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SCALE EFFECT OF STORM SEWAGE OVERFLOW STRUCTURE

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ABSTRACT

This paper describes an investigation into the scale effect of model sizes on the particle retention efficiency of the stilling pond type storm sewage overflows. The scaling criteria for model-prototype similarity were examined. Data from previous studies on scale effect were reviewed and analysed and their shortcomings discussed. A qualitative comparison of the present model results with the prototype data obtained by Saul (1977) were presented and confirmed the findings that an increase in model size resulted in a decrease in the efficiency of a chamber.

ABSTRAK

Kertas kerja ini menghuraikan suatu penyiasatan kesan skala saiz-saiz model ke atas kecekapan penahanan zarah oleh struktur limpahan kumbahan ribut, jenis `stilling-pond'. Kriteria untuk mencapai keserupaan di antara model dan contoh sulung telah dikaji. Data daripada penyelidikan kebelakangan ke atas kesan skala telah diperiksa dan dianalisis serta kelemahan kerja-kerja tersebut telah dibincangkan. Satu perbandingan kualitatif di antara keputusan daripada kajian model ini dan data contoh sulung yang diperolehi dari Saul (1977) telah dikemukakan dan mengesahkan bahawa tambahan saiz model menyebabkan kekurangan dalam kecekapan untuk sesuatu limpahan.

INTRODUCTION

In most old cities, especially the larger cities, the sewers were constructed many years ago and consisted mainly of combined systems in which one sewer accepts both foul sewage and surface water. During storms, the dry weather flow (DWF) in the sewer will be heavily diluted with a large quantity of incoming storm run-off. This combined wastewater or storm sewage becomes a burden to the treatment plant and excessive load has to be by- passed or untreated, to a river, an estuary or the sea. As efforts to achieve high water quality become more intensive, pollution problem of this type to our watercourses has become unacceptable.

The combined system and to a lesser extent the partially separate system, frequently make use of storm overflow structure to restrict the amount of sewage to be conveyed to treatment as a result of storm to a value which can be dealt with by the purification plant.

Ideally, the storm overflow would start to spill when the flow to treatment reached a predetermined maximum value, any excess then being spilled with little foul content, almost all polluting material being passed to treatment. In practise, however, it is impossible to achieve such performance and the degree of control of both the discharge and the pollution load of the spilled sewage are the main criteria upon which potential overflow structure are assessed.

To this end, numerous studies have been carried out to examine and develope the optimum design dimensions of overflow structure using hydraulic scale models (Sharpe and Kirkbride,1959; I.C.E.1967; Burrows and Ali,1982). Considerable work on the quantitative comparison of the performance between different types of overflow models have also been conducted. (Halliwell and Saul, 1980; Burrows and Ali, 1982).

The common practice for most of these work is to build the model as large as possible in the laboratory. This is plausible as tests conducted on a bigger model would give a better picture of the actual behaviour in the prototype situation than a smaller model. In the latter case, scale effect due to model size may arise and its effect has to be examined before the model results could be interpreted with confidence to predict the prototype situation.

In an earlier study, Ali, Burrows and Lim (1982) presented some results on scale effect using four geometrically similar models. The efficiency results showed that an increase in the model size resulted in a decrease in efficiency. This conclusion contradicted the findings of Frederick (1967). He reported that the smaller model gave lower efficiency results than the larger model.

In this paper, an attempt was made to clarify this confusion. Further tests have been conducted and some of these results were used to compare with the prototype results obtained by Saul (1977). The efficiency results from past studies were also analysed and their shortcomings discussed.

SCALING CRITERIA AND DIMENSIONAL ANALYSIS

The approach to assess the performance of a storm overflow model by many investigators (Sharpe and Kirkbride,1959; I.C.E.1967) is first to establish steady flow conditions, inject a batch of synthetic particles and record the number of losses during a test run of a particular duration. This method provides a convenient and nondimensional measure of the efficiency η of the chamber, which is defined as the proportion of particles not discharged through the overflow pipe.

The flow of water in a storm overflow, such as the stilling pond type shown in Fig (1) is a gravity phenomenon and thus Froudian scaling law should be adopted. If m refers to the model and p refers to the prototype, geometric similarity requires that

$$D_p/D_m = \alpha \tag{1}$$

where D is the diameter of the inlet pipe and α is the scale ratio. All linear dimensions can be scaled quite easily according to Eq. (1)

For kinematic similarity, the flow pattern at a particular point in the model must be similar and correspond to that occurring in the prototype situation. If only steady-flow conditions are considered, then the dynamic flow similarity, based on the Froude number may be fulfilled without much difficulty,i.e,

$$(U^2/gD)_p = (U^2/gD)_m \tag{2a}$$

or

$$U_p/U_m = \alpha^{1/2} \tag{2b}$$

In Eq 2(a), g is the acceleration due to gravity and U is the mean inlet pipe velocity. With Eq 2(b) as the scaling criterion for flow, it is immediately clear that the viscous forces and the surface tension forces will be incorrectly represented. The effect of these two forces will be insignificant if the flow regime in the pipe is mainly turbulent and the Reynolds number UD/υ where ν is the kinematic viscosity, exceeds 2000.

When representative particulate of the storm sewage is added to the flow, the problem becomes a two-phase flow situation in which the flow conditions together with the characteristics of the particulate need to be considered. If spherical particles are introduced, then the particles may be defined by its diameter d and terminal velocity W.

It has been shown (Ali, Burrows and Lim,1982) that the dimensionless particle parameter $C_D^{1/2}W/U$, first used by Frederick and Markland (1967) and based on the ratio of buoyancy to inertia forces experienced by the particle as it enters the chamber, can be used in unifying the efficiency results for a wide range of flows and particle diameters, where C_D is the drag coefficent of the particle. A typical set of this scheme of plotting is as shown in Fig. 4.

The distribution of the particles as it enters the overflow chamber can also have a marked influence on its subsequent distribution. This distribution may be defined by the characteristics of the particle and the lateral diffusion coefficients, E for the flow in the pipe. According to Saul (1977) as long as the Reynolds number in the model is high, then E will be representative of a prototype situation and its exact value is not important.

