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COMPARATIVE EFFICIENCIES STUDY OF SLOT MODEL AND MOUSE MODEL IN PRESSURISED PIPE FLOW

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Abstract: The flow in sewers is unsteady and variable between free-surface to full pipe pressurized flow. Sewers are designed on the basis of free surface flow (gravity flow) however they may carry pressurized flow. Preissmann Slot concept is widely used numerical approach in unsteady free surface-pressurized flow as it provides the advantage of using free surface flow as a single type flow. Slot concept uses the Saint-Venant's equations as a basic equation for one-dimensional unsteady free surface flow. This paper includes two different numerical models using Saint Venant's equations. The Saint Venant's equations of continuity and momentum are solved by the Method of Characteristics and presented in forms for direct substitution into FORTRAN programming for numerical analysis in the first model. The MOUSE model carries out computation of unsteady flows which is founded on an implicit, finite difference numerical solution of the basic one dimensional Saint Venant's equations of free surface flow. The simulation results are compared to analyze the nature and degree of errors for further improvement.

Keywords: Storm sewer network, Pressurized flow, Preissmann slot, Slot Model, Mouse Model

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INTRODUCTION

The flow in storm sewer networks is one of the most complicated hydraulic problems. The flow is unsteady and variable between free-surface to full pipe pressurized flow. Sewers are designed on the basis of free surface flow (gravity flow) however they may carry pressurized flow. Pressurized full pipe flow occurs when the sewer pipe is under design, the flood exceeds that of the design return period etc. In such condition, the waves would travel toward the upstream end from downstream with the filling up of the pipe. The pressure rise produced may cause pressure transients and backflow in the drainage system along with various system damaging activities. Although many numerical methods have been developed to simulate the unsteady flows in sewer and storm water systems, including those based on explicit numerical schemes and those based on implicit schemes, limitations in most of models exist (Fread, 1993). The two characteristics in storm sewer networks raise challenges to the numerical description of the flow transition. For modeling transient from free surface to pressurized flow in pipe lines, Preissmann & Cunge (1961) and later Cunge & Wegner (1964) introduced a slot concept. Abbott & Verwey (1970) adapted this method to model the flows in storm-sewer pipelines. It has become one of the most extensively used numerical approaches for transient flow in closed conduits.

Slot concept behaves the pressurized flow as open channel flow by adding a hypothetical narrow, open slot at the top of the pipe:

$$c = \sqrt{g \frac{A_p}{B_s}} \tag{1}$$

in which g = acceleration due to gravity, A_p = cross sectional area of pipe, B_s = width of the slot and c = wave celerity. According to the **Eq. (1)**, slot width, B_s can be sized so that the assumed celerity c in the pressurized portion of the flow could be matched.

The slot concept provides the advantage of using free surface flow as a single type flow throughout the sewer system and makes easy to quantify the pressure head when pipes pressurize. In case of surface flow, the slot has no effects and the open channel flow equations apply as usual.

Slot concept of modeling uses the Saint-Venant's partial differential equations of continuity and momentum as a basic equation for one-dimensional unsteady flow. This paper uses two different methods of simulations using slot concept i.e. using a computer compiler language, FORTRAN and MOUSE model. There is no general solution to the partial differential equations, however there are number of numerical methods available to solve them. The Method of Characteristics (MOC) is the best known method used for transient flow in a closed conduit Chaudhary (1978) and Wylie & Streeter (1993) due to its simplicity and good physical insight. The first model uses a pair of Saint Venant's partial differential equations which are transformed into a particular total differential equations by MOC. The later equations are integrated to yield finite difference equation, which are presented in forms for direct substitution into FORTRAN and are handled numerically. The second model, MOUSE Model, carries out computation of unsteady flows which is founded on an implicit, finite difference numerical solution of the basic one dimensional Saint Venant's equations of free surface flow. It performs computation of unsteady flow by solving the vertically integrated equations of conservation of continuity and momentum, based on the assumptions: the water is incompressible and homogenous, the bottom slope is small, the wave lengths are large compared to the water depth and the flow is sub-critical unless some special cases.

The MOUSE Model describes free surface and pressurize flows within the same basic algorithms as other slot models, to ensure the smooth and stable transition in all situations. The implementation algorithm has a self-adapting time step.

However Courant's stability condition imposes slot models with limitation on the size of the time step. In fact the slot concept produces large wave celerity and a corresponding strict time step limitation with too small slot width where as remarkable drop in water level due to frictional head losses may result with too large slot width.

