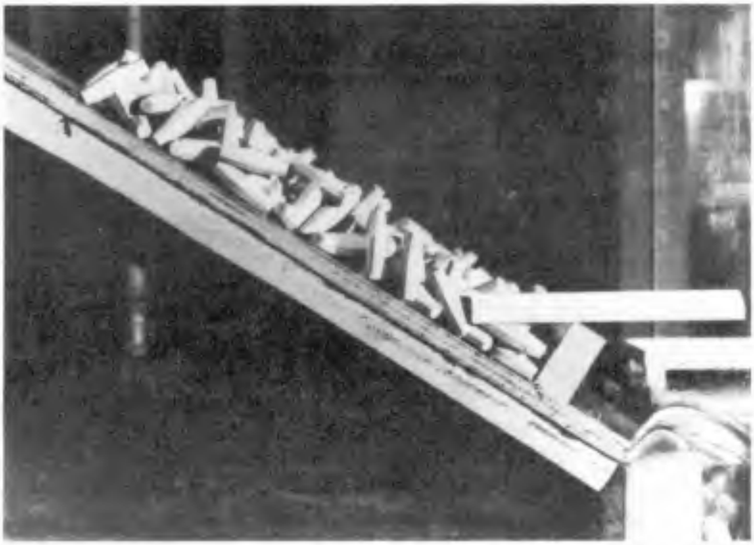

Photo 1 Dolosse layer.

Photo 2 Rock layer.

the layer the water levels would change again. The experiment was performed with two observers so that the water levels could be followed and so that one was always watching the slope. After these levels had been measured the water level upstream of the V notch was read using a pointer gauge mounted on a calibrated screw in a stilling tube. If the slope had not failed the flow rate was increased slightly and further readings taken.

The occurrence of failure was usually quite obvious but with careful control of the flow rate different stages could be observed, and the conditions just prior to failure established. Without close observation and control the failure flow could be exceeded giving complete collapse of the dolosse layer or large holes in the rock layer, as the first change noted. With a layer of dolosse a slight settling down the slope could be observed before failure, followed by the opening of gaps in the layer at a slightly larger flow, this is the failure condition and any further increase in flow would usually result in all the dolosse sliding down and off the slope. Occasionally larger gaps would open before total failure happened. With a layer of rocks the indication of failure was the displacement of individual rocks from their original position to positions lower down the slope, leaving holes in the layer. When 2 or 3 rocks had been moved in this way the flow could be increased without increasing the head drop and further rocks would move leaving more holes, as the flow was raised. The displacement of 2-3 rocks was taken as the failure condition for rock slopes. The rock layers never slid right off the slope as the dolosse layer often did.

Once the failure condition had been determined the flume was emptied, the slope angle changed and the layer rebuilt for another test. Slope angles α of 43.5°, 36.7°, 23.6° and 18.6° were tested, first with dolosse and then with rock. the next set of vanes was then fitted to the test rig and the tests repeated so that results were obtained for vane angles β of 90°, 45° and 20°. The head loss through the apparatus without a layer of armour units in place was found so that the head drop across the layer of units could be estimated.

After the main test had been completed a scale model of the apparatus was built based on the size of small dolosse available. These weighed 14.5 gm and had a height of 3.7cm. A plate to fit over the original flow opening was built, containing an opening scaled down in the ratio $3.7/7.0 = 0.486$. A set of vanes set at $\beta = 90^{\circ}$ was also built to this scale and a step to hold the bottom of the layer. Expanded metal mesh of very nearly the correct scale (0.5) was used for the base of the layer. The flow and head drop at failure was found for the dolosse layer and for a layer of 14.5 gm stones, using this scaled down version of the original test.