In an actual overflow structure the flow will be unsteady during the passage of a storm. Thus, if full simulation is desired, the storm flow hydrograph has to be scaled accordingly in the model. Some success in this area has been obtained by Saul and Delo (1982). In the present work, it was decided that, for the comparative testing programme envisaged, a definite measuring period would be applied to all test runs to determine the particle retention efficiency for a particular model size. The time scaling factor may be expressed as

$$(gT^2/L)_p = (gT^2/L)_m \tag{3a}$$

or

$$T_p/T_m = \alpha^{1/2} \tag{3b}$$

Summarising, therefore we can expect the efficiency to be a function of the various dimensionless parameters listed as follows:

$$\eta = f(q/Q, d/D, H/D, \rho UD/\mu, U^2/gD, \rho U^2D/\sigma, C_D{}^{1/2}W/U, gT^2/L)$$

$$(1) \quad (2) \quad (3) \quad (4) \quad (5) \quad (6) \quad (7) \quad (8)$$

..........(4)

where Q is the quantity of water entering the chamber and q is the quantity leaving to treatment, ρ is density, υ is viscosity and σ is the surface tension. H is the water level in the chamber, L is the length of chember and all other variables have been defined previously. In Eq.(4),terms (4), (5) and (6) are forms of Reynolds, Froude and Weber numbers respectively.

PREVIOUS STUDIES

A detailed literature survey showed that there is little work being done on the effect of model sizes on the performance of storm water overflows (Lim 1985).

Sharpe and Kirkbride (1959) performed some tests on two geometrically similar models of the stilling pond with an end-weir type overflows. The inlet diameters, D of the two models were 0.152 m and

0.076 m respectively. The inflow rates were scaled according to Eq.(2b). From their paper it was not clear whether they considered a similar variation of the surcharge ratio, H/D between the two models. No mention was made regarding the size of the particles used. It does appear that the particle size was not scaled correctly. The efficiency results from these two tests were presented in the form of η versus the Boussinesq number, $U^2/(gD/2)$. They found that there exists a critical inlet velocity, U for the two models above which it was difficult to create a favourable flow conditions for the stilling pond chamber to perform satisfactorily. This corresponds to a Boussinesq number of 0.867 or an equivalent Froude number, U^2/gD equals to 0.613.

Fig.2 shows Sharpe and Kirkbride's results re-plotted in the form of η versus U^2/gD. Two smooth curves are drawn through the data points. This figure indicates the efficiency decreases slightly with the increase in model size. It should be pointed out that the term d/D (Eq.4) was not scaled correctly.

Frederick and Markland (1967) also examined scale effects in three geometrically similar models of the stilling pond type with a siphon overflow. They concluded that the efficiency results increased slightly as the model size was increased. Close examination of their results revealed that the terms gT^2/L, d/D and U^2/gD in Eq.(4) were not scaled correctly for each model size. For all three models the measuring period was 2 minutes and flow Froude numbers were not kept the same in all the models, as can be seen in Fig.3. The largest model (D=8 in.) used a comparatively smaller range of Froude numbers ($Fr < 0.363$) than the medium size model (D=4in., $Fr < 1.466$) or the smallest model (D = 1 in., $Fr < 1.441$).

Fig.3 also shows that d/D varies considerably for the three models. For the largest model, d/D is 0.055 whereas it is 0.11 and 0.22 for the medium and the smallest models respectively.Studies by Halliwell and Saul (1980) and Ali, Burrows and Lim (1982) have shown conclusively that d/D had little effect on the efficiency results provided that it did not exceed about 0.07. For the same value of W/U, the bigger particles recorded higer efficiency than the smaller ones.

From the above discussion, it is clear that the efficiency results obtained by Sharpe and Kirkbride and those of Frederick and Markland for different scaled model sizes were not compared under identical conditions explaining, therefore, the conflicting conclusions.

In the present investigations, great care was taken to ensure that the efficiency results from different model sizes were compared under identical conditions. To this end, the terms d/D, H/D, U^2/gD, gT^2/L in Eq.(4) were kept the same for all the models. The experiments and the results are described below.

EXPERIMENTAL ARRANGEMENT AND PROCEDURE

The procedure and the models were similar to those reported by Ali, Burrows and Lim (1982).Two out of the four geometrically similar models were used in this study and had inflow pipe diameters of 0.140m and 0.050m. The details and dimensions of the largest one are given in Fig.1a.

Special red sealing wax was used to obtain buoyant spherical particles ranging in diameter from 1 to 20mm. These particles were made of B.D.H.`Sira' adhesive wax, which has a specific gravity of 0.98. The material was weighed to give a sphere of the required diameter and shaped into spherical form by rubbing between the hands. The rising velocities of all the particles were obtained using a 2 metre long vertical cylinder. Great care was taken to control the water temperature.

Fig 1(b) shows a schematic sketch of the laboratory set up. As the objective was to compare the performance of different sized models, it was decided to ignore the dry weather flow from the chamber since this is often small in relation to total flow rates during severe rainstorms. This assumption eliminates the flow ratio i.e.term (1) in Eq. (4).

A constant head arrangement was used for all the models and discharges were measured volumetrically. The procedure used to determine the efficiency for each model under steady flow conditions was similar for all runs. After setting the flow rate and water level in the chamber to the desired value, a batch of 15 or 20 particles of the same diameter was injected at the upstream end of the inflow pipe. The time at which each particle was lost from the chamber was noted. At the end of a predetermined time period, the separation of particles was recorded as those that have lost through the overflow pipe and those remaining in the chamber. A minimum of 5 runs or the equivalent of 100 particles through the inflow pipe were conducted for each flow condition and particle size. The overall behaviour of the particle can be described by the efficiency of retention, η , defined as the percentage of particles remaining in the chamber to those injected.

EXPERIMENTAL RESULTS

As stated earlier, the experiments have been conducted by keeping terms (1), (2), (3) and (8) in Eq.(4) constant between the two models.Assuming that the out of scale effects of viscosity (term 4) and surface tension (term 6) can be neglected, Eq.(4) becomes

$$\eta = f\left(U^2/gD,\ C_D^{1/2}W/U \right) \qquad (5)$$

Fig.4 shows a typical set of results plotted in the form of Eq.(5). Eight particle diameters were used in these tests.This figure clearly shows the unifying characteristics of using $C_D^{1/2}W/U$ as the main parameter in the presention of efficiency results for a given size of overflow.

