CHAPTER 199

OSCILLATORY FLOW INVESTIGATIONS IN POROUS MEDIA

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INTRODUCTION

A series of experiments has been conducted at the Coastal Engineering Laboratory of Queen's University in order to investigate the characteristics of accelerating flow through porous media. The nature of the steady flow law in coarse granular material has been reasonably well defined from a large number of previous studies. Variations on this steady flow law have been applied to the case of oscillatory flow, in numerical models of forces in breakwaters for example, with the explicit assumption that the steady law is applicable to the unsteady case. Few experimental investigations have been conducted to verify this assumption. Hence the present study was designed specifically to test the applicability of the steady flow law (Forchheimer's equation) to oscillatory flow.

EXPERIMENTAL PROCEDURE

Parameters relevant to this study include the grain size and porosity of the test sample (and shape), bulk or macroscopic velocity of flow through the sample and the pressure loss associated with the flow. A test programme was established to measure these quantities for both steady unidirectional and oscillatory flows.

Tests were conducted in an oscillating water tunnel (Figs 1,2). A test section of porous material was installed in the centre of the measuring section. Both unidirectional and oscillatory flows could be generated within the tunnel. The

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test section had a height of 85cm, width of 45cm and the length varied according to the test material.

Tests were made on three different types of materials: 75 mm diameter plastic spheres, 42 mm spheres (golf balls) and one sample of rock (M_{50}=1.43 kg; D_{50}=100mm). Each type of sphere was tested at high and low porosities (cubic and rhombohedral packings, respectively). The effect of the dimples on the golf balls was not considered in the analysis. The use of these different sizes of spheres allowed an illustration of the wall effect of the tunnel on the measurements. In situ porosity measurements were made on all samples.

Head losses across the test section were measured with four pressure transducers (Data Instruments AB/99; 0 to 6 psi), installed in the centre of the sample; two near the upstream end and two near the downstream end. Samples were measured at 10 Hz for all tests; this provided adequate resolution of the pressure traces while minimizing the storage space required. Sampling was controlled by a Zenith 386 microcomputer.

The transducers were calibrated over their full range in a 4.5 metre high water column periodically during the test programme but it was found that no significant changes occurred to their calibration curves. For tests on the spheres, the transducers were mounted inside of the spheres for placement in the test section (Figure 3). This allowed for measurement without interference with the flow. For the test on the rock sample the transducers were set in the voids and rocks were placed around them so as to hold them securely and prevent movement. During the first test series, the 75mm spheres in rhombohedral packing, two transducers were installed side by side,but facing opposite directions at both the upstream and downstream ends of the section. This was to compare measurements of the transducers themselves and to test if orientation altered the readings. Orientation made no difference and both sets of transducers provided identical readings. Subsequent tests were made with two sets of transducers located at two elevations within the section to investigate any differences due to possible flow variations. The majority of tests showed no difference in these readings. Where differences did occur, the readings were averaged; no attempt was made to include effects of non-uniformities in flow or pressure readings.

Velocity measurements were made using a laser doppler anemometer (LDA). This consisted of a DISA 15 mW helium-neon laser, photomultiplier and a frequency tracker. Only the amplifier component of the tracker was used; since no frequency shifting was employed the tracker was not adequate to measure small and reversing flows generated for the experiments. Instead, the photomultiplier signal was sampled directly by a VAXstation 3200 mini computer, via an analogue to digital converter. The photomultiplier outputs a voltage signal, the frequency of which is directly proportional to the velocity of flow. After this signal was acquired (and time stamped), its peak (Doppler) frequency was determined by power spectrum analysis software. Velocities were computed by the relation

$$V = \frac{\lambda}{2\, Sin\frac{\theta}{2}} \times f_D$$

where V = velocity of flow
λ = wavelength of laser light = 632.8 nm
θ = beam intersection angle
f_D = Doppler (signal) frequency.