The first method of modeling in this paper will be termed simply a Slot Model although both the models use the concept of slot over the invert of the pipe.

The paper is organized in four sections. Section 2 includes the two different forms of Saint Venant's Equations as governing equations for two models. In section 3, the numerical experiments of pipe networks with four different diameters are carried out. The computational performance, accuracy and errors of the models are studied and discussed on the basis of their numerical results. Section 4 draws the conclusion for further improvement of two modeling for future use.

GOVERNING EQUATIONS

The Saint Venant's equations of continuity and momentum are implemented in both models. However, in first model, 'slot' is considered as part of flow sectional area where as MOUSE Model assumes the volume of water added in pipe section is balanced by an increase in cross sectional area, *i.e.* storage. The derived forms of equations of both models are shown below.

(1) Slot Model (written in FORTRAN)

The corresponding St. Venant's equations of momentum and continuity in a sewer pipe with a slot at the top of the pipe are given by

$$\frac{1}{g}\frac{\partial V}{\partial t}+\frac{V}{g}\frac{\partial V}{\partial x}+\frac{\partial h}{\partial x}-S_0+S_f=0 \quad (2)$$

where, $S_f=\dfrac{n^2|V|V}{R'^{\frac{4}{3}}\left\{1+\dfrac{B_s}{A_p'}\left(h-D'\right)\right\}}$ $\qquad \dfrac{\partial h}{\partial t}+V\dfrac{\partial h}{\partial x}+\dfrac{c^2}{g}\dfrac{\partial V}{\partial x}=0 \quad (3)$

where, $c=\sqrt{g\left\{\dfrac{A_p'+B_s\left(h-D'\right)}{B_s}\right\}}$

Here, h = flow depth; V = flow velocity; c = celerity of pressure wave; A_p = cross sectional area of pipe; S_0 = pipe slope; S_f = energy slope; g = acceleration due to gravity; x = distance coordinate and t = time. Similarly A'_p = cross sectional area of pipe without considering slot; D' = depth of pipe without considering slot; R' = hydraulic radius without considering slot; B_s = slot width and n = Manning's coefficient. For the derivation of equations obtained above, it is assumed that the water is incompressible and sewer pipes are rigid.

(2) MOUSE Model

The corresponding Saint Venant's Equations for continuity and momentum for MOUSE model can be written as:

$$\frac{\partial Q}{\partial x}+\frac{Q}{\rho}\frac{\partial \rho}{\partial x}+\frac{gA_0}{a^2}\frac{\partial y}{\partial t}=0 \quad (4)$$

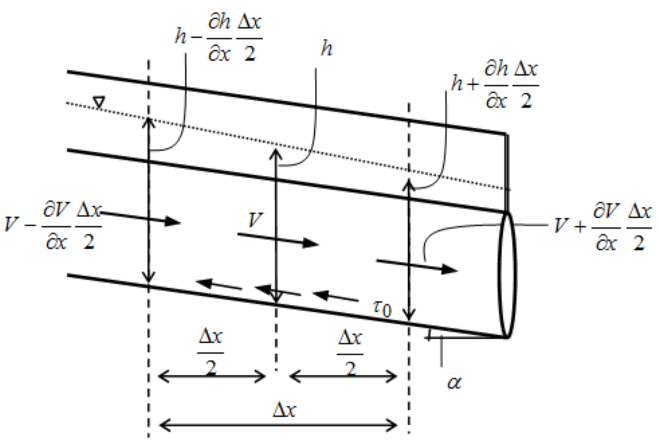

Fig. 1 Longitudinal section of sewer pipe with slot (Pandit *et al.*, 2007).

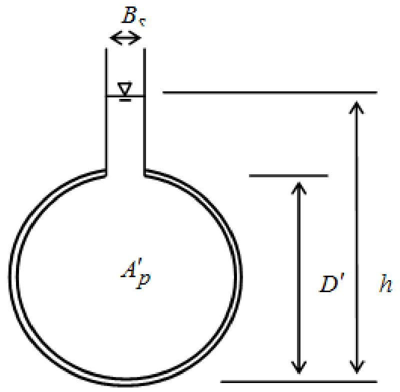

Fig. 2 Cross section of sewer pipe with slot.

