2D SIMULATION OF NON-UNIFORM SEDIMENT TRANSPORT IN A CHANNEL BEND IN UNSTEADY FLOW

By

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Submitted by

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Has been accepted towards the partial fulfillment

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DEDICATION

Dedicated to my parents, whose prayers are always supporting me, to my siblings who always guide me to success, to my classmates and friends who allowed me to dedicate time for the successful completion of this thesis.

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I am thankful to my Creator Allah Subhana-Wataala to have guided me throughout this work at every step and for every new thought which You set up in my mind to improve it. Indeed I could have done nothing without Your priceless help and guidance. Whosoever helped me throughout my thesis, whether my parents or any other individual was Your will, so indeed none be worthy of praise but You.

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Finally, I would like to express my gratitude to all the individuals who have rendered valuable assistance to my study.

(Mohammad Daud)

ABSTRACT

The interest in rivers is as old as human civilization itself. The rivers seldom flow in a straight path and usually trace out in curved paths. An alluvial river is having the same bed material as the material it moves along the bed and in suspension. The movement of water is intimately linked to the sediment load that it carries.

These morpho-dynamic processes cause the river to change its shape, slope, sediment sorting/, etc. Riverbeds of natural streams are more vulnerable to temporal and spatial changes. These processes are mostly found in river bends as river bends are mostly subjected to sorting processes.

There are two objectives of this research, first, we have to check the 2D model (Basic Simulation Environment) capability to reproduce experimental results of channel bend having an angle of 180^0 and a constant radius. The second objective is to perform the sensitivity analysis of the 2D model, in which inner particles will inform us about the most sensitive model parameters that decisively influence the results.

The research simulates the changes in bed topography in an alluvial channel bend under unsteady flow conditions with non-uniform sediment. Experimental data collected during experimental research having a channel bend of 180^0 and a constant radius of curvature was used to validate the numerical results. Five experiments were done on the channel bend in a laboratory having different inflow hydrographs.

The numerical results in the bend showed scouring at the outer bank and deposition at the inner bank, which tallied with the observed behavior. The research showed that a 2D model can successfully predict the morpho-dynamic changes in a laboratory channel.

The sensitivity analysis is also done in this research which shows the sediment transport formula is the most sensitive parameter in the basement model.

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LIST OF ABBREVIATIONS

No.	Abbreviation	Description
1	2D	Two dimensional
2	3D	three dimensional
3	M	Meter
4	D	Dimensional
5	CFL	Courant-Friedrichs-Lewy condition
6	Min	Minute
7	Hr	Hour
8	Mm	Millimeter
9	Cm	Centimeter
10	m^3/s	Cumecs
11	Basement	Basic Simulation Environment for Computation of Environmental Flow and Natural Hazard
12	Pa	Pascal (N/m^2)

LIST OF NOTATIONS

Notation	**Description**
B	Channel width
D	The median diameter of sediment.
h_o	Baseflow depth at the upstream end.
H	Flow depth
h_p	Flow depth at peak of hydrograph at an upstream end
G	Gravitational acceleration
Q	Mean discharge of hydrograph
R	A radial coordinate of a channel bend
RC	The radius of curvature along the centerline of the
$\boldsymbol{Q_o}$	bend
$\mathbf{N_*}$	Discharge of baseflow
t	Curvature factor
$\mathbf{t_d}$	time
$\mathbf{Z_b}$	duration of hydrograph
$\mathbf{U_{*o}}$	bed surface elevation
	the shear velocity of baseflow in upstream straight
$\boldsymbol{\alpha}$	reach
$\boldsymbol{\beta}$	the shape factor of upstream particle
$\boldsymbol{\Delta Z_b}$	$(\delta_s-\delta)/\delta$
$\boldsymbol{\delta}$	Change in bed surface elevation
$\boldsymbol{\delta_s}$	Density of water
Ƒ$_{\mathbf{bn}}$	The density of sediment particle
Ƒ$_{\mathbf{bs}}$	N component of bed shear stress
$\mathbf{S_o}$	S component of bed shear stress

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INTRODUCTION

1.1 GENERAL

In this Universe, countless rivers streams are present on the earth in which water flows from the upstream areas to the downstream oceans with the help of slopes, gravity, or topography of rivers, etc. So the flow of water in river streams can carry anything which comes in its way which is a sign of danger for human beings. Mostly river carries sediments in the form of sand, boulders, and gravel, etc, these flowing sediments create problems, because it changes the whole topography of a natural river stream. The most vulnerable reason for sediment flowing is flooded because flood carries all types of sediments which come in their way.

The temporal and spatial changes on the bed of natural streams is due to the carrying sediments on it. Natural streams are mostly found in meander form (bend) rather than in straight form. This study focuses on the phenomenon which occurs in river bends. The processes which occur in a river bend are too complex than that which occurs in the straight reach of a river. These complex phenomena are the main reason behind the bed deformation in the river stream.

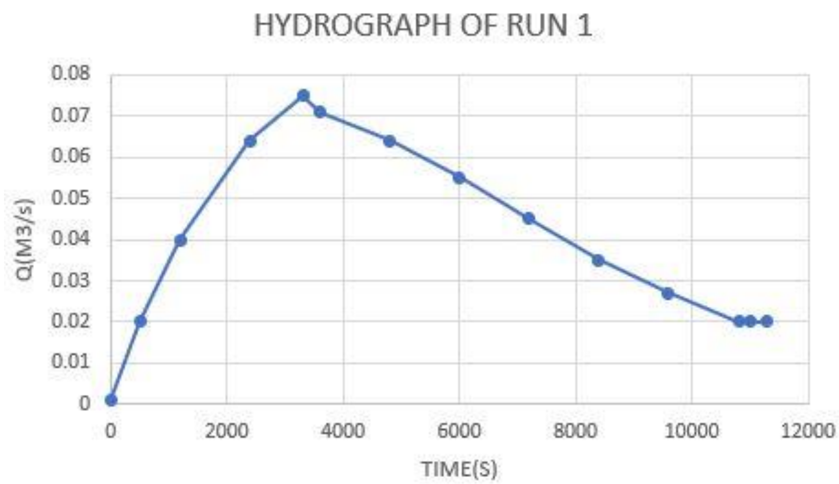
The complexity of processes that occurs in bends is due to the spiral motion of the flow which exhibits secondary currents. Non-uniform sediments in a bend exhibit both the longitudinal and transverse transport and also transverse sorting as well due to the spiral motion of the flow made by secondary currents.

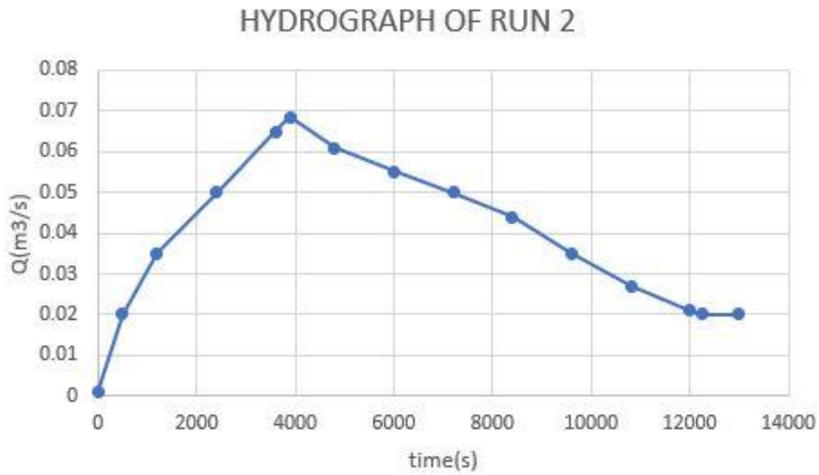
Due to secondary currents scouring takes place at the outer portion of the river bend and deposition at the inner portion of the river bend, finer material deposits at the inner part of the river bend, and coarser at the outer part of the river bend. Bed changes made by scouring and deposition disturb the flow which in turn effects the change in bed shear stress and bed topography. In this study, all these processes will be investigated using a 2D numerical model. The curvature effect will be induced in this model to create better results.

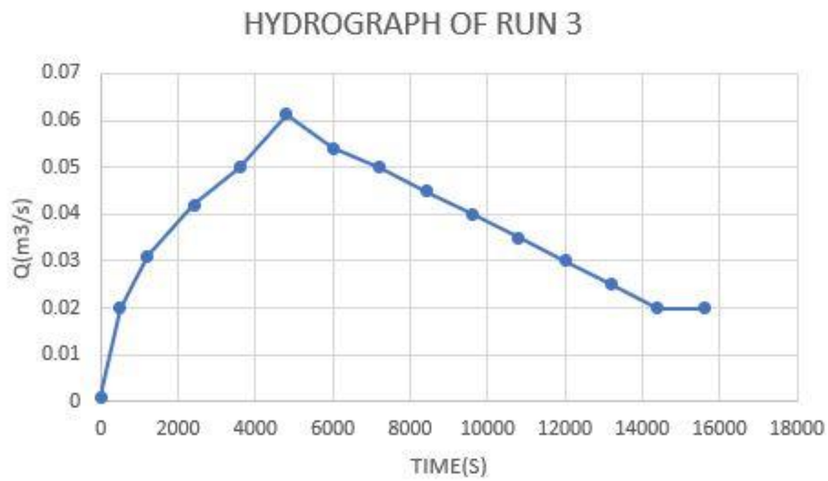
1.2 LABORATORY EXPERIMENTS

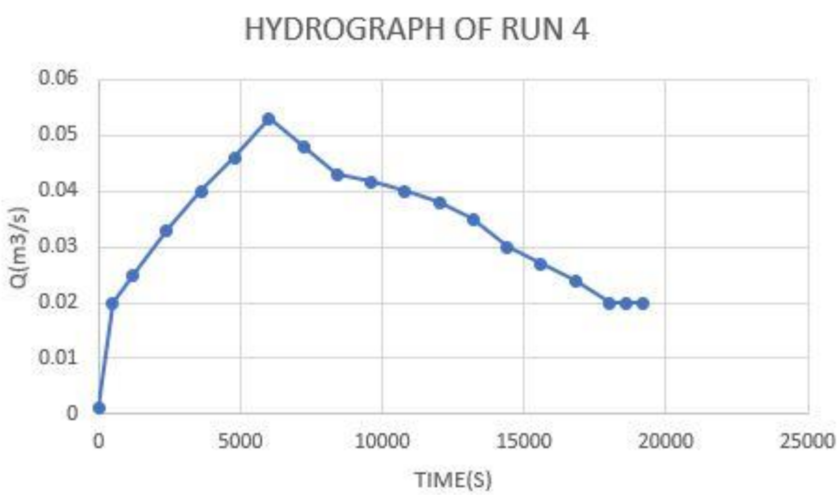
Laboratory data which will be used to authenticate the numerical model were collected by Yen *et al.* (1995). The five experiments were achieved in a laboratory channel bend having a central angle of 180◦, a radius of curvature along the central bend line of r_c = 4m, and channel width of B = 1m. The base flow was set at Q_o = 0.02 m^3/s, corresponding to a base flow depth of h_o = 5.44 cm, a mean velocity of u = 0.38 m/s and corresponding shear velocity of u_{*o} = 0.031 m/s. Reynolds number was R = $(uh_o)/\nu$ = 20, 672. Sediments were quantified by the initial median diameter of d_{50} = 1.0mm and their standard deviation of σ_o = 2.5. Initial bed slope was S_o = 0.002.