For each flow condition tested, velocities were measured at several locations across the tunnel section in order to determine the average velocity. The velocity distribution was not uniform, varying typically +/- 10% from the mean from top to bottom and inside to outside walls of the tunnel. Measurements were taken at only one position along the length of the tunnel, that being approximately 2.1 metres upstream of the upstream end of the test section. This was due to space restrictions for location of the laser equipment. As it was only the "bulk" or average velocity that was required, this was considered adequate since the flow rate at any given instant in time must be constant along the length of the tunnel. No effects of the non-uniformity of the velocity profile were considered and only (spatial) average velocities and hydraulic gradients were compared.

A concern of velocity values derived from bulk discharge measurements is that higher discharge rates occur near the walls of the permeameter. This causes the "bulk" velocity value to be higher than that actually flowing through the centre of the section. Direct measurement of velocities near the centre of the tunnel should minimize this error. Ideally the velocity measurements should be made adjacent to the test section but it was found that large fluctuations occur in that area due to rapid expansions and contractions from the pore exits and entrances. Without the use of a frequency shifter and a two component LDA it was not possible to obtain reasonable measurements in that location.

Steady flows in the tunnel were generated with a constant speed pump. The flow rate was varied by means of two valves which controlled the amount of water directed into the measuring portion of the tunnel. Water prevented from entering the test section was recirculated into a stilling basin behind the tunnel. Flow rates tested in these experiments ranged from approximately 1.5 cm/sec to 30 cm/sec.

Oscillatory flows were generated by means of a piston driven by a variable speed motor. The stroke length of the piston was also variable. Tests were conducted with stroke lengths of 2.5 cm, 5.0 cm and 10.0 cm for each sample, and periods ranging from 3 seconds to 12 seconds. These values represented the widest ranges that could be tested without damaging the test sections, although the piston is capable of operating over greater ranges.

The porosity of each sample tested was measured by sealing off the test section from the rest of the tunnel and adding measured amounts of water. The volume of water added indicated the volume of voids in the section. The section was sealed using metal plates fitted with a rubber gasket around the edges, which could then be expanded outward by tightening a series of screws, thereby providing a tight seal around the edges of the tunnel. However, initial measurements revealed significant leakage from the lower corners of the plates as well as through the false floor inside the tunnel (although no water leaked out of the tunnel itself). Further attempts to seal these areas were only partially successful at preventing leakage as the head of water in the section increased. To further reduce leakage secondary partial barriers were installed in the tunnel, adjacent to the metal plates and the space between was filled with water to the same elevation as that within the section. This was found to adequately minimize any leakage.

Water was added to the section by buckets, each bucket containing a known volume, and the water level in the section was measured after each bucket was added. This provided a means to determine if any leakage had occurred (fig 4). For the sections with spheres in rhombohedral packing, no half spheres were used around the edges so the porosity was much higher in that region. In order to calculate the porosity of the section proper, the volume of these extra voids was calculated and subtracted from the volume of water added. Porosity values for the five test sections are listed in the table below.

The values for the spheres differ slightly from the theoretical values which can be calculated precisely. These differences arise from the fact that the packing arrangements were not perfect, since the spheres did not fit exactly into the tunnel section; there were always some small gaps here and there that caused the porosity to be somewhat higher than that for perfect packing.

No attempt was made to make highly accurate measurement of the porosity in this study. Previous work has shown that permeability is highly sensitive to porosity while accurate measurements of porosity are very difficult to make owing to factors such as surface adsorption and air entrapment in the voids. This has been discussed by Dudgeon (1968). On the other hand, the goal of such research is to provide a method of predicting the hydraulic performance of coarse granular structures where porosities can not be accurately estimated. Porosities were measured in this study only to provide some comparison to other work, rather than to define the exact form of their relationship to the hydraulic conductivity of the sample.