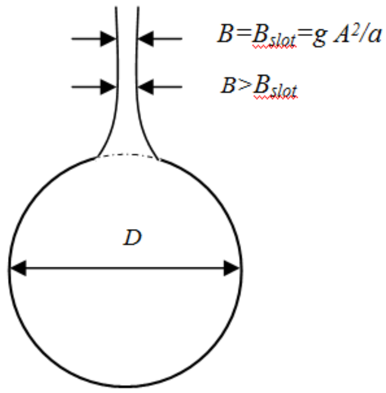

Fig 3 Pipe with the fictious Slot.

where, $\rho\approx\rho_0\left(1+\dfrac{g\left(y-D\right)}{a^2{}_0}\right)$

$$\frac{\partial Q}{\partial t}+\frac{\partial\left(\alpha\frac{Q^2}{A}\right)}{\partial x}+gA\frac{\partial y}{\partial x}=gA(I_0-I_f) \quad (5)$$

Here, Q = discharge, A = flow area, y = flow depth, g = acceleration due to gravity, ρ = density of water, ρ_0 = density of water for free surface flow, a_0 = speed of sound in water, x = distance in flow direction, t = time, α = velocity distribution coefficient, I_o = bottom slope and I_f = friction slope.

The equations above are valid for free surface only. They can, however, be generalized to include flow in full pipes (pressurized flow). The continuity equation expresses the volume of water, ∂Q, which is added in pipe section of length, ∂x, is balanced by increase in cross sectional area ∂A.

NUMERICAL EXPERIMENTS, RESULTS AND DISCUSSION

The Slot Model (written in FORTRAN) and MOUSE Model are used to perform a series of numerical experiments on unsteady flow simulations in closed circular conduit. The test series were designed to study unsteady flow in a close circular conduit. The conduit's initial conditions were completely full gravity flow conditions. The surcharge flow conditions were facilitated through the use of concept of Preissmann's slot in both cases. A series of numerical experiments were performed to investigate the influence of Preissmann slot on unsteady flow simulations.

In the simulations the upstream boundary condition was defined by an inflow hydrograph and the outflow was simply a free flow. The four cases of single pipe networks of lengths 30, 45, 60 and 80 meters and diameters 0.25, 0.5, 1 and 2 meters, respectively, were simulated with slot widths 0.0001, 0.001, 0.01 and 0.05m. The selected slope of the network was in decreasing order with the increase of diameters. The number of pipes considered in the first three cases were 17 and 13 for the network of diameter 2 meters. The base flow is considered to be equal to full pipe discharge. In all cases the peak flow is 1.3 times the full pipe discharge, which indicates the pressurized flow in the system. A summary of the study conduit is shown in the table below.

Table 1. Specifications of pipe networks

Specification	Diameters (m)			
	0.25	0.50	1.00	2.00
Length (m)	30	45	60	80
Slope	0.0083	0.0054	0.0038	0.0025
Manning's n	0.013	0.013	0.013	0.013
Manhole area (m^2)	0.611	0.9	2.332	2.935
Ht. of Manhole above invert (m)	1.75	2.5	2.5	2.8
Number of pipes	17	17	17	13
Full pipe discharge (m^3/s)	0.0542	0.2775	1.478	7.6118
Base flow (m^3/s)	0.054	0.278	1.485	7.65
Peak flow (m^3/s)	0.0705	0.3608	1.924	9.8953

Sewer Pipe Networks tested in Numerical Simulations

The hydraulic inputs, inflow, in specific time specify depth hydrograph at the upstream manhole as major outputs. The four cases of inflow duration, 5, 10, 30 and 60 minutes, were tested for all networks. It seemed relevant to include the depth and discharge hydrographs of 1 meter diameter network in the paper as it gives clear concept of all simulation tests.

The remarkable series of hydrographs illustrated and the simulation returned to the original initial flow values demonstrated the accuracy of model's algorithm. The discharge hydrographs in all cases are more or less similar, however the output i.e. the depth hydrographs at the upstream manhole are distinct for Slot and MOUSE Models as shown in **Figs 5–6**. The depths were observed somehow similar in MOUSE model however there was remarkable decrease in Slot Model with the increase of slot widths. This is an indication of existence of serious error in Slot Model.

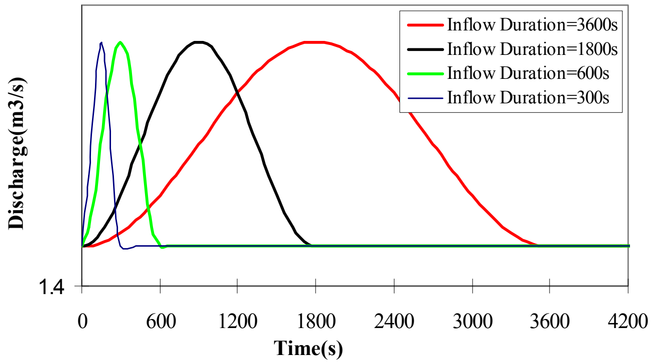

Fig. 4 Discharge Hydrograph of 5, 10, 30 and 60 min.