Transverse sediment sorting and bed topography were investigated. Five experiments were executed, each having the same initial sediment-size gradation but different inflow hydrographs.




HYDROGRAPH OF RUN 2
Q(m3/s)
time(s)


HYDROGRAPH OF RUN 3
Q(m3/s)
TIME(S)


HYDROGRAPH OF RUN 4
Q(m3/s)
TIME(S)

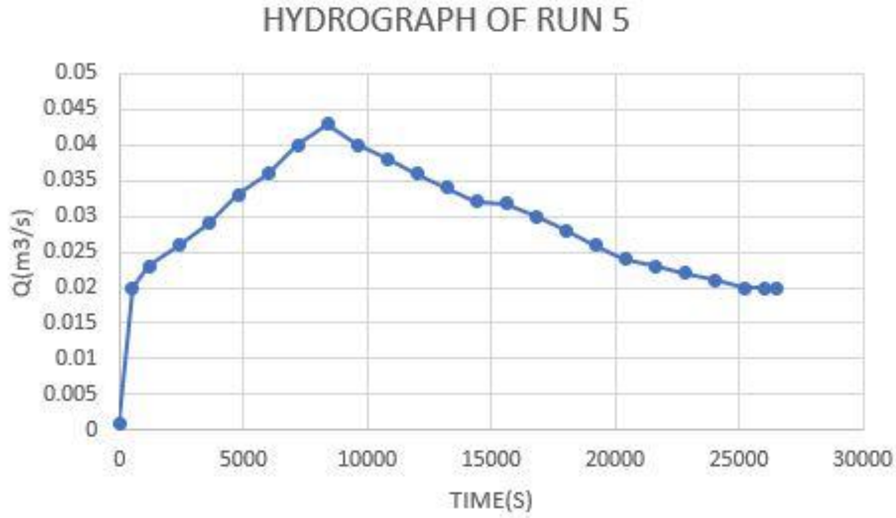


Figure 1.1 Hydrographs of all runs

At a number of bend sections, bed elevations were measured and bed surface sediments were sampled at the peak and at the end of a hydrograph in each run.

The results specify that bars always developed at the inner side of the river bend while scour was produced at the outer side of the river bend. As a result, lateral sorting processes occurred with the largest intensity around 90◦, directed by diameters larger than d_{50} at the outer and smaller than d_{50} at the inner sides of the river bend. The maximum deposition height was set up between 75◦ and 90◦, and the maximum scour depth take place between 165◦ and 180◦.

The measurements point out that the hydrograph characteristics had a noticeable effect on bed topography and transverse sediment sorting. According to Yen et al. (1995), the cases with a higher ramping rate of the hydrograph have greater deposition heights near the inner bank and larger scour depths near the outer bank. Furthermore, the sediment is finer near the inner portion of the river bend while sediment is coarser at the outer region of the river bend for a higher ramping rate.

1.3 THE PHENOMENON OF SCOURING AND DEPOSITION

Most natural rivers exhibit bends which are mildly curved but sometimes there are sharp curves as well due to these curves of the river the secondary currents are produced due to the development of strong centrifugal force. The secondary currents deposit sediments at point bars at the inner portion of the river bend and dig out pools at the outer portion of the river bend.

The deposition of sediment particles at point bars at the inner portion of the river bend is known as a deposition, while the dig out of pools at the outer portion of the river bend is known as scouring.

The sharp bend will create more strong secondary currents due to which scouring and deposition at the outer and inner side of the river bend will be more.

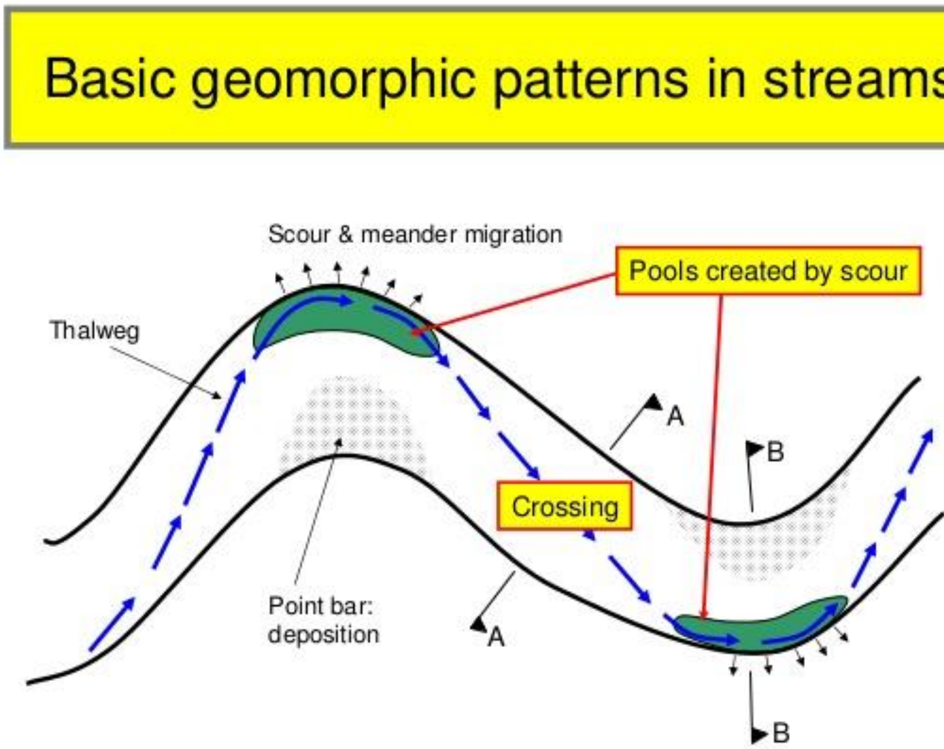


Figure 1.2 Scouring and Deposition

<Source: Internet>

1.4 RESEARCH OBJECTIVES

- To simulate the complex hydraulics, sediment transport, and morphological change processes occurring at a channel bend using a 2D model.
  (Normally, such a model cannot simulate secondary currents and a 3D model is required. However, 2D models incorporating the curvature transport factor, as proposed by Engelund (1974) are capable of reproducing the observed bed morphology.)
- Validate the model results using flume experiments.
- To perform sensitivity analysis.

1.5 SIGNIFICANCE OF THE STUDY

Bends are a common occurrence in natural rivers which are the main issue for water resource engineers and geotechnical engineers for designing purposes. To check the characteristics of bends in the laboratory is too much time-consuming and expensive, that's why we will check the 2D Basement model capability to reproduce the results the same as the experimental results. If the model reproduces the results then it will save user time and money.

We will also perform a sensitivity analysis to check which parameter is more sensitive.

1.6 THESIS LAYOUT

This thesis contains a total of four chapters. Introductory discussion including the definitions of different terminologies and introduction about this research discussed in the 1st Chapter. Different models and case studies were deliberated upon in the Literature review. In the 3rd Chapter, model simulation and parameters are discussed. Discussion on results is discussed in the 4th Chapter. Finally, in the last chapter 4 certain conclusions and recommendations are drawn.

CHAPTER 2

LITERATURE REVIEW

2.1 GENERAL

Flow shape of the river, changes regularly from straight to meandering form due to some phenomenon occurring naturally and also man-made. Even natural floods can change river behavior, the shape of the river, and also producing bends at most places. The importance of predicting river behavior at bends is more important since natural rivers not often run on straight paths in nature and most natural rivers have meandering forms. For rivers having a bend in its flow area, then flow patterns are very complex with specific characteristics at the bends. In general, factors influencing flow at a bend includes centrifugal force due to flow curvature and non-uniformity of vertical velocity profiles, the cross-sectional stress, and the pressure gradient in radial direction caused by the lateral slope of the water surface (Chow 1959). Synchronous effects of such factors create a flow called helical flow. The spatial distribution of bed material reflects the sediment sorting effects of flow in a river bend, coarse size materials are more abundant in the outer portion of a river bend while finer materials are more common inward over the bend point bar. (Parker & Andrews , 1985)

2.2 SECONDARY CURRENTS

The secondary currents are generated in planes perpendicular to the primary direction of motion. These currents form a helical motion in which water in the upper portion of the river bend is driven outward, whereas water near the bottom portion is driven inward in bend. When phase shift angle reduces then the river channel changes from straight to meandering form and then from meandering to braided form. This is because of resistance which secondary currents causes on the primary flow which increases, with a decrease in phase shift angle and hence triggering more deposition which leads to braiding.

Secondary currents are much focused on the riverbanks and therefore producing more erosion on the concave bank and more deposition on the convex bank of a river bend at a small phase shift angle. Flow behavior is a function of the magnitude of secondary currents. (Njenga, Kioko, & Wanjiru, 2013).