RESULTS

The Forchheimer equation can be linearized if written as

$$\frac{S}{V} = a + bV$$

where S = hydraulic gradient
V = macro. velocity
a,b = coefficients

The coefficients a and b can be found by regression analysis. Steady flow data for each test is plotted on figure 5 and the associated a and b values are:

	a (sec/m)	b $(sec/m)^2$	porosity
75mm spheres			
Rhombohedral:	0.32	12.0	0.32
Cubic:	0.06	2.60	0.52
44mm spheres			
Rhombohedral:	0.38	26.1	0.30
Cubic:	0.06	5.92	0.52
Rock:	0.06	3.25	0.49

It is evident that geometrically similar packing arrangements display similar values of the intercept a, indicating similar permeability coefficients as defined by Ward (1964) but the slope b is steeper by a factor of two for the smaller 42mm spheres. The length of the test section was 15 diameters for both the large and small spheres, hence the amount of surface area of each sample was of similar magnitude (within 10%). Evidently, using material that is large compared to the tunnel dimension will lead to underestimation of the energy losses. The 42mm spheres correspond to the general rule of maximum grain size to container dimension of 1/10 as proposed by Rose and Rizk (1949). The data for the rock sample falls close to the cubic arrangement of the 75mm spheres, ie. offering the least resistance.

Results from the oscillatory tests are presented in phase averaged form. Typical phase averaged curves for velocity and hydraulic gradient are shown in figure 6. When this data is plotted in the form of figure 5 above, it becomes apparent that the points do not all follow the steady flow curves (figure 7). Also, the traces for increasing velocity are slightly different than those for decreasing velocity and the differences increase as acceleration increases. There also seems to be a general trend that the magnitude of these differences increases as the period decreases, which supports the findings of den Adel (1987), who concluded that inertial effects are most dominant at smaller periods, especially at periods less than 1 second.

Figure 8 shows values of S/V vs. V for two periods (5 and 10 seconds) for the 42mm spheres in cubic packing, along with the steady flow regression line. The steady flow line passes through the lower curve for both data sets. As is the trend with all results, the upper ends of the oscillatory curves follow the steady flow regression lines. At smaller velocities, however, significant deviations occur as the accelerations increase. These deviations are larger for smaller periods with the associated higher mean velocities, ie. with higher magnitudes of acceleration. Den Adel (1987, 1990 pers. comm.) has shown that such deviations can arise from a phase shift between the velocity and hydraulic gradient. The occurrence of an added mass effect may also cause part of this deviation, as proposed by Hannoura and McCorquodale (1978) and Abdel-Gawad and McCorqodale (1985).

Similar effects are evident in figure 9, which shows data for various piston stroke lengths. The period of oscillation was constant at 8 seconds and stroke lengths of 25, 50 and 100mm were tested. Shorter stroke lengths produce smaller flow velocities and therefore smaller accelerations.

Results presented herein are preliminary in nature and more detailed data analysis is in progress. Specifically, the effect of phase shifts between velocity and hydraulic gradient and the presence of added mass effects will be given further consideration. At the present time, the data suggests that the steady coefficients in the Forchheimer equation describe oscillatory conditions reasonably well where the velocities are maximum and accelerations minimum. at higher accelerations, differences between steady and oscillatory curves can be significant.

REFERENCES

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Ward, J.C. (1964): "Turbulent Flow in Porous Media", J. Hydraulics Div., ASCE, Vol. 90, No. HY5, pp. 1-12.

Rose, H.E. and Rizk, A., (1949): "Further Researches in Fluid Flow through Beds of Granular Material", Proc. I, Mech. Eng. Vol. 160, pp. 493-511.