A short series of tests which we refer to as 'overflow' tests was performed by blocking the hole in the sloping board and letting water flow over the top. The layers were built on the top half of the board supported by a new step fixed above the original opening. Layers of the large units were tested at several slope angles. In each run the slope of the board was set and the layer was built in the same way as for the throughflow test. The flow rate was gradually increased until the layer failed or the maximum flow rate was reached. The depth of flow above

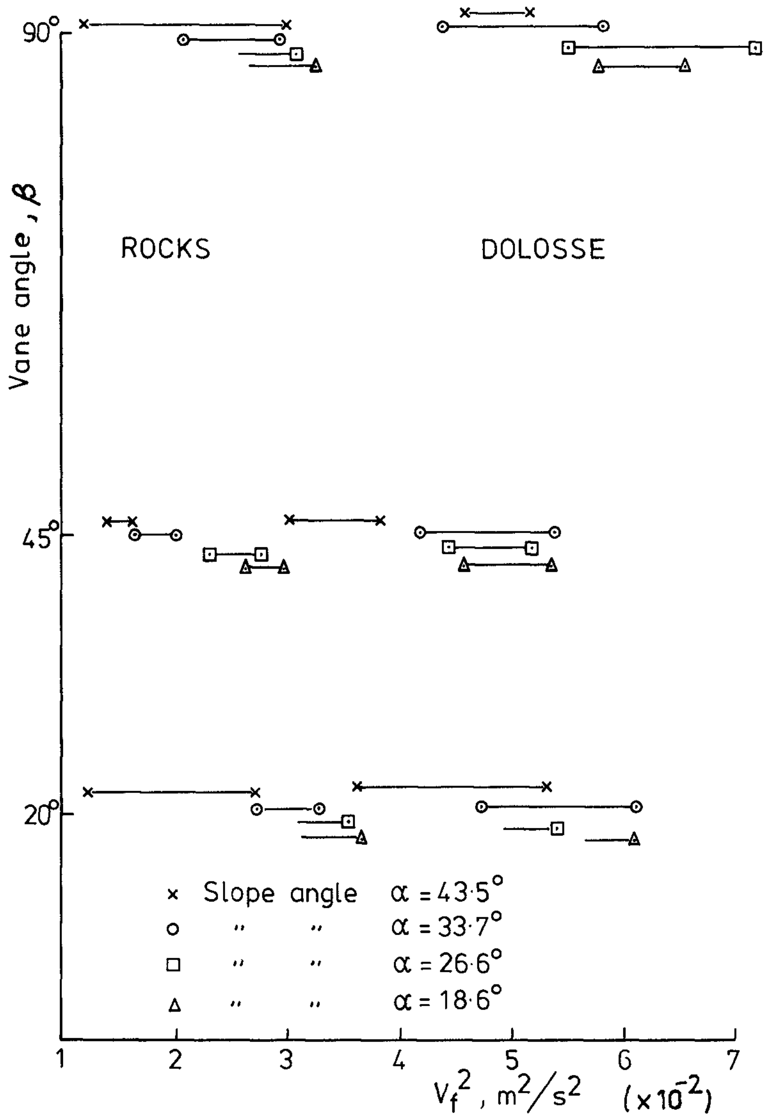

Figure 2 Filter Velocity Squared at Failure

the board and the flow rate were measured at several settings below failure. Depth was measured using a rule looking through the glass side of the flume half way down the slope where water surface is roughly parallel to the bed. This measurement was inevitably approximate until the water surface was well above the surface of the layer and became smooth.

Test Results

The test results were plotted in three graphs shown in figs. 2, 3 and 4. In the first of these the square of the filter velocity, V_f^2, at failure was plotted against vane angle, β. These results for the large units only. The slope angle α was indicated by the different symbols shown in the figure and the failure condition is indicated by a range of values in some cases. V_f was defined as the discharge at failure divided by the area of the opening in the slope. This plot shows that the vane angle had little effect on the stability of either type of layer. The dolosse could withstand a higher filter velocity but this was because the permeability was higher as discussed below. It is interesting that the effect of slope angle, α, is not great, with only $\alpha = 43.5^{o}$ giving obviously lower V_f^2 at failure, in this figure.