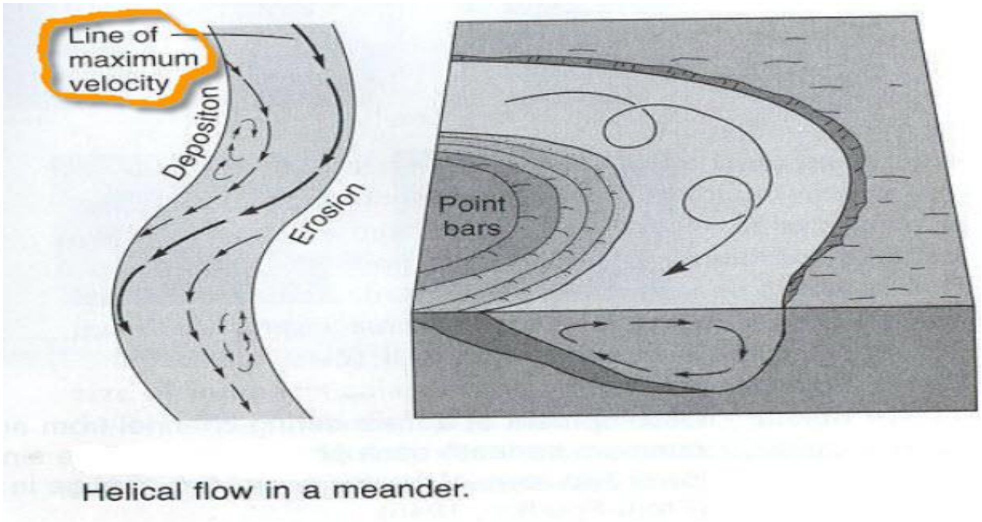


Figure 2.1 Phenomenon of scouring and deposition

<Source: Internet>

Secondary currents are originated from near the bottom region of the river bend, relatively than the main flow region. If a little disruption is created near the bed flow region then it may create secondary currents, which will be resulted in the form of turbulence in the main flow region. The maximum secondary flow (secondary flow from the bottom of river bend) is always from the lower to higher velocity zone. The location where the near bed velocity changes sharply, are the main source where the largest secondary flow is detected. (Yang, Tan, & Wang , 2012)

2.3 EFFECTS OF BEND IN 2D MODELLING

Bend has more effects on the flow pattern, it can change the whole structure of flow in a channel and also can change the topography of a channel by flowing through it. There are two types of bend which are listed below:

i) Sharp bend
ii) Mild bend

The ratio of radius of curvature to channel width (Rc /b), is a factor that affects flow pattern, and on the basis of it the bend type is identified. According to Leschziner and Rodi (1979), if $Rc/b < 3$, the bend is sharp. Or else, the bend is mild. With growing Rc/b value, the secondary current power drops along the bend. In sharp bends, the longitudinal flow power is so high that it succeeds over the secondary current, and the maximum velocity occurs near the inner channel wall along the bend, (DeMarchis and Napoli, 2006; Naji et al., 2010).

Velocity pattern in river bends are fixed. The maximum velocity occurs in a river bend near the internal wall, and minimum velocity near the external wall. After the bend, the pattern is reversed. Bend also affects the water surface slope before and after the bend. Ehsan, Ali, and Seyed (2009).

2.4 RIVERBED DEFORMATION AND CHANNEL MIGRATION

The water flow which carries sediments in it is the main reason for the change of river bed and channel size which occurs in a river channel. When the channel bed and size is deformed then it also affects the flow pattern. Channel bend migration is directly affected by lateral sediment transport and this lateral sediment transport is occurred in bends due to the secondary flows, so the main reason behind the channel migration can also be secondary flows. The channel size in lateral direction of a channel changes due to the effect of secondary flow, so if the effect of secondary flow in modelling is left behind then it will be a big mistake in terms of channel size in lateral direction. (SUN, LIN, & KUANG, 2015).

2.5 SECONDARY CURRENTS AFFECTS SEDIMENT TRANSPORT

In the presence of time-averaged wall-normal velocity, the mobility of some sediment particles is relatively high in the portion with the upward flow, while its mobility is relatively low in the zone of downward flow. This imbalance is the main cause of the formation of the sand ridge in the river. This shows that upward flow promotes sediment transport while downward flow reduces sediment transport. (Yang, Tan, & Wang , 2012)

It is concluded that bed material when the bed is deposited becomes finer, the bed material composition becomes coarser when the bed material is scoured. (Jing, et al., 2013)

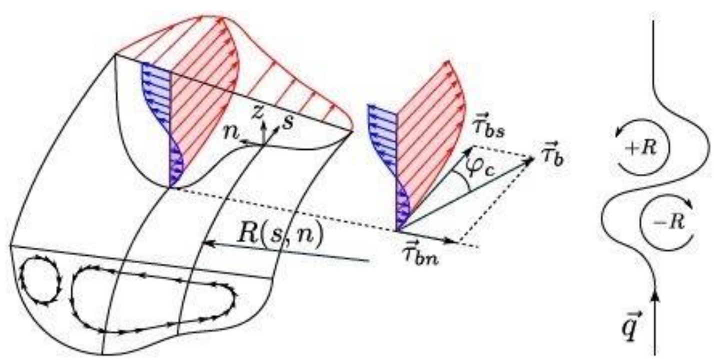
2.6 CAUSES OF EROSION AND DEPOSITION

Scouring and deposition occur normally in a natural river bend having erosion on the outer part of the bend known as a concave bank, while deposition at the inner part of the bank is known as a convex bank. The main cause of scouring and deposition is secondary currents which form a helical motion in water resulting in the phenomenon of scouring and deposition. Due to 3D spiral motion, the bedload direction tends to point towards the inner side of the curve, while the flow direction point towards the outer side. Due to this spiral motion effect, the outer side of the curve is eroded and the inner side of the curve is filled with point bars. (BASEMENT REFERENCE MANUAL).

2.7 ROLE OF CURVATURE EFFECT IN 2D MODELLING

The role of the curvature effect is very important in a 2D model, without introducing a curvature effect in the model it will give wrong results. Most of the models can produce a curvature effect while simulating some curvature type problems through it. Curvature in rivers may cause the deviation of bedload direction from the depth-averaged flow direction. The curvature effect is taken into account according to an approach proposed by (Engelund,1974), where the deviation *angle* $\breve{\alpha}_c$ of the bottom shear stress f_b (positive counterclockwise and vice versa) from the main flow direction is determined as

$$\tan \breve{\alpha}_c = |f_{bn}| / |f_{bs}| = -N_* h/R \text{………………} (1)$$



Effect of spiral motion in river bend on bed shear stress $\vec{\tau}_b$ with deviation angle from main flow direction φ_c (Vonwiller, 2017)

Figure 2.2 Effect of spiral motion in a river bend

<Source: Basement Reference Manual>

Where f_{bn} and f_{bs} are the bed shear stress normal to and in the flow direction respectively, h denotes the water depth and, N is a curvature factor, and R denotes the radius of the river bend (positive for curvature in a counterclockwise direction and vice versa).

Note that curvature factor N mainly depends on bed roughness. Therefore $N \approx 7$ for natural streams (Engelund,1974), and values up $N_* \approx 11$ for laboratory channels (Rozovskii,1961). (BASEMENT REFERENCE MANUAL).

2.8 ROLE OF SECONDARY FLOW EFFECT IN 2D MODELLING

Most of the models can't predict the secondary flow effect in the modeling of flow in a channel bend, it will give unsatisfied results in bend problems because most of these models consider the bend channel mesh as a straight channel mesh and don't apply the mechanism of secondary flow effect in the simulation. So that's why most of the simulated results are quite different from the experimental results. That's why secondary flow effect must be introduced into 2D model to get the required behavior of the bend like deposition at the inner part of the river bend and scouring at outer part of the river bend.

The effect of secondary flow also transports sediments in the lateral direction which results into building up pools and bars at the inner portion of the river bend, which in turn affect the water flow. This further contributes to sediment transport and modifies the bed topography. (Engelund, 1974).

2.9 ROLE OF FRICTION FORMULAS

There are different friction formulas available for the simulation and, the selection of a specific friction formula depends on the condition of bed, material size and distribution. Many friction formulas are used in flow simulations. The most used and reliable formula is the Manning formula which is used extensively. The Manning friction coefficient is represented by '*n*'.

$$V=1/n\ (R_h^{2/3} S^{1/2}) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ (2)$$

Eq (2) is used for the estimation of velocity in open channel flow, here are some terms used in the manning formula which are described here: 'V' is cross-sectional average velocity and its unit is (m/s), 'n' is manning coefficient and its unit is ($s/m^{1/3}$), 'R_h' is hydraulic radius and its unit is (m), 'S' is the slope of hydraulic grade line and it is dimensionless.

Hydraulic radius is defined as the ratio of the cross-sectional area of the flow to its wetted perimeter. $R_h=A/P$.

Manning coefficient 'n' value for the vegetation area will be in between the values of 0.002-0.100, it depends on the amount of vegetation if vegetation is in small amount then the coefficient value will be nearer to value of 0.002, and if vegetation is in large amount then the coefficient value will be nearer to the value of 0.100.

Manning coefficient '*n*' value for the straight channels depends on the bed material and size of the bed material, for example the bed material is sand and its bed material size varies from 0.2mm to 1mm then the '*n*' value will be in between 0.012 to 0.026.

Manning coefficient '*n*' value for curved channels is increased to 30 percent where flow is confined within a stream channel.

By putting the wrong value of friction coefficient in simulation the whole result can be wrong i-e, the computed result will not be like the experimental result. So the choice of friction value depends on the condition and it will be time-consuming for putting different values in the model to check the accuracy of results, so accurate friction value saves time and also the results will be matching with experimental results. (JING1, Chun, GUO2, Li- ZHU3, Yi-tian ,2014)

2.10 ROLE OF SEDIMENT TRANSPORT FORMULAS

At a bend, deposition occurs at the inside of the bend while erosion takes place at the outside of the bend. While modeling sediment transport problems there are many transport formulas present that will transport sediment in any type of trajectory of rivers in models.

Meyer-Peter & Muller formula is used for bedload sediment transport and its equation is given below:

$$qBg = \alpha\ [(s-1)\ gd^3g\ ]^{1/2}\ (\theta_q g - \theta_{cr},\ g)^m \text{............ (3)}$$

Eq (3) is used for bedload transport and its various terms are defined below:

α represents the bedload factor (originally $\alpha=8$), the bedload exponent (m=1.5), qBg is the specific bedload transport rate of grain class g, θ g is the effective dimensionless shear stress for grain class g, d_g is the diameter of grain class g, $s=\rho_s/\rho$ and g stands for the gravitational acceleration. MPM formula is used for single grain simulation.

According to (Iqbal, Ghumman, Haider, Hashmi, & Khan, 2018) "The Engelund and Hansen formula for sediment transport is accurate for performance and total eroded volume of sediments with a bedload factor of 0.5".

For a general range of conditions, the formula proposed by Meyer-Peter and Muller (1948) with factor 8 being replaced by 12 is recommended. (Abderrezzak & Paquier, 2011).

2.11 SCOURING AND DEPOSITION IN 90º BENDS

In natural rivers, generally scouring occurs near the outer bank of the river bend while deposition occurs near the inner bank of the river bend. A 90^0 experimental bend concludes that the maximum scouring depth was found around 30^0 sections, while the maximum deposition depth in between 20^0 to 60^0 in a horizontal 90^0 bend. (Biswas & Barbhuiya, 2015).

2.12 SEDIMENT SORTING IN BEND CHANNELS

In channel bends sediment is sorted in the main flow region due to the presence of sediment transport flowing through it. Sediment sorting is the main source of channel migration and if the sediment flow is high then channel migration will be more from its main flow path.

For the development of characteristics sorting patterns, in addition to channel curvature sufficient sediment supply is necessary. Width to depth ratio and sediment supply control specific bend channel morphology and sorting patterns. (Andrews, & Parker 1985).