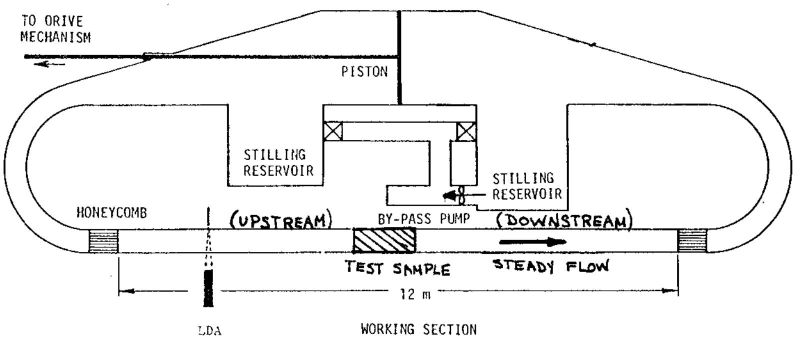

Figure 1

Figure 2

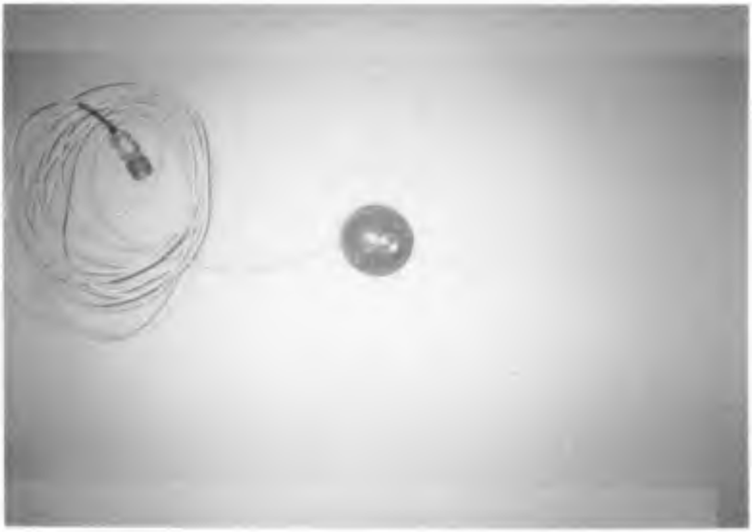

Figure 3

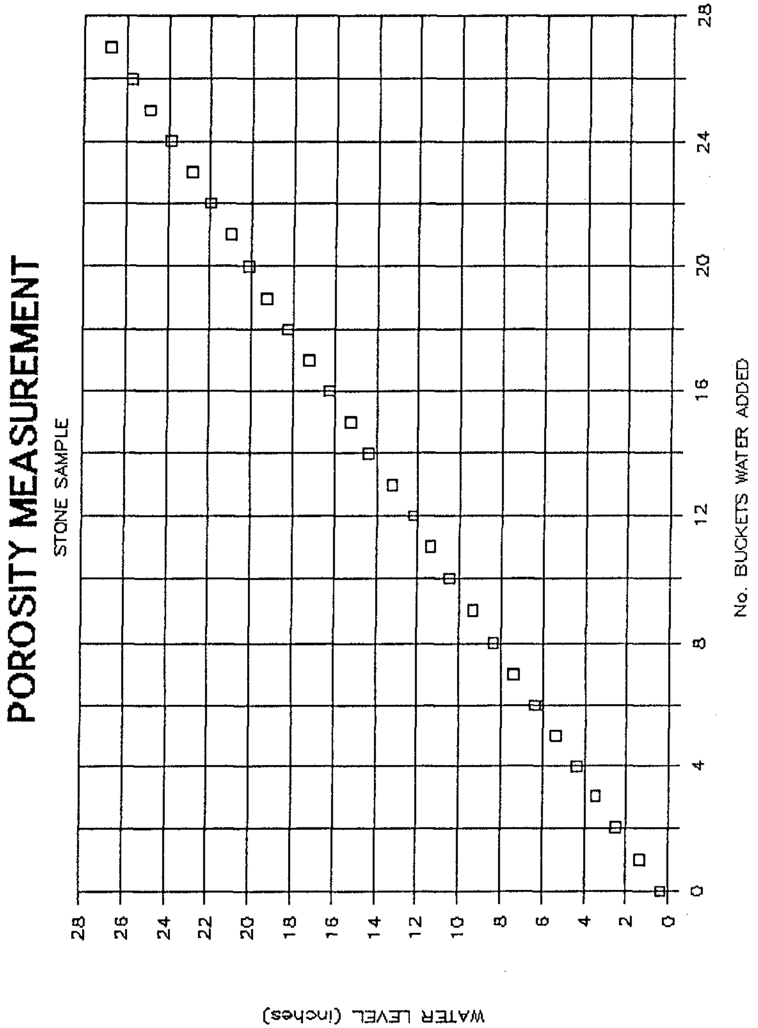
POROSITY MEASUREMENT
STONE SAMPLE
WATER LEVEL (inches)
No. BUCKETS WATER ADDED
0
4
8
12
16
20
24
28
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28