Fig.5 gives a direct comparison of efficiency results between the two models. In Fig.5 the particle sizes used were also included to show their geometric similarities. This figure shows that for $C_D^{1/2}W/U$ less than 0.18, efficiency increases with the decrease in model size. This result is similar to the findings of Ali, Burrows and Lim (1982), which is shown in Fig.6. Hence, efficiency results from model tests will give an optimistic view of the performance of a large scale prototype. Care should be exercised when such data are used to assess the prototype behaviour. It should be remembered that the effects of viscosity and surface tension have not been considered in Eq.(5).In order to minimise the effects of these two forces,it is important that models should be built as large as possible.

In an attempt to give further evidence to the above findings, some of the results from Fig.5 have been used to compare with the prototype data of Saul (1977).

In so far as the authors are aware, the only previous work on prototype efficiency measurements was that carried out by Ackers, Brewer, Birkbeck and Gameson (1967) using crude sewage. In Saul's case, weighed wooden beads of 25.4mm diameter and paper towels of the Hi Fi type cut out to a size of 300 mm square were used. The main objective was to assess the ability of a full size, stilling pond type storm overflow to 'separate out' the simulated gross sewage solids under steady flow conditions. Because of the difficulties of access, a proportion of the 'beads' introduced were not recovered in some of the tests.

Fig.7 shows comparison between Saul's prototype and his nearest possible model results. In the figures, the prototype results are shown in histogram form and the two efficiency curves are from the model tests. Examinations of the results revealed that with respect to the total flowrate, flow ratio and position of the baffle plate, Saul's prototype and model test conditions were not identical. The effect of the particle size was also not considered, as for exact comparison, the prototype particles should have been 60 mm diameter. However, in general,Saul stated that the comparison of the results was good for the rising particles. The large differences observed for particles with a fall terminal velocity in the range of 6-10 cm/s was attributed to the fact that a large number of rags were retrieved from the throttle filter. Saul explained that these rags may have caused a partial blockage of the throttle pipe during the test.

Saul concluded that reasonable overall agreement was observed between the efficiency histograms for the prototype and the corresponding efficiency curves predicted by the model tests.

In the following treatment, the present model results were compared with Saul's work. It is clear that exact comparison with the prototype results was not possible. However, it is still possible to obtain a reasonable comparison since both the prototype and the present models were designed approximately to the recommendations of Sharpe and Kirkbride (1959). The details of the model - prototype similarities are shown in Table 1. It can be seen that the model-prototype similarities were quite close in terms of the particle characteristics (d,W) and the measurement periods. It is clear that the present model is larger in size than Saul's prototype, particularly the width of the chamber, being about twice that of the prototype. However, Sharpe and Kirkbride have found that beyond a certain value (their recommended value was 2.5D) the width of chamber has little effect on the efficiency. In Saul's work, the water level in the chamber was not mentioned, it is however, assumed that the surcharge ratio was small.

Fig.8 shows the comparison of the model and the prototype efficiency results plotted in the form of η against U^2/gD. It should be pointed out that only the rise particle results are compared. Fig.8 demonstrates that the model results give a generally higher efficiency than the prototype, especially when compared with the Model M-50 results. It is interesting to note that the results of the large model (M-140) are reasonably close to the prototype values for U^2/gD from 0.22 to 0.25. This suggests that that it is important to build the model as large as possible in order to predict accurately the performance of the prototype.

From Table (1), it can be seen that the throttle (DWF) flow for the prototype and the model is different (prototype q = 0.14 m^3/s, model q = 0). Saul (1977) and Frederick and Markland (1967) found that the efficiency results generally increased with the increase in the throttle flow. An empirical equation has been suggested by Frederick and Markland to take into account the effect of the flow ratio, q/Q which has the form

$$\eta = \eta^1 + q/Q\,(1-\eta^1) \qquad (6)$$

where η^1 = efficiency of particles when the throttle flow is blocked ie.q=o.

Using Eg.(6) the results of Model M-140 were calculated to give an equal throttle flow between the model and the prototype. Fig.8 shows that higher efficiency is obtained with the throttle pipe opened. The above comparison confirms the authors' earlier results that the efficiency results increased with the decrease in model size.

CONCLUSIONS

The following conclusions can be drawn from the present investigations:

1. Experimental findings of past investigations on scale effect of overflow chambers have been conflicting and misleading because the tests have not been conducted under identical conditions.

2. This work has shown that the efficiency of the overflow chambers decreases with the increase in model size. This indicates that the efficiency results of scale model tests will give a somewhat optimistic view of the performance of a large scale prototype. Hence, caution should be applied when such results are used to assess the prototype performance.

3. Comparison of the model results with Saul's prototype data gives encouraging results. The efficiency of the model was found to be higher than the prototype.

4. It has been assumed that the scale effects of viscosity and surface tension forces are negligible. It is recommended that models should be built as large as is feasible so as to minimise the influence of these two forces. Further work should be carried out to assess their combined effect on the performance of storm sewage overflows.

NOTATION

B	Breadth of chamber
C_D	Drag coefficient of particle
D	Diameter of inlet pipe
d	Diameter of spherical particle
E	Lateral diffusion coefficient for flow in the inlet pipe
f	Function of the efficiency
g	Acceleration due to gravity

H	Depth of water in the chamber
h	Height of scum board above invert
L	Length of chamber
l	Distance between scum board and overflow weir
m	Suffix referring to the model
P	Height of overflow weir above invert
p	Suffix referring to the prototype
Q	Quantity of water entering the chamber per second
q	Quantity of water leaving to treatment per second
S	Specific gravity of particle
T	Measuring period
U	Average velocity of fluid in the inlet pipe
W	Rising velocity of particle in still water
α	Scale ratio
η	Efficiency, defined as the fraction of particles introduced through the inlet pipe not discharged through the outlet pipe.
μ	Dynamic viscosity of water
ρ	Density of water
σ	Surface tension

REFERENCES

Ackers, P., Brewer, A.J., Birbeck, A.E and Gameson, A.L.H. 1967. *Storm overflow performance studies using crude sewage.* I.C.E. Symposium on Storm Sewage Overflows:Paper No.6,63-77.