2.13 BEDLOAD TRANSPORT IN CURVED CHANNELS

Bedload transport is the transport of sediments (suspended sediments and bedload sediments) in the channel from the upstream side to the downstream side of a channel river. In straight channels, bedload can be simulated by a 2D model because it does not involve complex physical processes while simulating bedload transport for a bend is more difficult because it involves many physical processes which cannot be neglected.

For the prediction of bedload transport in a curved channel by the 2D model at least three forces should be considered, which includes:

1) The lateral component of the gravitational force on the sloping channel bed.
2) The bed-shear stress in the longitudinal direction.
3) The lateral bed-shear stress due to curvature-induced secondary flow in the transverse direction. (Jennifer & Pierre, 2010)

CHAPTER 3

MODEL SIMULATIONS

3.1 GENERAL

A simulation may be defined as an approximate imitation of the operation of a process or system, that represents its operation over time. It is the process of creating and analyzing a digital prototype of a physical model to predict its performance in the real world.

The purpose of the simulation is to predict the future behavior of a system and to determine what you can do to influence that future behavior.

3.2 MODEL SETUP

The model setup which is discussed in this 3rd chapter required some parameter values based on which we will simulate our model and get our required results. We have simulated our model for five runs each having different hydrographs and for different simulation run times. Each hydrograph has a different peak and total time.

The model is run for different discharges, however the total run time and the rest of the parameters were kept the same for each run. Normally there are different parameters for simulating bend-type problems in the BASEMENT model which were adjusted to obtain a better convergence between the model and experimental results.

Generally, the basement model requires various types of parameters for simulation purpose, which includes hydraulics, morphological, geometrical and output data based on that basement model runs and give us the simulated results

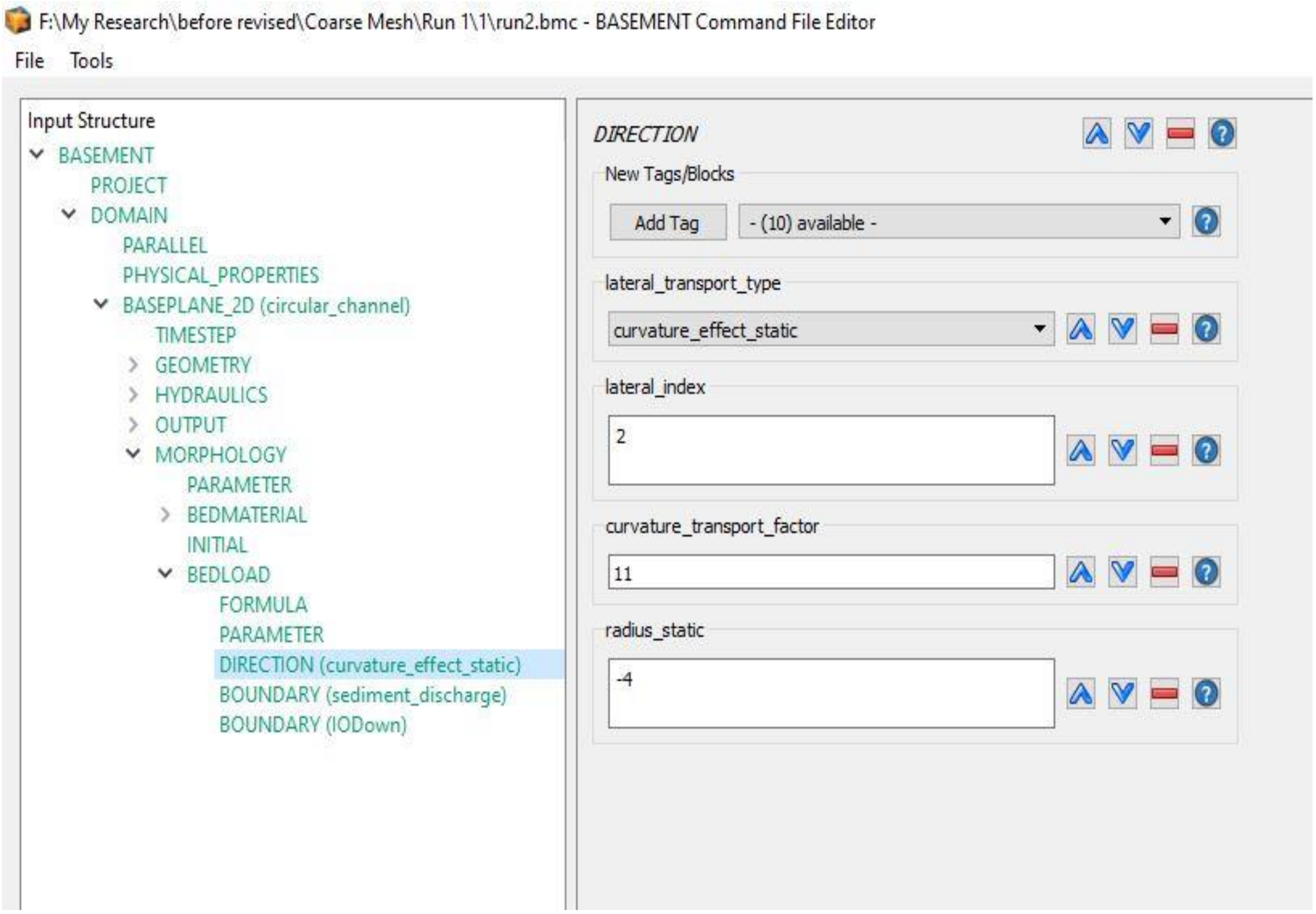


Figure 3.1 Direction parameters

After inputting all the parameters discussed in the preceding chapters in the model, the simulation was run on the BASE PLANE and the output option given was SMS 10 format. The output can be obtained in the form of change in bed elevation *(deltaz)*, velocity, water surface elevation, and depth. The *deltaz* output obtained will be compared with the experimental *deltaz* data.

There are five different hydrographs based on which simulated our model and obtained five different types of results and compare it with the experimental results of these five hydrographs and will draw our conclusion.

Below are shown the five hydrographs used in the experiments:

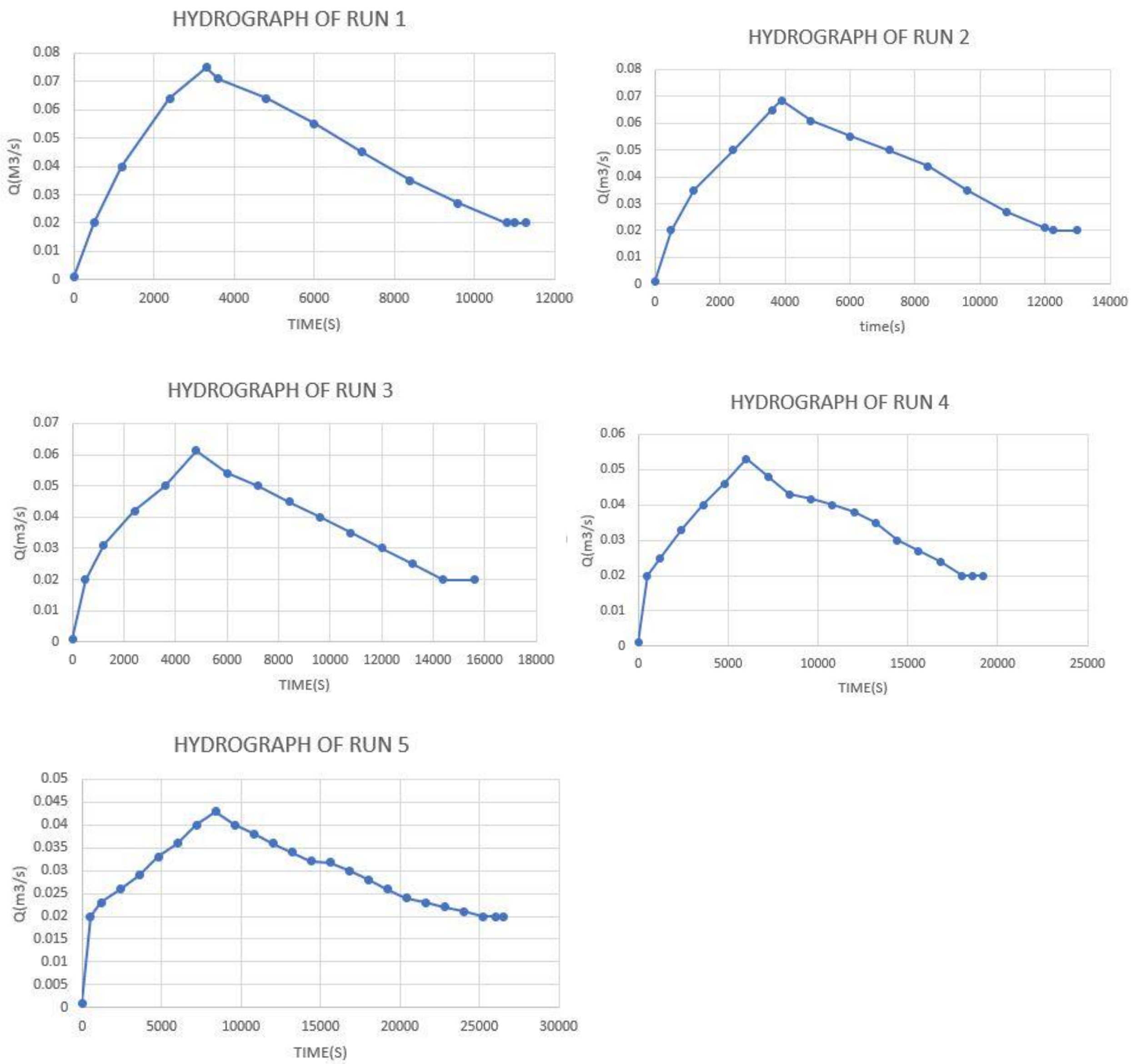


Figure 3.2 Five different hydrographs

By putting all these hydrographs in a text format in the model, we will have to put different parameters for different hydrographs simulations. In every simulation, the total run time will be different for different hydrograph simulation.

3.3 2D BASEMENT MODEL PARAMETERS

There are different parameters required in the basement model, first of all, we will have to put a geometry prototype in the format of 2dm and then the inflow and outflow nodes ids. Then we have

to put the time-step value of different hydrographs and a CFL value. Below are the parameter values which I have used in my simulation.