Figure 4

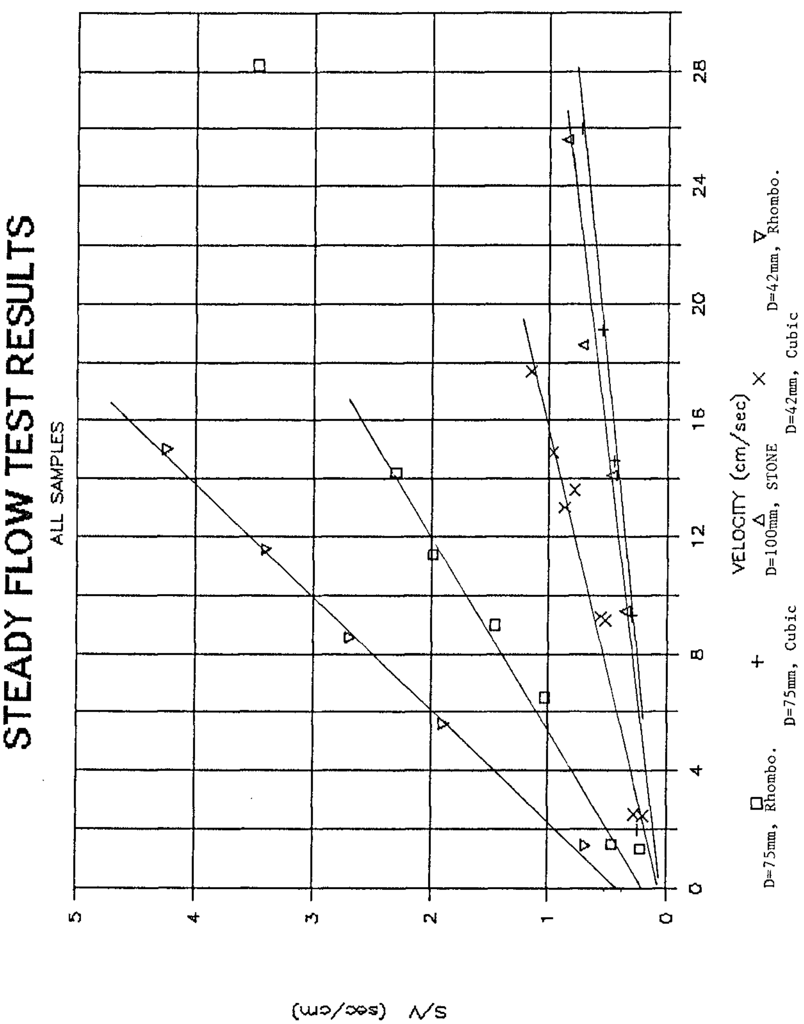
STEADY FLOW TEST RESULTS
ALL SAMPLES
S/V (sec/cm)
0
1
2
3
4
5
VELOCITY (cm/sec)
0
4
8
12
16
20
24
28
D=75mm, Rhombo.
D=75mm, Cubic
D=100mm, STONE
D=42mm, Cubic
D=42mm, Rhombo.