The second plot, fig. 3, shows the hydraulic gradient, i, across the layer at failure, versus the slope angle. This is expressed in a non dimensional form as follows. The hydraulic gradient i was calculated from:

$$i = \frac{(\Delta H - VL)}{t} \qquad (1)$$

where ΔH = total measured head loss
VL = Vane loss of same flow rate
t = thickness of layer

The layer thickness, t, is difficult to measure directly but an average value was found from the equation

$$t = \frac{W'N}{A(\rho_s - \rho)g(1 - n)} \qquad (2)$$

where W' = submerged weight of a unit
N = number of units in layer
A = area covered by layer
n = porosity of layer
ρ_s = density of armout unit material
ρ = density of water

A critical hydraulic gradient i_c was calculated for the condition that the pressure force across the layer is equal to the component of the weight of units and water in the layer at right angles to the layer. This gives the expression

$$i_c = - (\frac{\rho_s}{\rho} - 1 (1 - n) \cos \alpha \qquad (3)$$

Equations (1), (2) and (3) were then combined to give the quantity

$$\frac{i}{i_c} = \frac{(\Delta H - VL)\ \rho g A\ (\frac{\rho_s}{\rho} - 1)\ (1 - n)}{W'N\ (\frac{\rho_s}{\rho} - 1)\ (1 - n)\ \cos\alpha}$$

i.e.

$$\frac{i}{i_c} = \frac{\rho g\ (\Delta H - VL)\ A}{W'N\ \cos\alpha} \tag{4}$$

Figure 3 shows i/i_c versus slope angle α. These results are for a vane angle β of 90^o and include the tests on the small units. For the two lowest slope angles α of 18.6^o and 26.6^o the layer fails for i/i_c between 0.85 and 1.0 for rocks and dolosse of both sizes tested. At $\alpha = 33.7^o$ there was slightly more variation in the results with most layers failing at i/i_c between 0.8 and 1.0, and the small dolosse failing at i/i_c between 0.75 and 0.8. At the highest slope $\alpha = 43.5^o$, all layers except the small stones failed at lower values of i/i_c between 0.65 and 0.8. Although rock and dolosse layers failed at similar values of i/i_c the mode of failure was different. In rock layers individual units were removed from the layer leaving holes and were deposited lower down the slope. Dolosse layers failed by the whole layer sliding down the slope. Sometimes a slight settlement or bowing out of the layer can be seen shortly before the complete collapse.

The third graph, fig. 4, gives the head drop across a layer $(\Delta H - VL)$ against the filter velocity squared, V_f^2. Results for the small units are plotted scaled up according to a Froudian law using the length scale $\lambda = 0.486$. The results for large rocks and large dolosse fall on straight lines indicating that the flow is turbulent and viscous scaling effects are absent in this size of model. The results from the small units fall mainly on or below the same lines.

The results of the overflow tests are given in table 1. Both types of layer dolosse and rock failed in a similar way. A few units were removed from the layer soon after the water covered most units. The flow could then be increased without further losses until a level where units began to be removed again, and once 2 or 3 had been removed the layer failed completely, being progressively washed away by the flow. A dolosse layer that was slightly looser in build than normal failed by sliding at a low flow rate, when the water just covered most units. The water which flowed through the layer and out at the toe never removed any units from the outflow region, with either dolosse or rock.

Interpretation of Results

The first fact apparent from the results is that the angle of flow at the bottom of the layer, β, does not affect the failure conditions of dolosse or rock. The higher stability dolosse under attack by steep waves is not due to an effect of the angle of flow through the layer.

The results did show a difference in permeability between dolosse and rock but an equal drop in total head across the layers required to produce failure. The critical head gradient i_c is much lower for