Ali, K.H.M., Burrows, R. and Lim, S.Y. 1982. *Scale-model investigation of storm water overflows.* Int. Conf. on the Hyd. Modelling of Civil Engrg. Structures, U.K.(Sept.):357-79.

Burrows, R. and Ali, K.H.M. 1982.*The shaft overflow: a storm sewage overflow device appropriate to differential head applications.* Jour. Inst. Mun. Engineers,(U.K.).

Frederick, M.R. 1967. *The stilling pond with siphon overflow.* Ph.D.Thesis,University of Nottingham,U.K.

Frederick, M.R., and Markland. E. 1967. *The performance of stilling ponds in handling solids,* I.C.E. Symposium on storm sewage overflows:Paper No.5, 51-61.

Halliwell, A.R. and Saul, A.J. 1980. *The use of hydraulic models to examine the performance of storm-sewage overflows.* Proc. Instn. Civ. Engrs.,U.K., Part 2, 69 (June): 245-59.

Institution of Civil Engineers. U.K. 1967. *Symposium on Storm Sewage overflows.*

Lim, S.Y. 1985. *Scour and particle diffusion caused by water jets.* Ph.D Thesis, University of Liverpool,U.K.

Saul, A.J. 1977. *The performance of storm sewage chambers.* Ph.D Thesis, Heriot-Watt University,U.K.

Saul, A.J. and Delo, E.A. 1982. *Laboratory tests on a storm sewer overflow chamber with unsteady flow.* Proc. of the 1st Int. seminar on Urban Storm Drainage System, Southampton, U.K.(Sept.) :5.23-31

Sharpe, D.E., and Kirkbride, T.W. 1959. *Storm-water overflows: the operation and design of a stilling pond.* Proc. Instn. Civ. Engrs.,U.K.:445-66.

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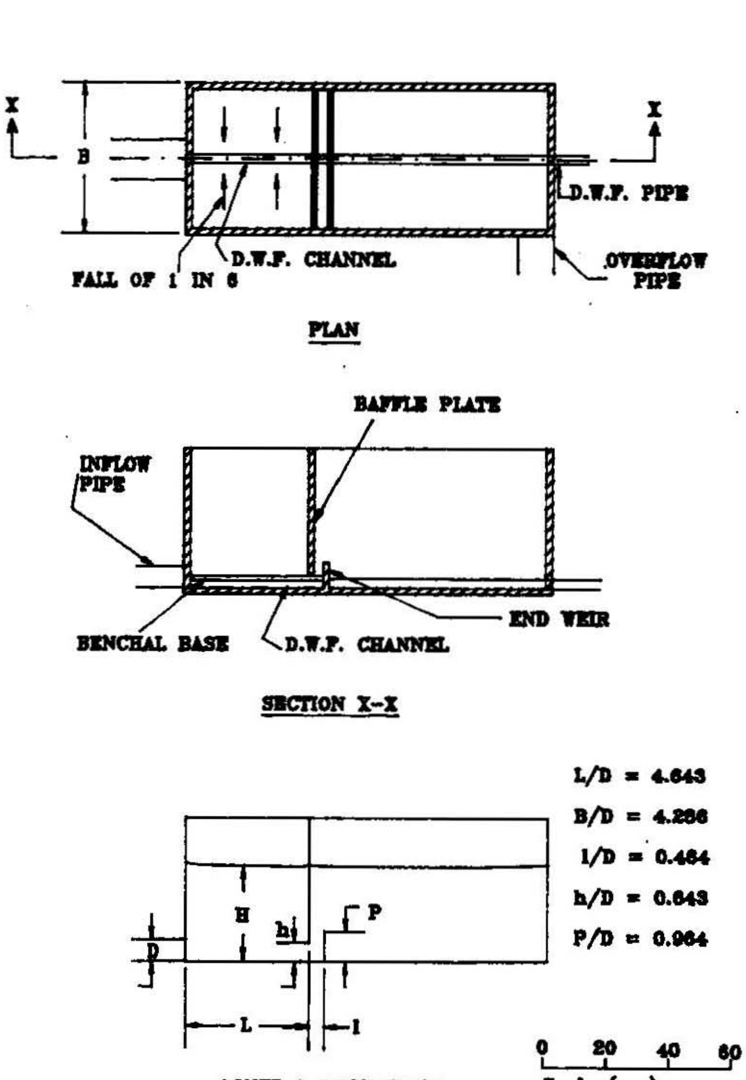
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L/D = 4.643
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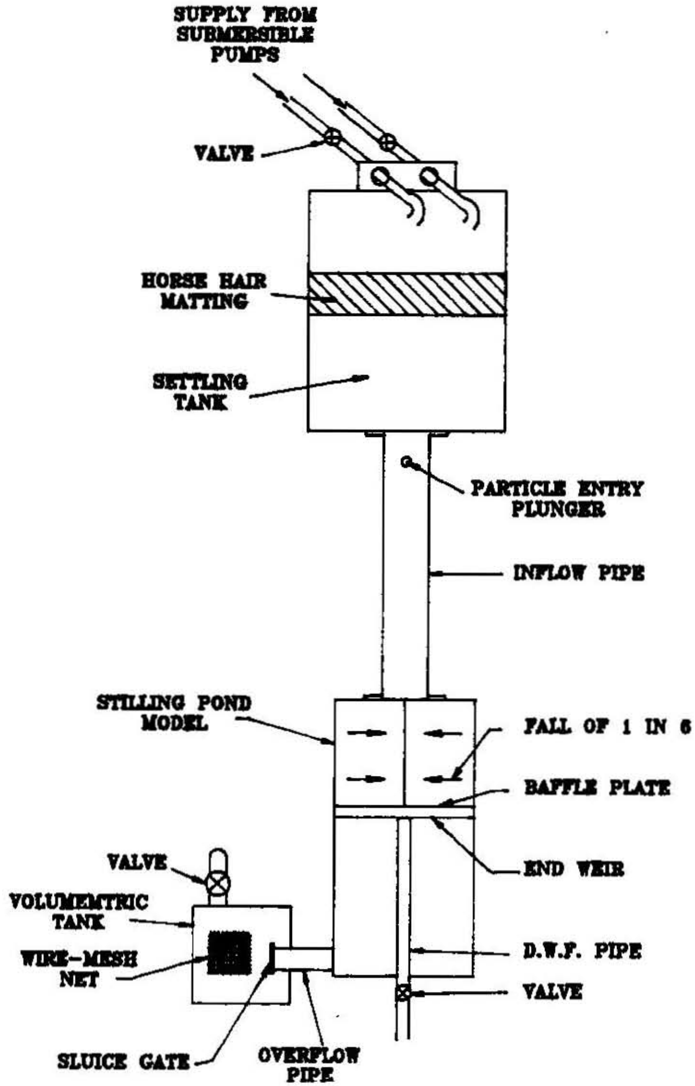
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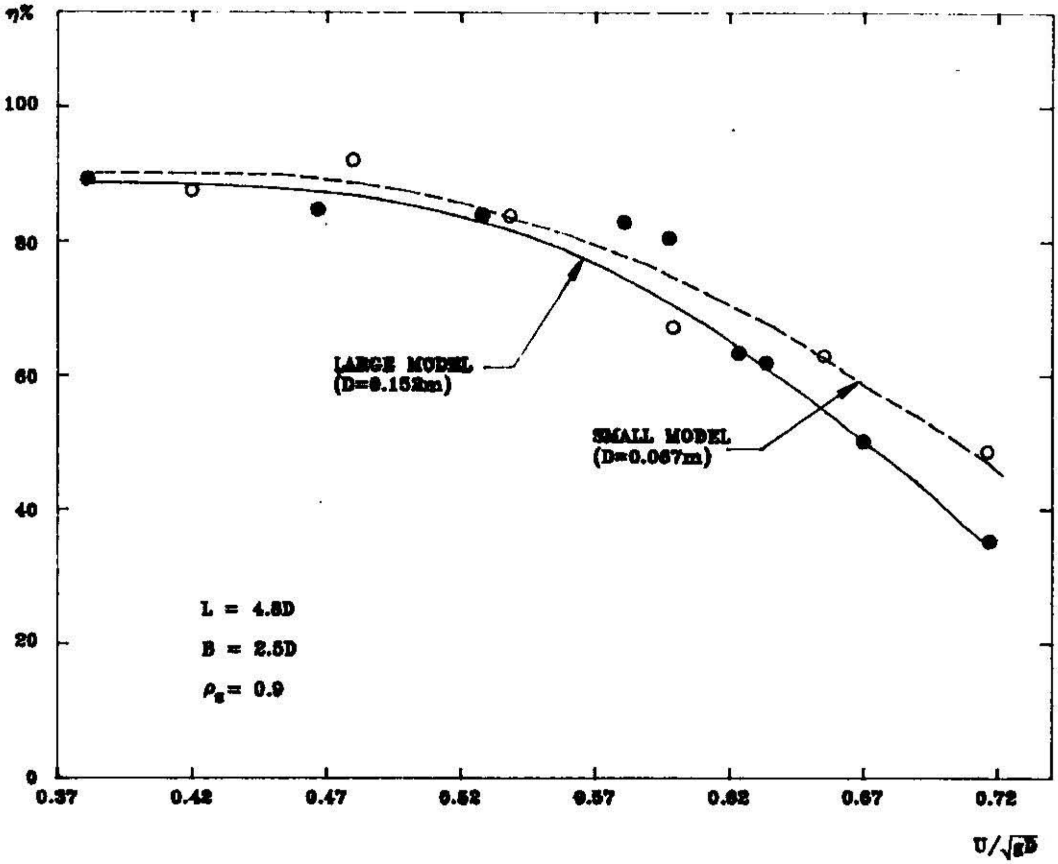