Figure 5

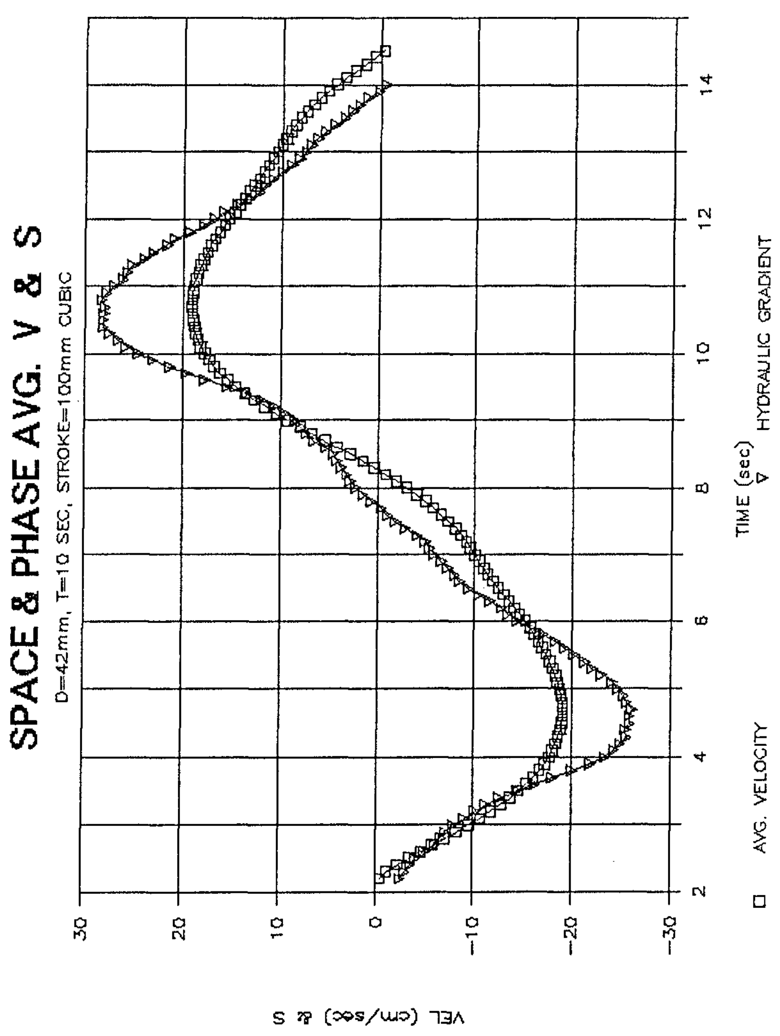
SPACE & PHASE AVG. V & S
D=42mm, T=10 SEC, STROKE=100mm CUBIC
VEL (cm/sec) & S
30
20
10
0
−10
−20
−30
2
4
6
8
10
12
14
TIME (sec)
AVG. VELOCITY
HYDRAULIC GRADIENT