PARAMETERS			
S. No	**Type**	**Values**	**Units**
1	Total Run Time	10800	s
2	CFL	0.3	
	HYDRAULICS		
3	Initial	dry	
4	Inflow boundary	hydrograph	
5	Outflow boundary	HQ RELATION	
6	Friction	Stickler (75)	
7	Turbulence model	Algebraic	
	MORPHOLOGY		
8	Porosity	40	%
9	Density	2650	Kg/m^3
	BEDMATERIAL		

10	Diameter	1	mm
	SOIL ASSIGNMENT		
11	Index	1 2	
12	Volume fraction	100	%
13	Initial	Initial-mesh	
	BEDLOAD		
14	Formula	Engulendhansen	
	DIRECTION		
15	Lateral transport type	curvature effect static	
16	Lateral index	2	
17	Curvature transport factor	11	
18	Radius static	-4	
19	Inflow boundary	Sediment discharge	
20	Outflow boundary	IO down	
	OUTPUT		
21	Console time step	300	s
22	Type	node centered	
23	Output timestep	700	s
24	Values	DEPTH, WSE, VELOCITY, DELTAZ	
25	Format	SMS	

By putting all these parameters in the model and then simulating the model for different total run time gives us the results in SMS format. We will visualize our result in SMS software which will give us the result in the form of contour lines and will represent the values on every contour line.

3.4 CURVATURE TRANSPORT FACTOR:

Normally, a 2D model cannot reproduce a bend because it cannot simulate secondary currents. However, due to the Engelund approach, a 2D model can be modified to depict the physically observed phenomenon at a channel bend.

Engelund (1974) proposed an approach in which the curvature effect is taken into account, where the deviation angle φ_b from the main flow is determined as

$$tan\ \varphi_b = N \text{ x } h/R \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (4)$$

where N denotes a curvature factor, h denotes water depth, and R denotes the radius of the river bend. The curvature factor mainly depends on bed roughness. Therefore, $N = 7$ for natural streams (Engelund, 1974), and values up $N = 11$ for laboratory channels (Rozovskii, 1957).

Due to the above approach, the model can simulate a bend deposition-erosion pattern.

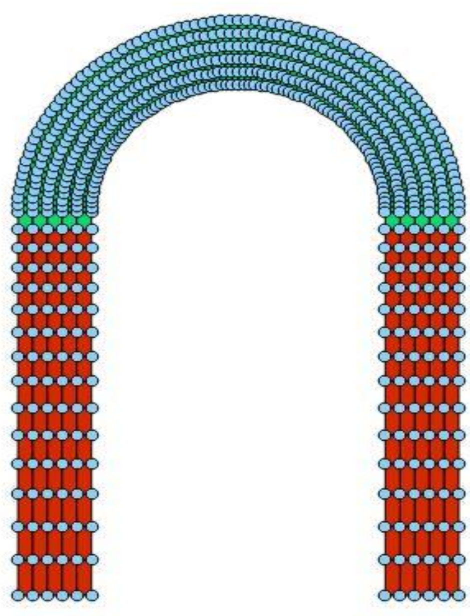
CHAPTER 4

RESULTS OF 2D SIMULATIONS

4.1 MODEL RESULTS

The results of the BASEMENT model can be seen in SMS software which is user friendly in the form of contours having erosion in the outer bend and deposition on the inner bend. The model has given us result in the form of contours which will be visualized in SMS software. The numerical model results values will be divided by h_o=0.056m which will give us the proper values of scouring and deposition and then those values will be compared with the values of experimental results. Our results are quite matching and are in an acceptable range. Here are the comparisons of the BASEMENT model results with the existing experimental results given below.

4.2 MESH



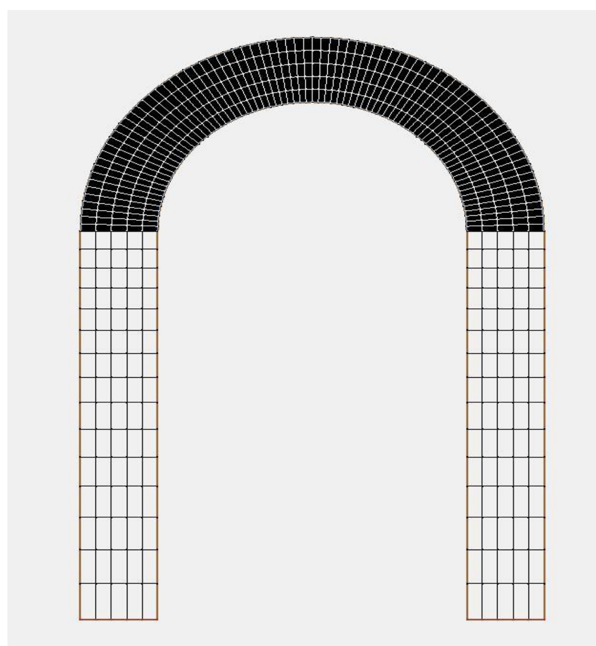
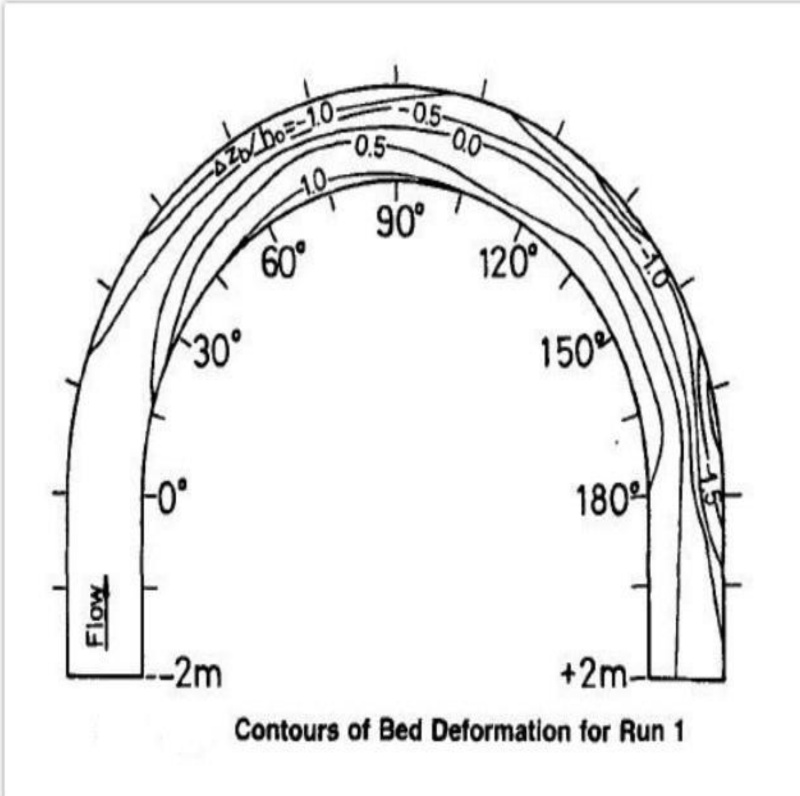


Fig 4.1(a): 2D mesh having elements and nodes **Fig 4.1(b): 2D mesh having radial elements**

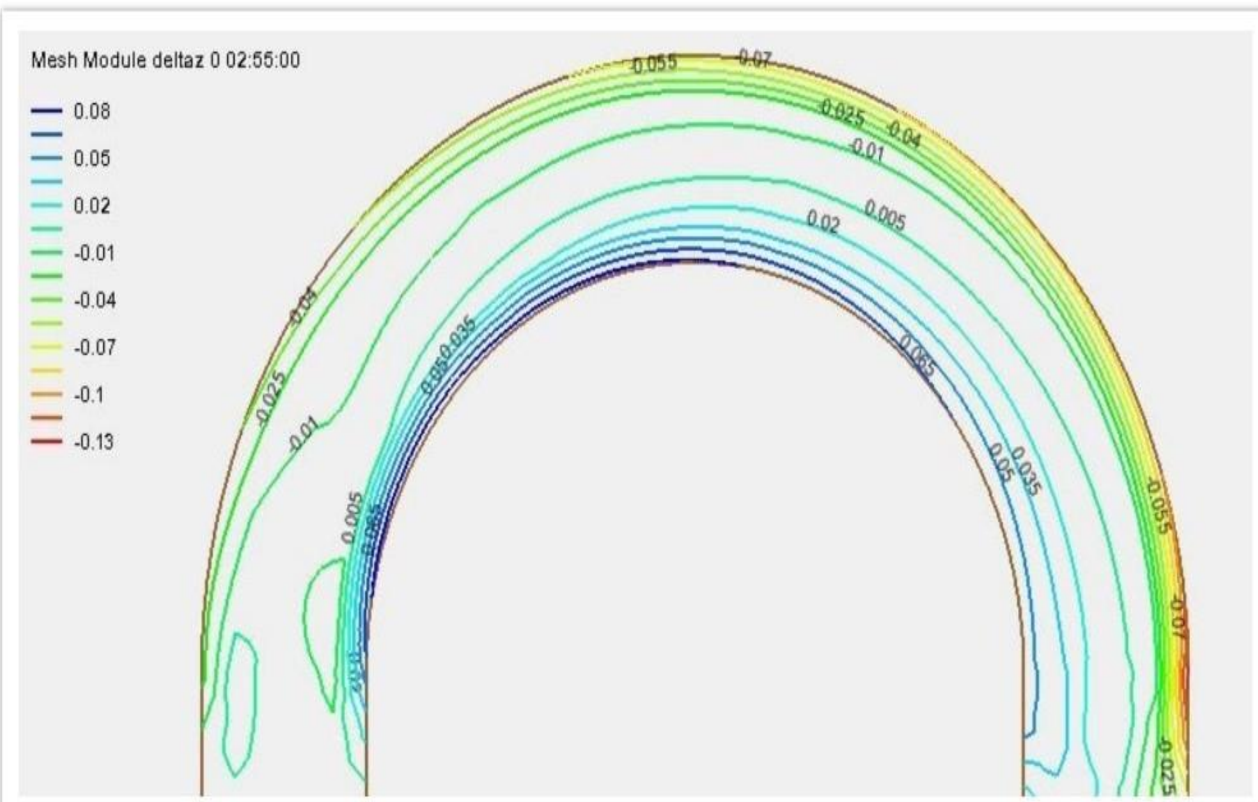
The mesh which is used in this analysis is quadrilateral in nature and contains 550 elements and 666 nodes. The element in the straight portion of the mesh has the area of $0.98ft^2$, its d_x length is 0.2ft and d_y is 0.282ft. The elements of the radial portion in the mesh have different areas and also lengths in both directions.