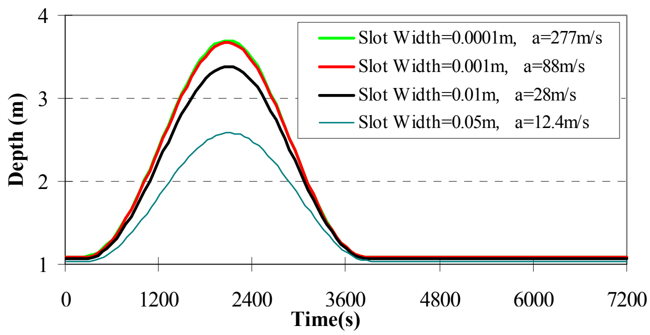

Fig. 5 Depth Hydrograph of Slot Model.

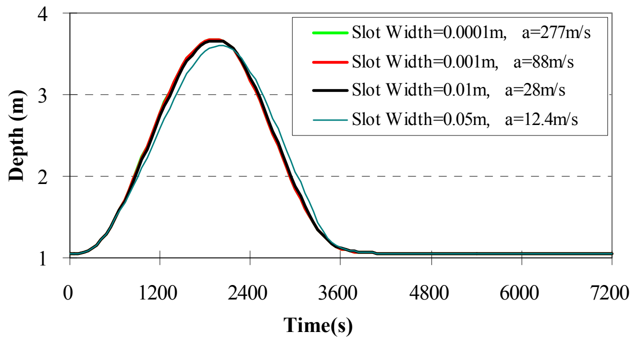

Fig. 6 Depth Hydrograph of MOUSE Model.

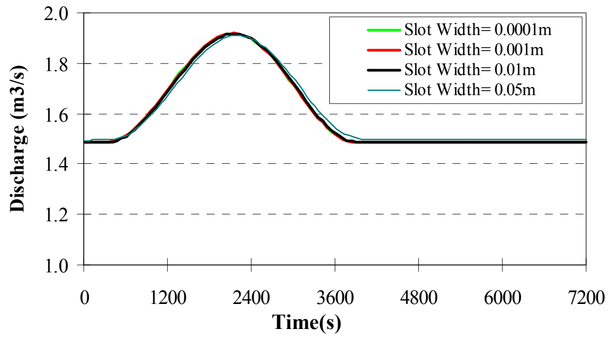

Fig. 7 Discharge Hydrograph of Slot Model.

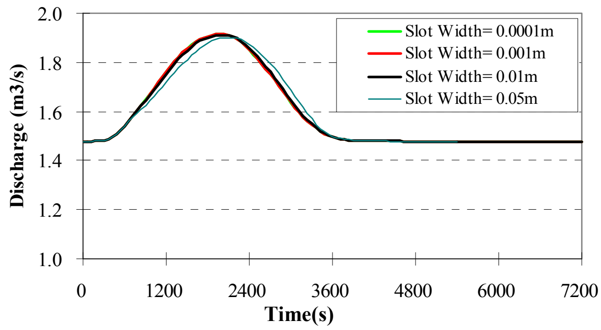

Fig. 8 Discharge Hydrograph of MOUSE Model.

The simulation results were used to study the efficiencies of two tested models by transforming into particular graphs. The effects of inflow duration for various slot widths are shown in the Figs. 9 -16. In both models, percentage of error decrease with the increase in pipe diameter however, the percentage of error is much higher for Slot Model than the MOUSE Model. The percentage of error in MOUSE model for short inflow duration is higher than for the longer duration except in 0.25 meter diameter. The inflow simulation time does not make big difference in Slot Model.