Figure 2 : Effect of Model Size (After Sharpe and Kirkbride, 1959)

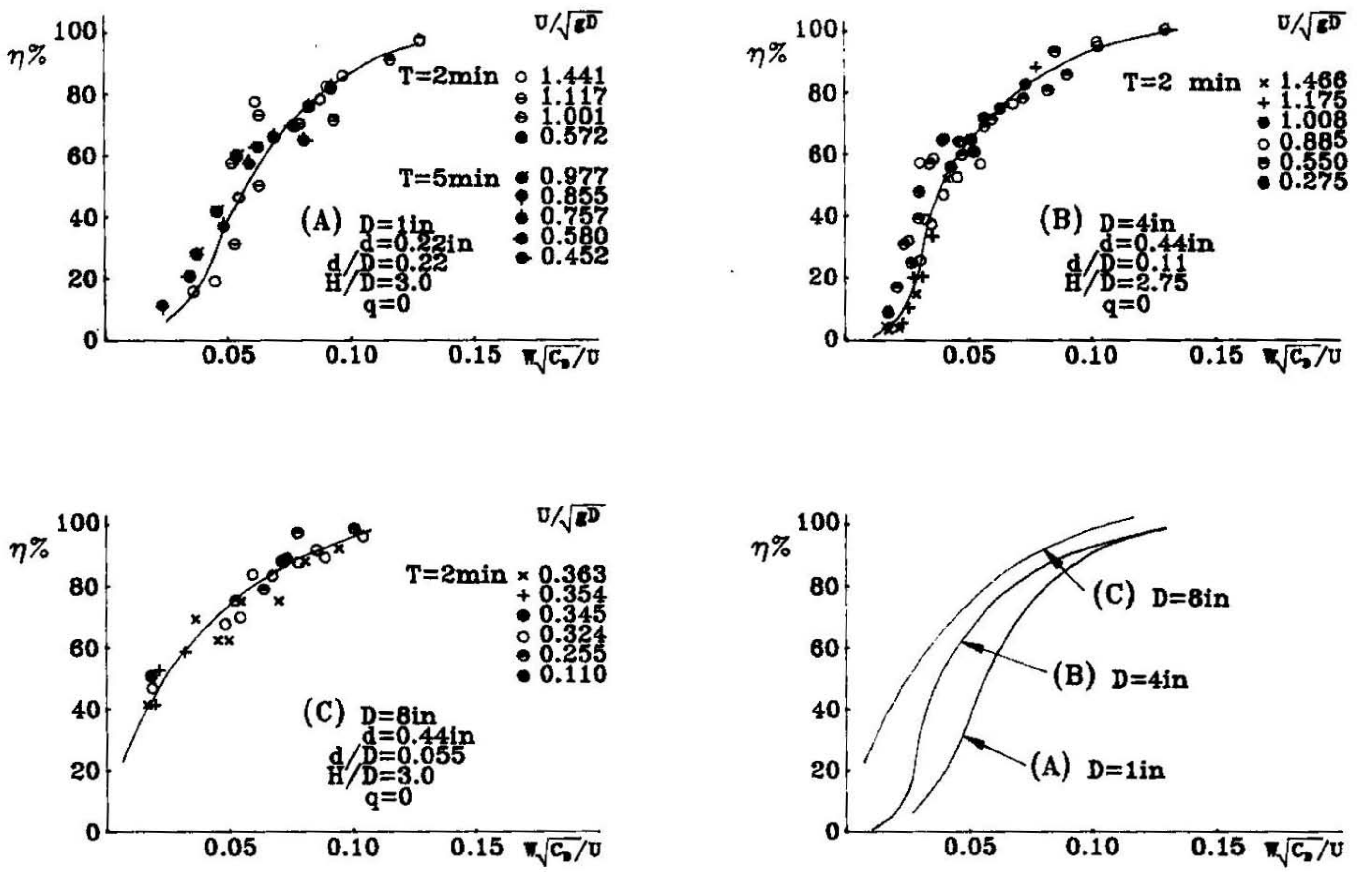
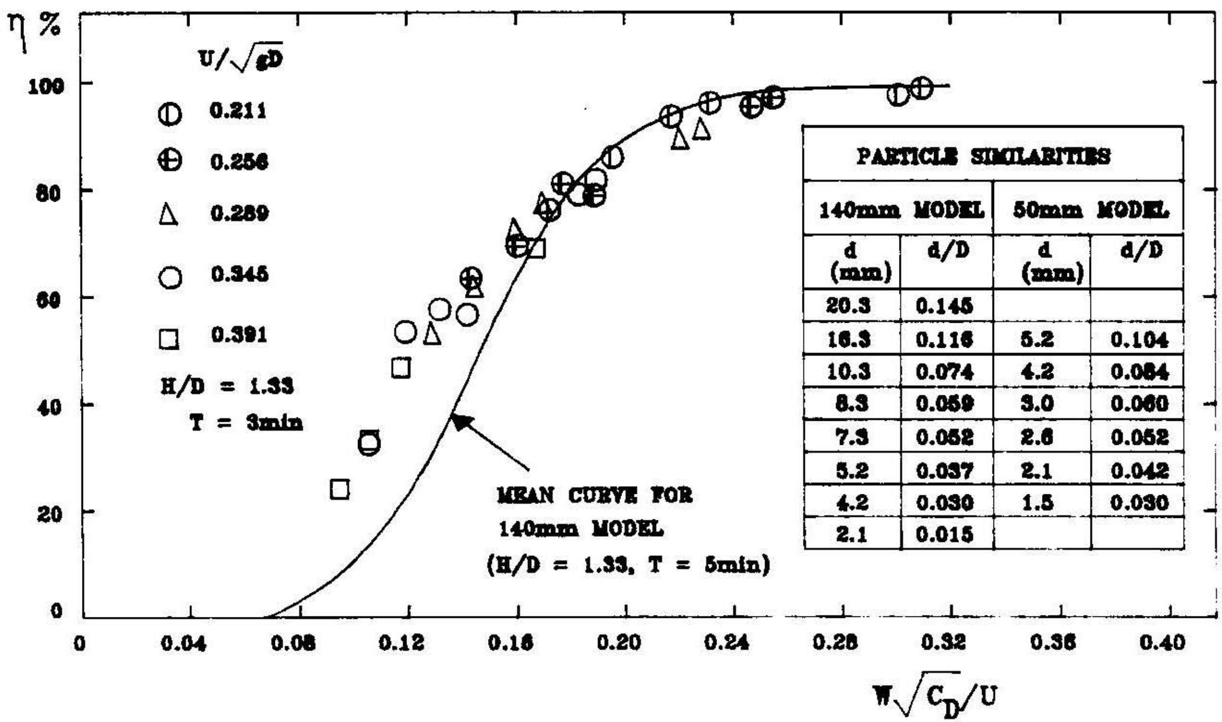


Figure 3 : Effect of Model Size (After Frederick, 1967)



PARTICLE SIMILARITIES

140mm MODEL		50mm MODEL	
d (mm)	d/D	d (mm)	d/D
20.3	0.145		
16.3	0.116	5.2	0.104
10.3	0.074	4.2	0.084
8.3	0.059	3.0	0.060
7.3	0.052	2.6	0.052
5.2	0.037	2.1	0.042
4.2	0.030	1.5	0.030
2.1	0.015		

Figure 5 : Stilling Pond - Efficiency Results of Models M-140 and M-50 with H/D = 1.33.