There are 5 elements in lateral direction, while 15 elements are there in longitudinal direction in the straight portion of the mesh. There are 5 elements in the lateral direction while 82 elements are in the longitudinal direction in the radial portion of the mesh.

a) *Yen et.al (1995)*



Contours of Bed Deformation for Run 1



b)

Figure 4.2 Bed deformation contours for run 1. (a) Experimental $\left(\frac{\Delta z}{h_o}\right)$ (b) Numerical (m). +/-, deposition/erosion

Table 4.1 RESULT COMPARISON FOR RUN 1

ANGLES	EXPERIMENTAL RESULTS $\left(\frac{\Delta z}{h_o}\right)$		NUMERICAL RESULTS(m)	
	DEPOSITION	EROSION	DEPOSITION	EROSION
60°-90°	1.0	-1.0	1.16	-0.98
120°-150°	0.5	-1.0	0.625	-0.98
150°-180°	0.5	-1.5	0.625	-1.25

The unit for experimental results is dimensionless, because in the experimental results $\Delta Z_b/h_o$ is dimensionless. ΔZ_b : change in bed elevation (+/-, deposition/erosion), h_o , uniform flow depth.

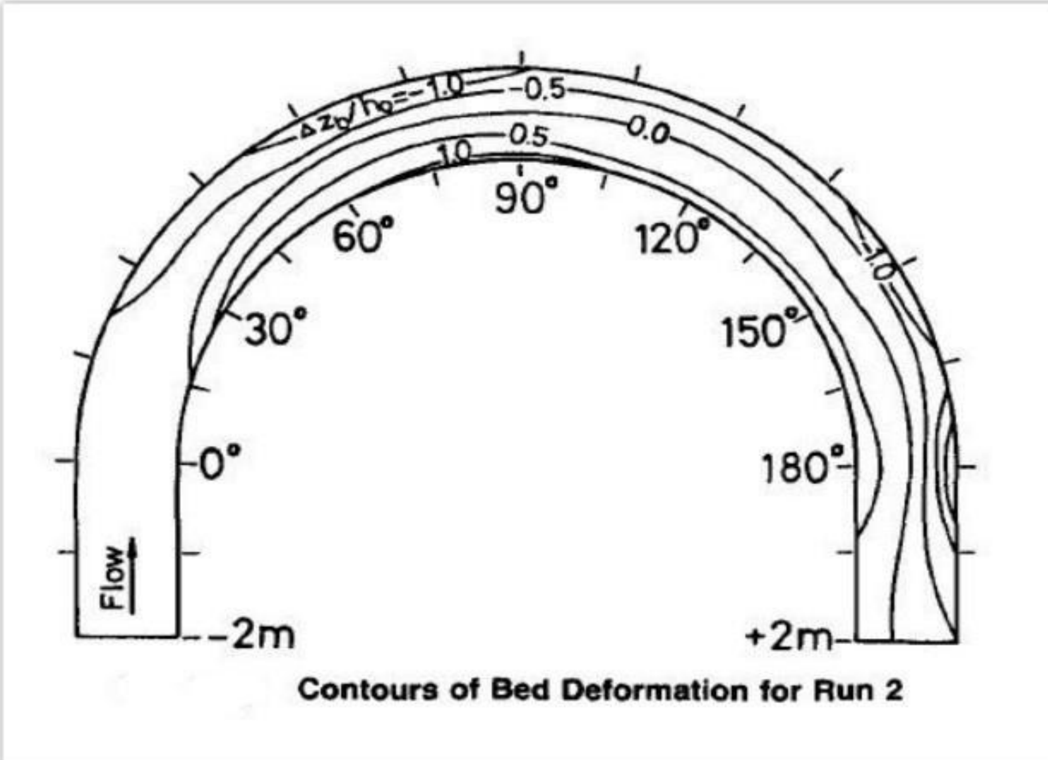
The unit of SMS software is meter(m) and that of experimental results are dimensionless. The comparison is only about general form. The comparison in the table is dimensionless because we have divided the erosion/ deposition values and then divided it by the value of h_o.

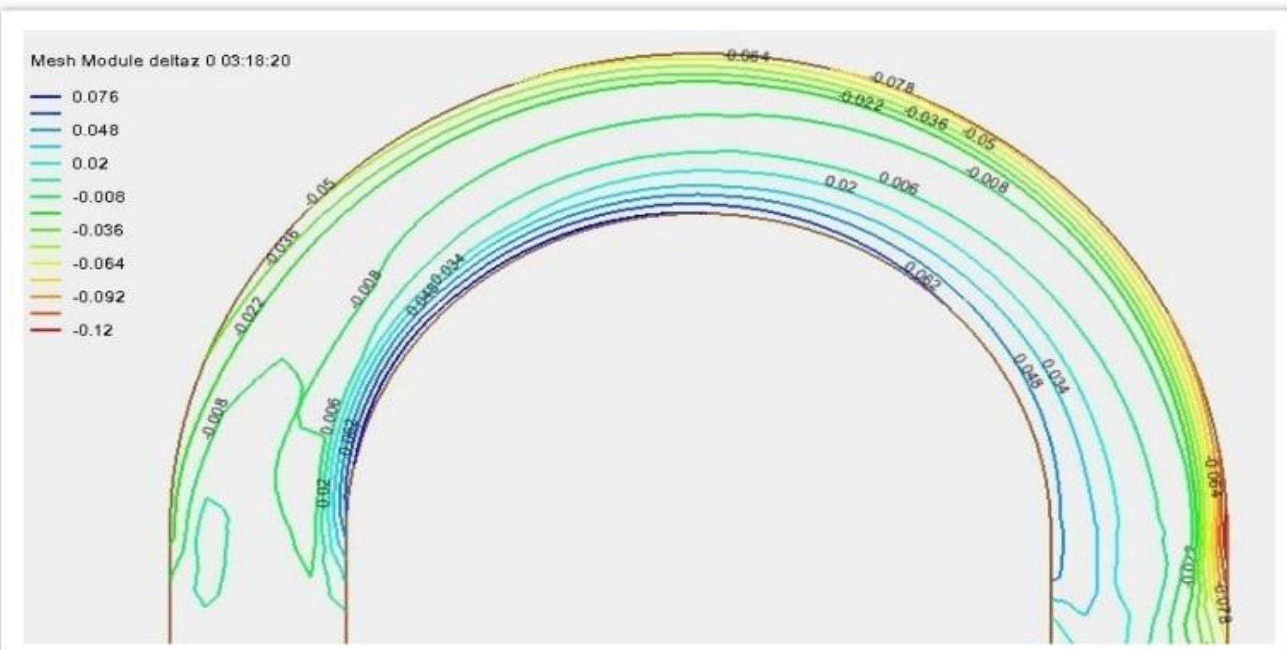
The 2D model result is generated in various formats e.g. ASCII, SMS and paraview, etc. However we have opted for the SMS format due to availability and ease of handling of SMS graphical tool for showing contours of bed change.

The table 4.1 shows us the values of different areas of deposition and scouring, the experimental values are given in the upper image while the numerical values are obtained from numerical model results which are further divided by $h_o=0.054m$ to obtain the values of numerical results present in the left side of table 1.

As you can see in the table the numerical model values are very nearer to the experimental values which describes the best accuracy of the model. The model better describes scouring phenomena and values are so close to each other while deposition is also better described by the model but there is a little difference in values of the experimental and numerical model.

a) *Yen et.al (1995)*





b)

Figure 4.3 Bed deformation contours for run 2. (a) Experimental $\left(\frac{\Delta z}{h_o}\right)$ (b) Numerical (m). +/-, deposition/erosion