CONCLUSIONS

The slot models are widely used numerical model of unsteady free surface-pressurized flow. It is very appropriate for the simulation of sewers in urban areas where the change in inflow is variable with the intensity

Fig. 9 Error for Slot Model, D=0.25m

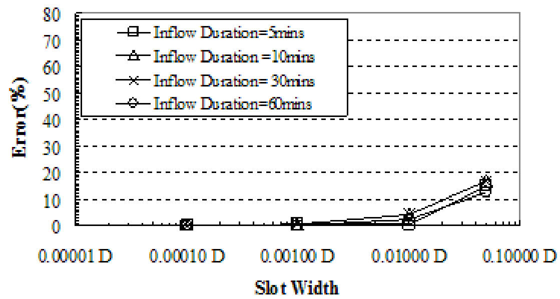

Fig. 13 Error for MOUSE Model, D=0.25m

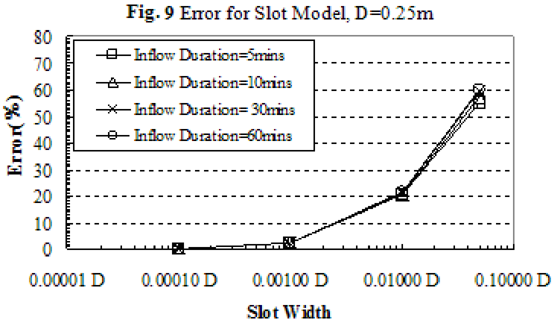

Fig. 10 Error for Slot Model, D=0.5m

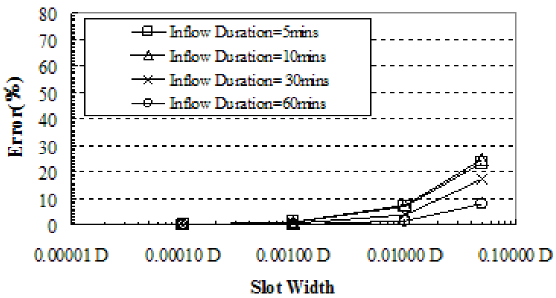

Fig. 14 Error for MOUSE Model, D=0.5m

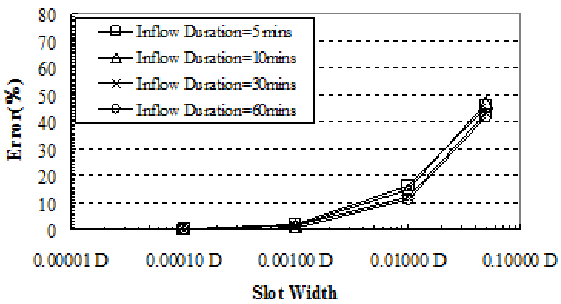

Fig. 11: Error for Slot Model, D =1m

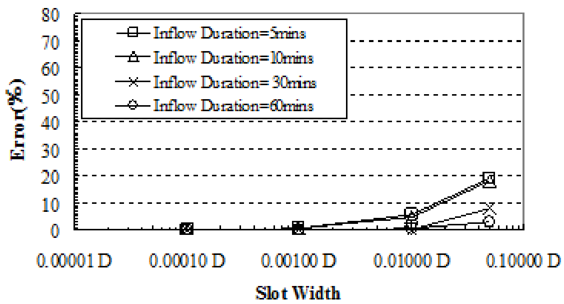

Fig. 15: Error for MOUSE Model, D=1m

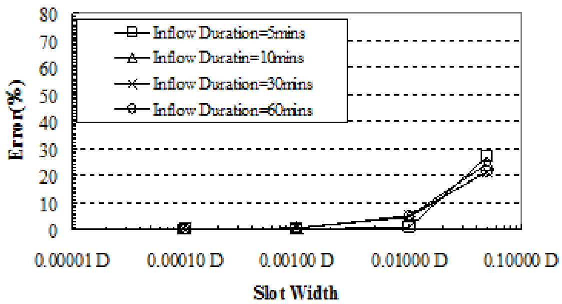

Fig. 12: Error for Slot Model, D=2m

Fig. 16: Error for MOUSE Model, D=2m

and duration of rainfall. The remarkable series of depth hydrographs illustrated in the paper and the simulation returned to the original initial flow values demonstrated the accuracy of model's algorithms. The simulation results transformed into the graphs have shown the higher percentage of error in the case of Slot Model. However the errors in MOUSE Model can not be neglected. The nature of errors in MOUSE Model is with inflow duration i.e. errors increase with the decrease of inflow duration.

In the Slot Model the friction is not accounted for the additional cross sectional area of slot. As a result the errors occur however it is higher for first modeling. This study suggests that it is possible for further improvement of Slot Model for precise performance if frictional coefficient for the additional cross sectional area could be accounted. Similarly MOUSE Model can be further improved to achieve errorless results for all inflow duration.

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