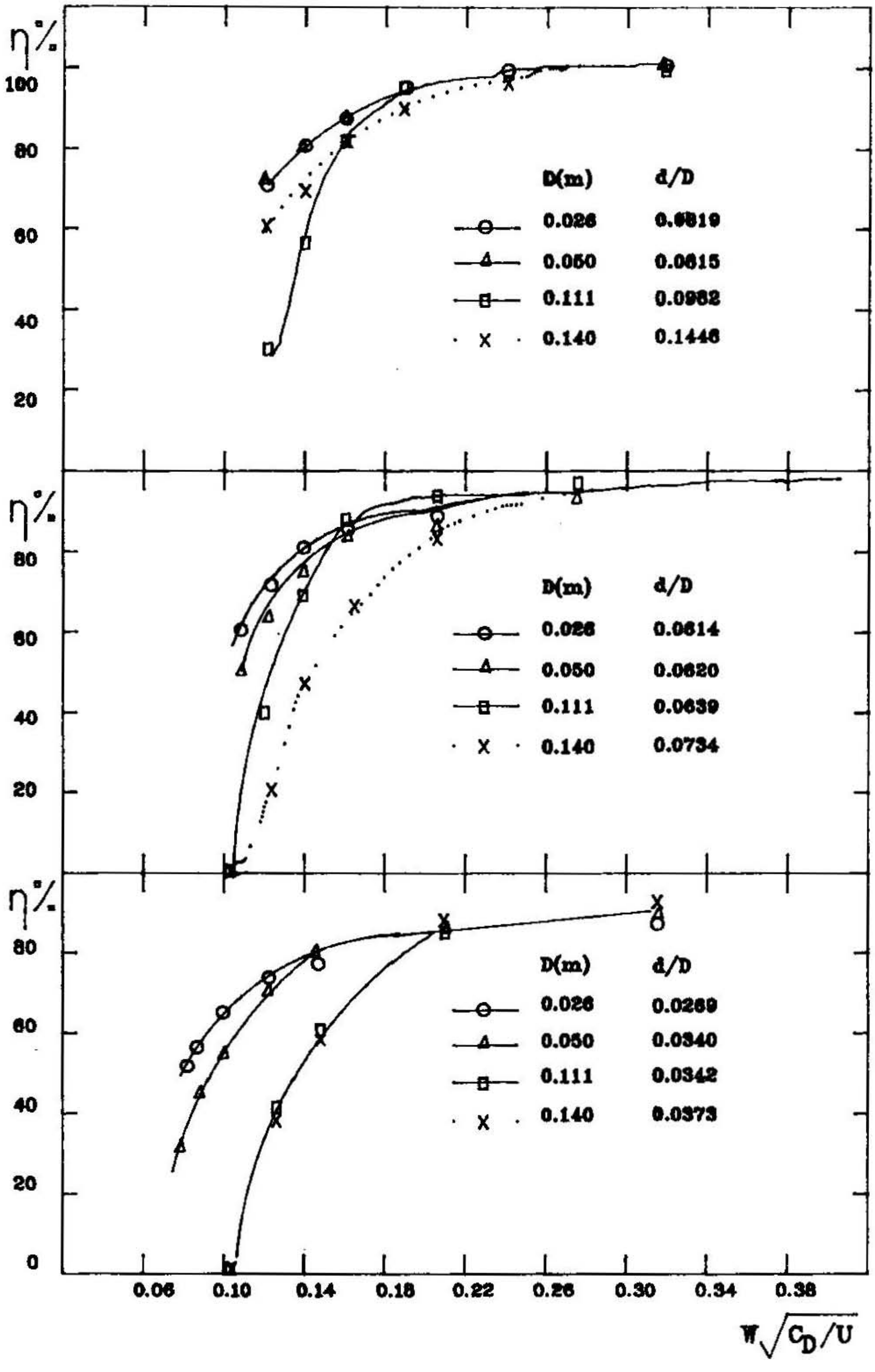


Figure 6 : Variation of η with $W\sqrt{C_D/U}$ for the various