Figure 6

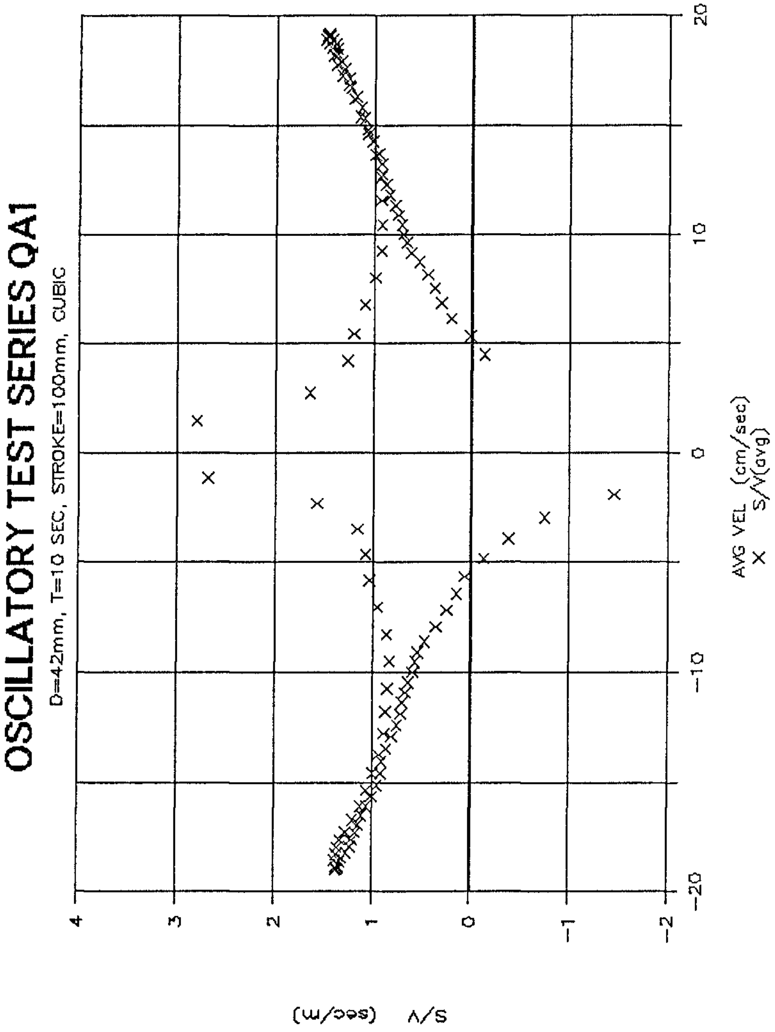
OSCILLATORY TEST SERIES QA1
D=42mm, T=10 SEC, STROKE=100mm, CUBIC
S/V (sec/m)
AVG VEL (cm/sec)
× S/V(avg)
4
3
2
1
0
−1
−2
−20
−10
0
10
20

Figure 7

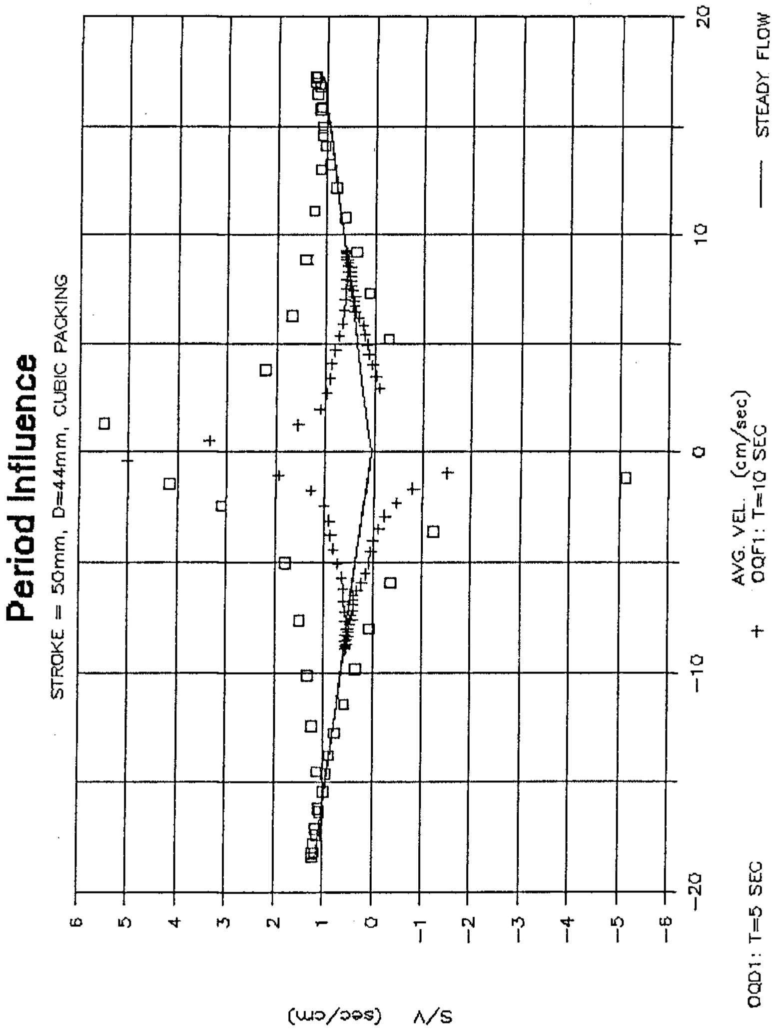
Period Influence
STROKE = 50mm, D=44mm, CUBIC PACKING
S/V (sec/cm)
6
5
4
3
2
1
0
−1
−2
−3
−4
−5
−6
−20
−10
0
10
20
AVG. VEL. (cm/sec)
OQD1: T=5 SEC
+ OQF1: T=10 SEC
— STEADY FLOW