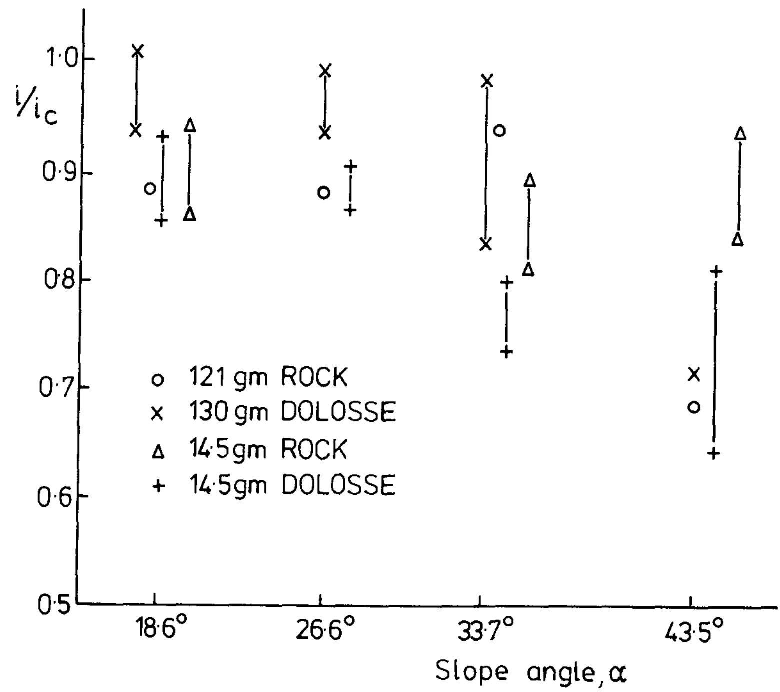

Figure 3 Hydraulic Gradient at Failure.

dolosse than rock but must act over the greater thickness of the dolosse layer. For example calculating i_c from equation (2) we find

For rock $(\frac{\rho_s}{\rho} - 1) = 1.65$, $n = 0.4$, $i_c = 0.99 \cos \alpha$

For dolosse $(\frac{\rho_s}{\rho}) = 1.4$, $n = 0.6$, $i_c = 0.56 \cos \alpha$

It is perhaps suprising that the angle of slope does not influence the head gradient at failure more than the cos α factor, at lower slopes than $\alpha = 43.5^o$. This is particularly so for rock where at cot α term appears in Hudson's Equation. This may be due to the placing of the rock layer by hand, rather than pell-mell dumping. Dolosse layers are often laid at steeper slopes and their structure does seem to make them less sensitive to slope than rock layers. The type of failure in throughflow, blanket as opposed to individual movement, may mean that dolosse layers will be more resistant to a localised critical head gradient. Certainly the gradient required to remove individual dolosse must be greater than that measured in the present experiments.

If it can be shown that the head gradient across the cover layer is near the critical value in a breakwater attacked by waves then these differences may explain the differences in stability between bulky and slender units in waves. Some evidence on this is provided by the results of Bavends et al (1). Calculations and measurements on a large physical model of Sines breakwater repaired section, both give the pressures in the region of maximum outflow. The wave height of 20m is sufficient to cause some damage according to the results of Mol et al (6). The parameter $\xi \approx \tan \alpha/\sqrt{H/L_o}$ can be estimated as between 2.05 and 1.083 if the wave period is in the same range, 22 to 16 secs. as that used by Mol et al. (6). The pressures under the first filter layer and above the cover layer are given. Calculating the thickness of the two armour layers and the filter layers from the details given by Barends the head gradient can be estimated as $i \cong 0.44$. This is well below the critical value. Evidence from the overflow experiment described above is that water rushing down through the cover layer and then out at the toe of the slope is unable to dislodge either dolosse or rocks. Finally in model tests on breakwater sections with a cover layer of dolosse damage occurs with single units being removed. That is, a different type of failure than in the throughflow test takes place. All this suggests that on a conventional design of rubble breakwater the cover layer is not damaged by throughflow before other types of damage start. In an earlier series of tests, Burcharth and Thompson (4) the authors showed that fully submerged layers of dolosse and rock have about the same stability in oscillatory flow parallel to the surface of the layer. It is suggested that the good stability of dolosse in steep waves is due partly to interlocking and partly to a reservoir effect. That is, the large voids in the dolosse layer absorb a significant proportion of the uprushing wave, and this water then runs down within the layer so that it cannot remove units from the layer.

Calculations by Koutitas (5) on a breakwater section of uniform permeability, indicate that hydraulic gradient i, can exceed the critical values found in the present tests. Throughflow might therefore cause damage in a breakwater with unusually permeable underlayers. This point can probably be explored by further calculations.