models H/D varies.

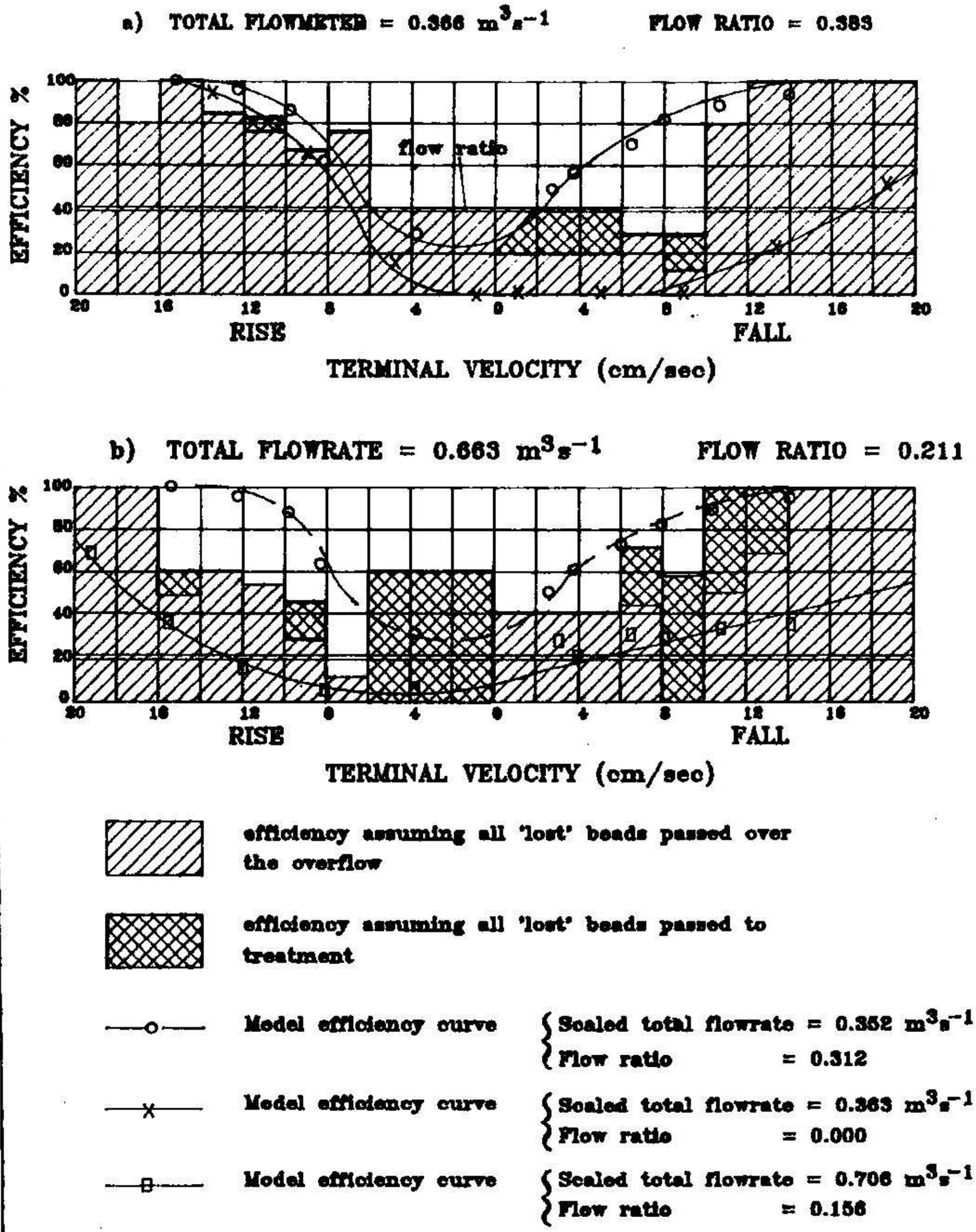
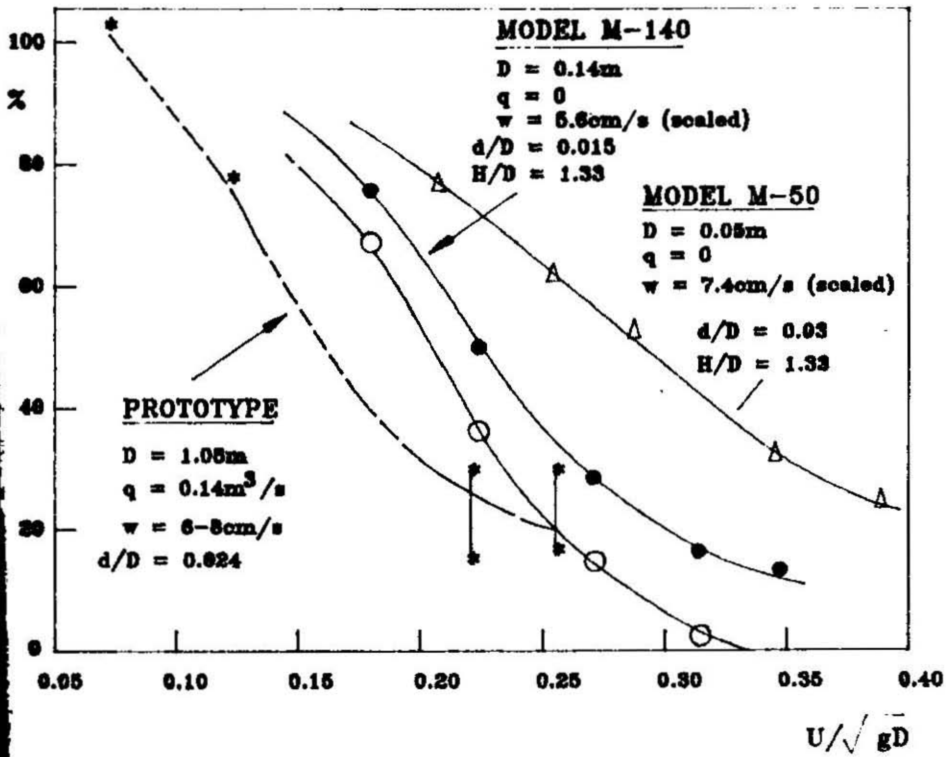