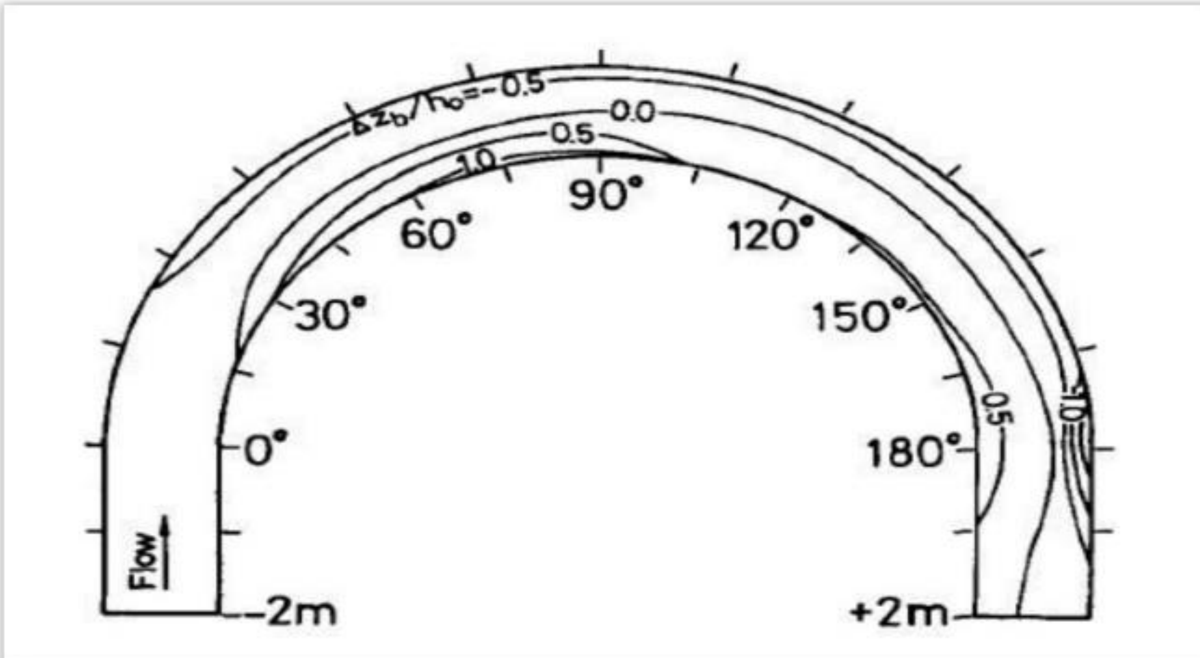
Table 4.2 RESULT COMPARISON FOR RUN 2

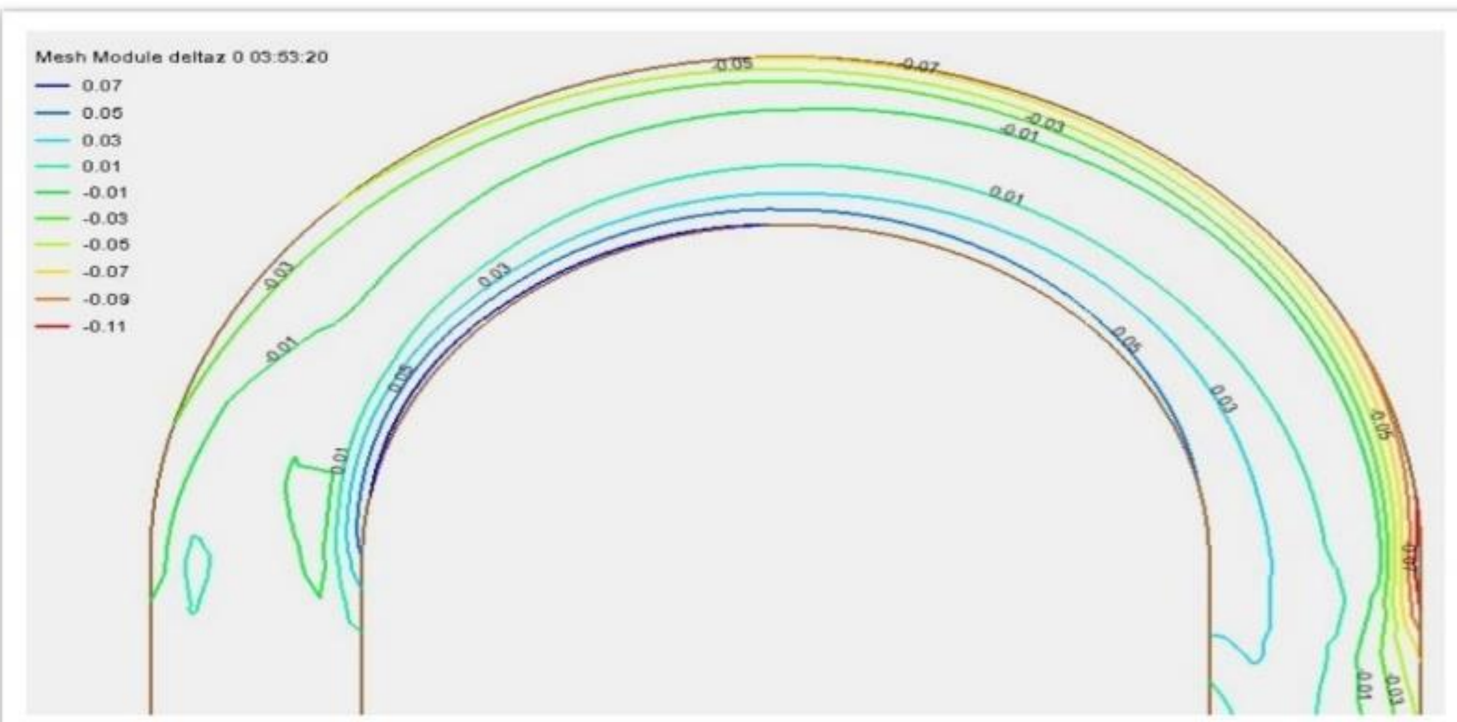
ANGLES	EXPERIMENTAL RESULTS $\left(\frac{\Delta z}{h_o}\right)$		NUMERICAL RESULTS(m)	
	DEPOSITION	EROSION	DEPOSITION	EROSION
60^o-90^o	1.0	-1.0	1.10	-0.89
120^o-150^o	0.5	-1.0	0.607	1.05
150^o-180^o	0.5	-1.0	0.60	1.14

Here is the second comparison of our results is placed in the upper table which shows quite good results of the model. In some areas, the results are quite nearer to each other.

The model reproduced deposition and scouring values like the experimental values which have been done in a laboratory. Most of the values of scouring and deposition resemble the values of experimental results, but little overestimation is seen in the values which is not a worrying condition for the accuracy and reliability of the model.

a) *Yen et.al (1995)*





b)

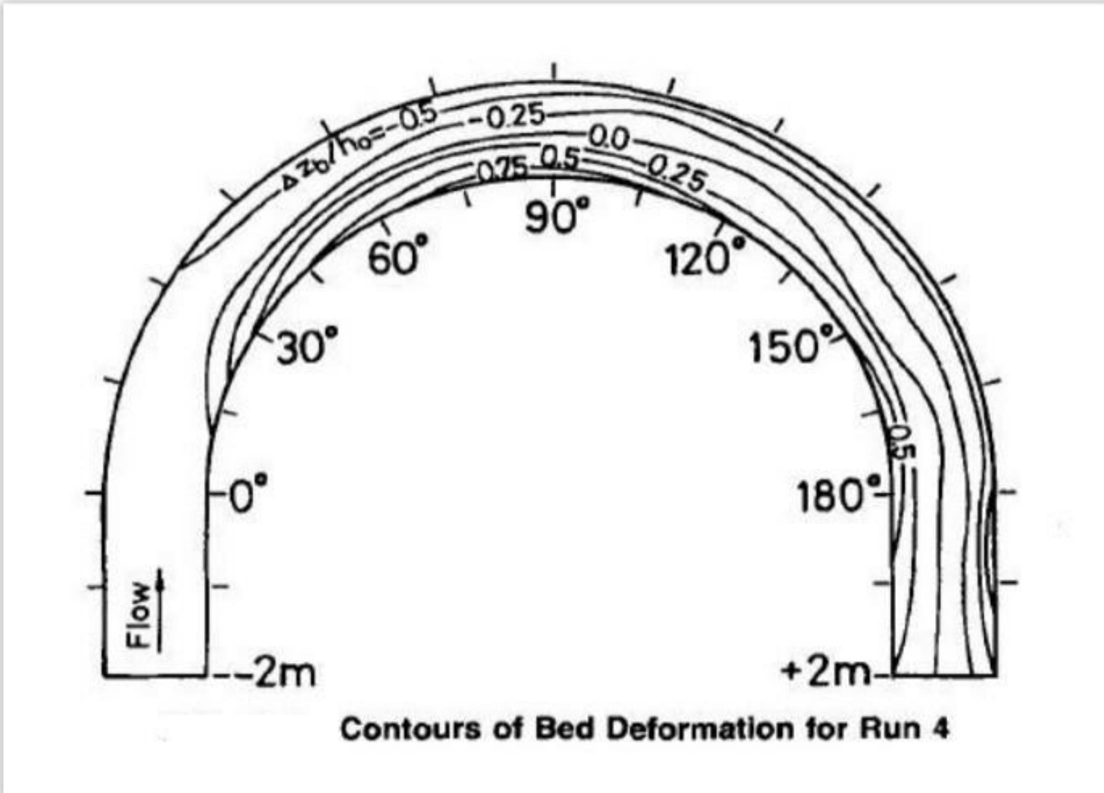
Figure 4.4 Bed deformation contours for run 3. (a) Experimental $\left(\frac{\Delta z}{h_o}\right)$ (b) Numerical (m). +/-, deposition/erosion

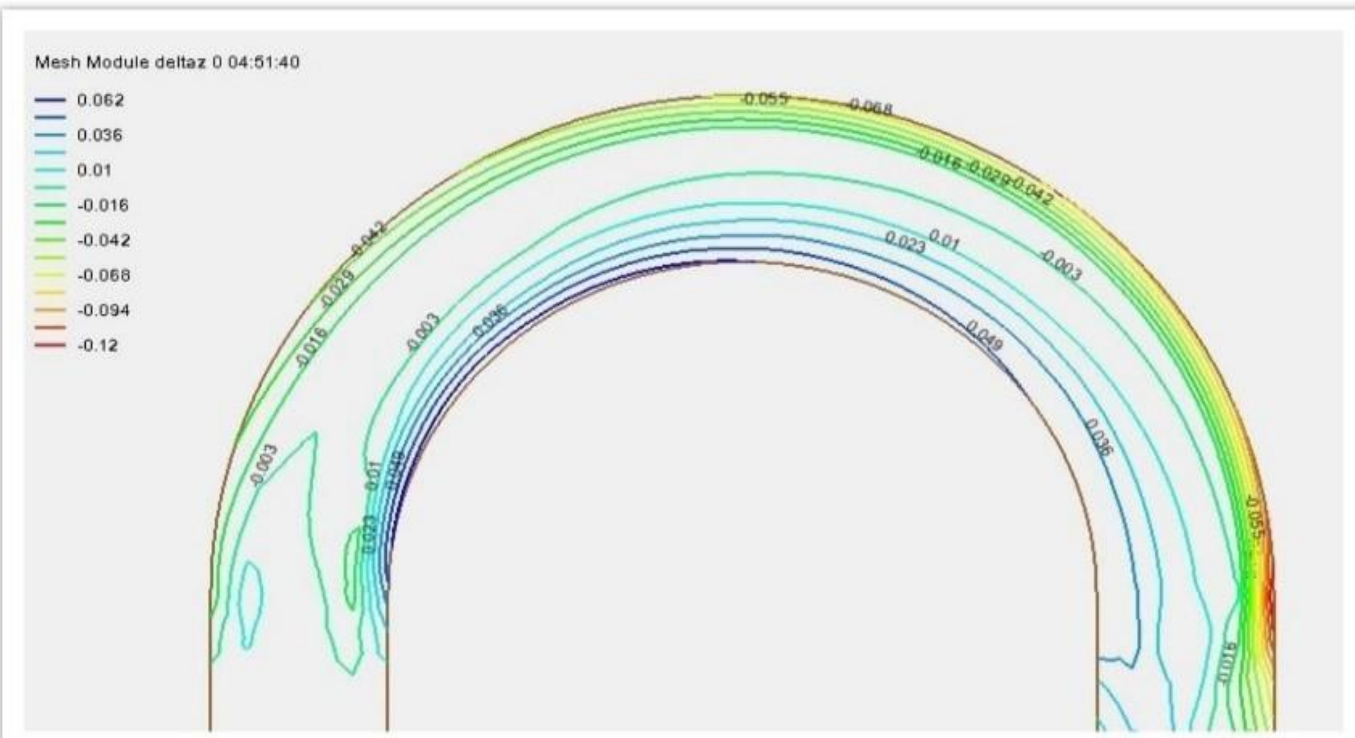
Table 4.3 RESULT COMPARISON FOR RUN 3

ANGLES	EXPERIMENTAL RESULTS $\left(\frac{\Delta z}{h_o}\right)$		NUMERICAL RESULTS(m)	
	DEPOSITION	EROSION	DEPOSITION	EROSION
60^o-90^o	1.0	-0.5	0.95	-0.54
120^o-150^o	0.5	-0.5	0.89	-0.71
150^o-180^o	0.5	-1.0	0.53	-0.89

In run 3 the best results of the model can be seen and the most accurate is found in this comparison. All the values of the experimental and numerical models are quite similar and most near to each other. But there is little overestimation occurred in the deposition and scouring in 120^o-150^o, but in the end, the result and accuracy of the model are at the top.

a) *Yen et.al (1995)*





b)