The measurements of head drop across the layers show no evidence of a scaling effect due to viscosity. The points predicted by scaling up results from the small units using Froude scaling fall close to the results from the large units. The units span the usual range of sizes used in models except in giant flumes. The Reynolds number of the flow through the small rock is $V_f D/\nu = 1.9 - 5.2 \times 10^3$. This is just above the limit of 2×10^3 for viscous effects in porous media suggested by Yalin (8). In the region of high outflows through the cover layer there should therefore be little viscous scale effect in models. A possible scale effect of a different sort is the force exerted in building the models. This will be relatively greater in small models where the units are placed by hand and could be responsible for the high strength of the small rock layer at $\alpha = 43.5^o$ in the present results. A similar effect was noted in the oscillatory flow tests.

Acknowledgement

The model tests described in this paper were carried out at

Table 1 Overflow Results

Q m^3/s	y m	Remarks
		Dolosse α = 33.7°
.0127	.05 approx.	No movement
.0180	.06 "	" "
.0215	.07 "	" " - Layer just covered
.0257	.075 "	" "
.0296	.08 "	3 lost
.0325	.0825 "	No more losses
.0390	.085 "	2 Lost at slightly higher flow
.0458	.09 - .10	Failure
		Dolosse α = 26.6°
.0571	.095 approx	
	.12 "	About 10 lost
.0839	.13 "	Failure
		Dolosse α = 18.4°
.0172		
.0172	.07 approx	Layer nearly submerged
.0335	.09 "	1 lost
.0946	.15 "	No movement, max. flow
		Rock α = 33.7°
.00963	.03 approx	
.0182	.05 "	Layer submerged, 2 rocked
.0223	.055	
.0283	.06	1 lost then failure (RH half)
		Rock α = 26.6°
.0074	.03 approx.	
.0144	.04 "	Most rocks covered
.0177	.05 "	2 lost
.0257	.06	
.0314	.065	2 lost then failure (RH half)

Hydraulics Research Wallingford. The authors express their thanks to the Director and his staff for their kind assistance and permission to use the photographs presented here.

REFERENCES

1. Barends, B.J., Van der Kogel, H., Uijttewaal, F.H. and Hagenaar, J. "West Breakwater Sines - Dynamic - Geotechnical Stability of Breakwaters". Coastal Structures '83, ASDC Conf. Washington 1983.

2. Brebner, A., "Performance of Dolosse Blocks in an Open Channel Situation". Proc. 16th ICCE Hamburg 1978.

3. Burcharth, H.F. 'The Effect of Wave Grouping on On-Shore Structures', Coastal Engineering, Vol.2, 1979.

4. Burcharth, H.F. and Thompson, A.C. "Stability of Armour Units in Oscillatory Flow". Coastal Structures '83, ASCE Conf., Washington 1983.

5. Koutitas, C. 'A Numerical Model for Rubble Mound Breakwater Stability'. Coastal Eng. (in press), 1982.

6. Mol, A., Ligtevingen, H., Groenweld, R.L. and Pita, C.R.A.M. 'West Breakwater Sines - Study of Armour _tability', Coastal Structures '83. ASCE Conf., Washington, 1983.

7. Willcock, A.F. and Price, W.A. 'Armour Blocks as Slope Protection'. Proc. 15th ICCE, Honolulu, 1976.

8. Yalin, M.S. 'Theory of Hydraulic Models'. Macmillan.

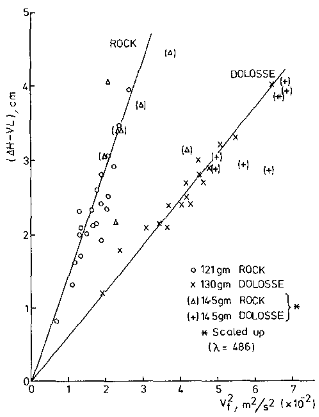

Figure 4 Head Drop Across Layers versus V_f^2.