Figure 7 : Comparison of Model and Prototype Results
(After Saul, 1977)

Table 1: Comparison for Model and Prototype Similarities

Description		Prototype	Model	
Inlet pipe diameter	D(cm)	108.0	14.0	5.0
Chamber length	Ls	3.7D	4.6D	4.6D
Chamber width	B	2.2D	4.3D	4.3D
Distance from scum board to weir	1	0.5D	0.46D	0.46D
Height of scum board	0.57D-h	0.80D	0.64D	0.64D
Water level in the chamber	H	not clear	1.33D	1.33D
Throttle flow	q(m3/s)	0.14	0	0
Measuring period (scaled)	T(Min)	15.0	14.0	14.0
Particle size rise velocity (scaled)	d W(cm/s) W(cm/s)	0.024D 12-14 6-8	0.03D 12.86 -	0.03D - 7.44
Particle size rise velocity (scaled)	d W(cd/s)	0.024D 6-8	0.015D 5.60	- -



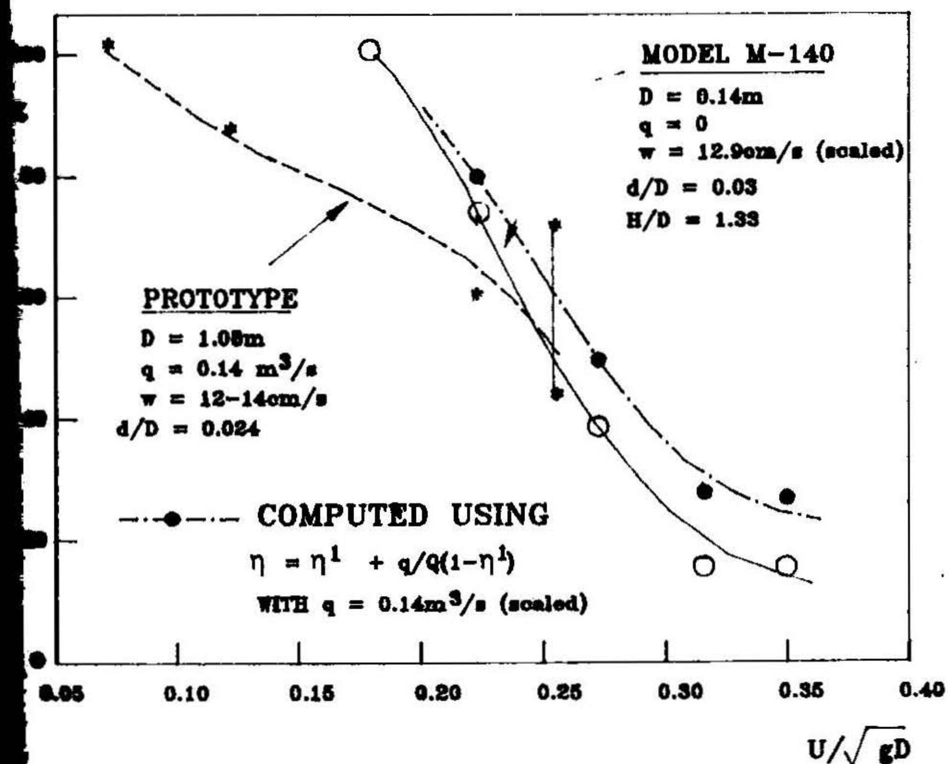


Figure 8 : Comparison of Prototype and Model Efficiency Results.