Figure 8

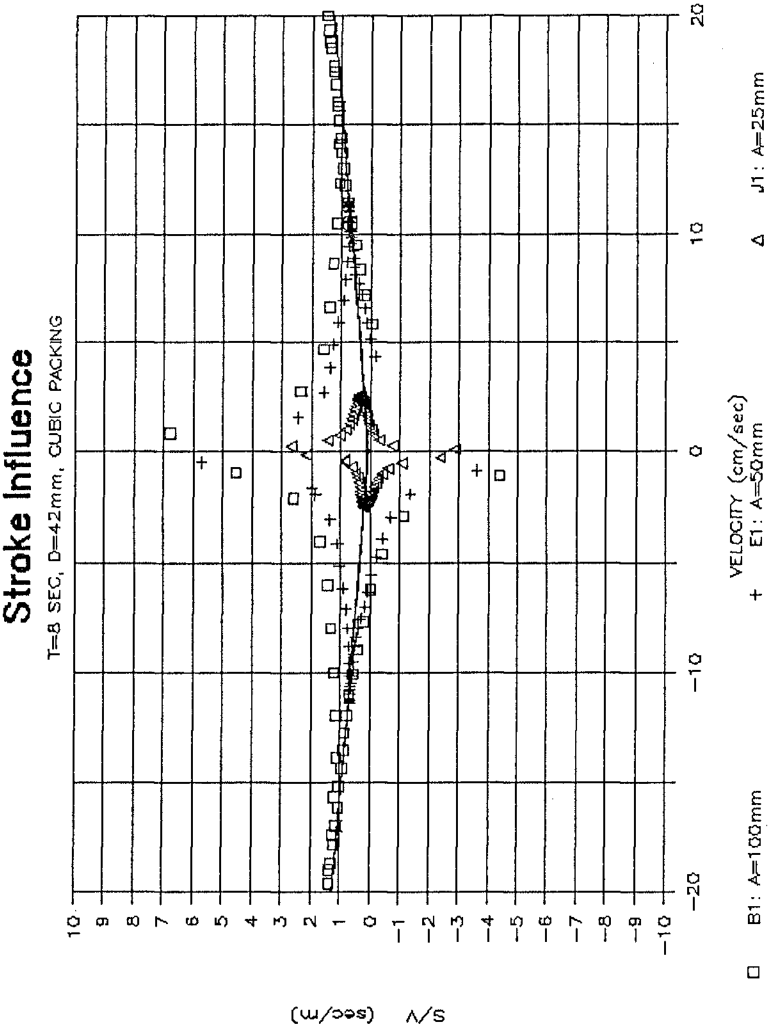
Stroke Influence
T=8 SEC, D=42mm, CUBIC PACKING
S/V (sec/m)
VELOCITY (cm/sec)
□ B1: A=100mm
+ E1: A=50mm
Δ J1: A=25mm

Figure 9