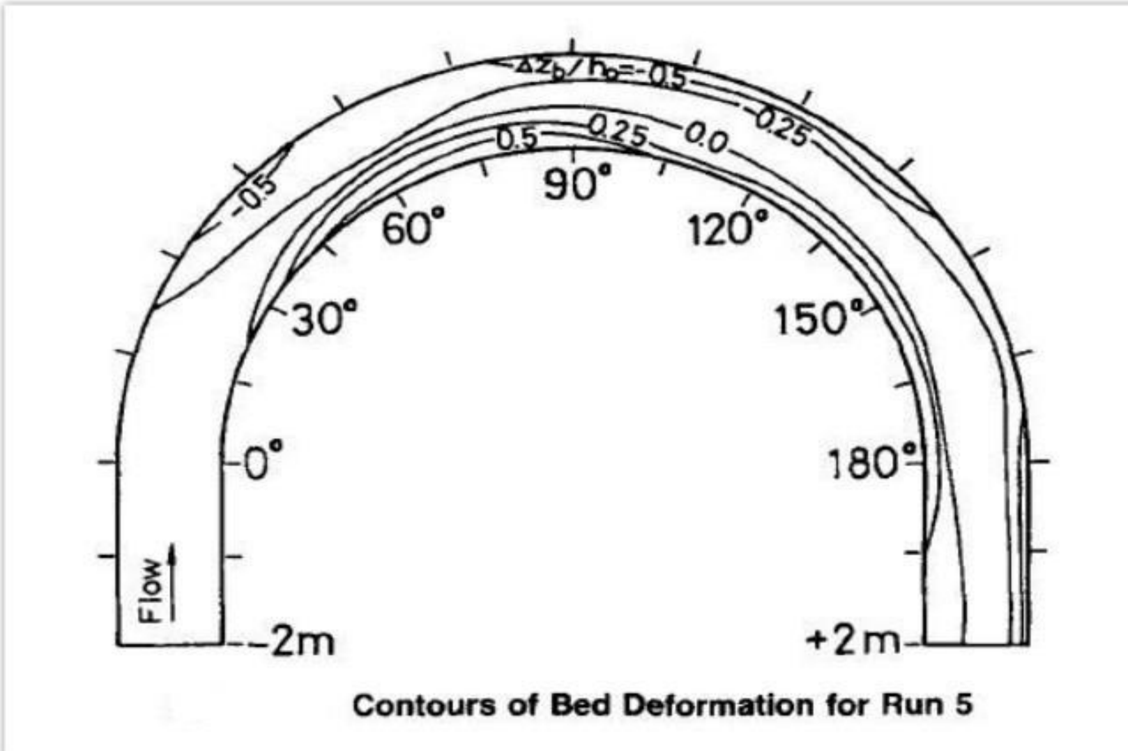
Figure 4.5 Bed deformation contours for run 4. (a) Experimental $\left(\frac{\Delta z}{h_o}\right)$ (b) Numerical (m). +/-, deposition/erosion

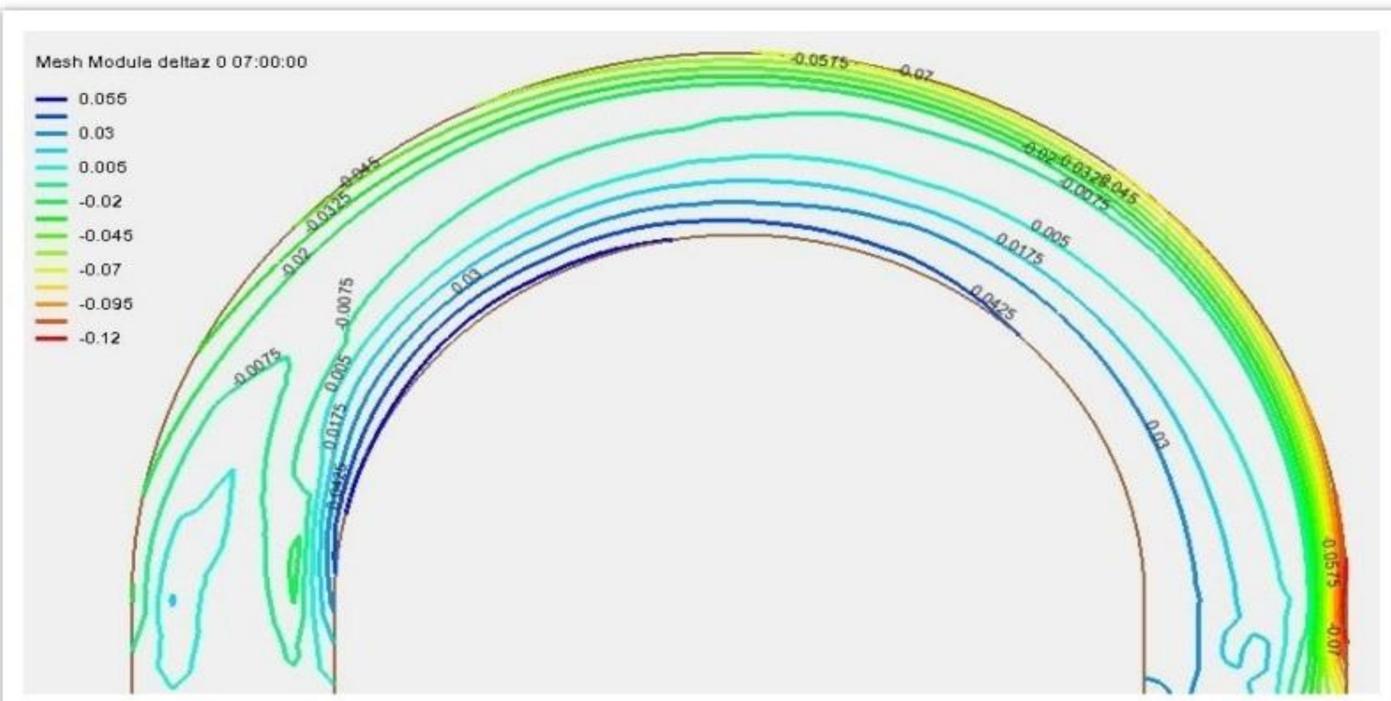
Table 4.4 RESULT COMPARISON FOR RUN 4

ANGLES	EXPERIMENTAL RESULTS $\left(\frac{\Delta z}{h_o}\right)$		NUMERICAL RESULTS(m)	
	DEPOSITION	EROSION	DEPOSITION	EROSION
60^o-90^o	0.75	-0.5	0.875	-0.55
120^o-150^o	0.25	-0.5	0.64	-0.75
150^o-180^o	0.5	-0.5	0.64	-0.98

The overestimation of deposition and scouring can be seen in this run 4 comparison, there is a little bit of high overestimation as compared to other runs in the above pages. The most overestimation occurred in the angle of 120^o-150^o of deposition and 150^o-180^o of scouring. Except for these values of overestimation, the overall comparison of results is satisfactory.

a) *Yen et.al (1995)*





b)

Figure 4.6 Bed deformation contours for run 5. (a) Experimental $\left(\frac{\Delta z}{h_o}\right)$ (b) Numerical (m). +/-, deposition/erosion

Table 4.5 RESULT COMPARISON FOR RUN 3

ANGLES	EXPERIMENTAL RESULTS $\left(\frac{\Delta z}{h_o}\right)$		NUMERICAL RESULTS(m)	
	DEPOSITION	EROSION	DEPOSITION	EROSION
30^o-60^o	0.5	-0.5	0.75	-0.58
60^o-90^o	0.5	-0.25	0.65	-0.57
120^o-150^o	0.25	-0.5	0.60	-0.80
150^o-180^o	0.25	-0.25	0.53	-1.01

As we move forward the results are coming quite worrying and are not matching to values of experimental results. This run model reproduced a large overestimation of values as compared to the last comparisons. The values of deposition and scouring in the angles (120^o-150^o and 150^o-180^o) are quite high from the experimental values, in this run model showed less accuracy as compared to the other runs.

4.3 SENSITIVITY ANALYSIS

"Sensitivity analysis is the study of how the uncertainty in the output of a mathematical model or system can be divided and allocated to different sources of uncertainty in its inputs".

"Sensitivity analysis is used to understand the effect of a set of independent variables on some dependent variable under certain specific conditions".

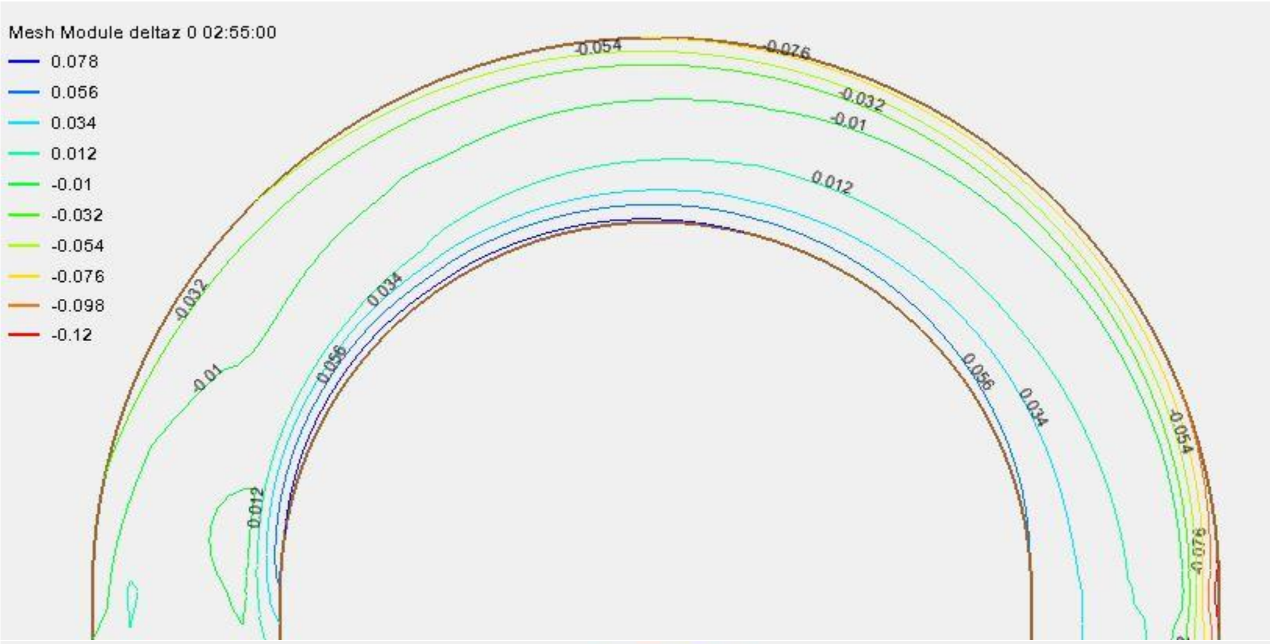
We will check the sensitivity analysis of our model with different parameters and will know that what parameter is more sensitive and most affect the results.

It will be based on three different parameters

1) CFL value

2) Friction value

3) Sediment Transport Formula



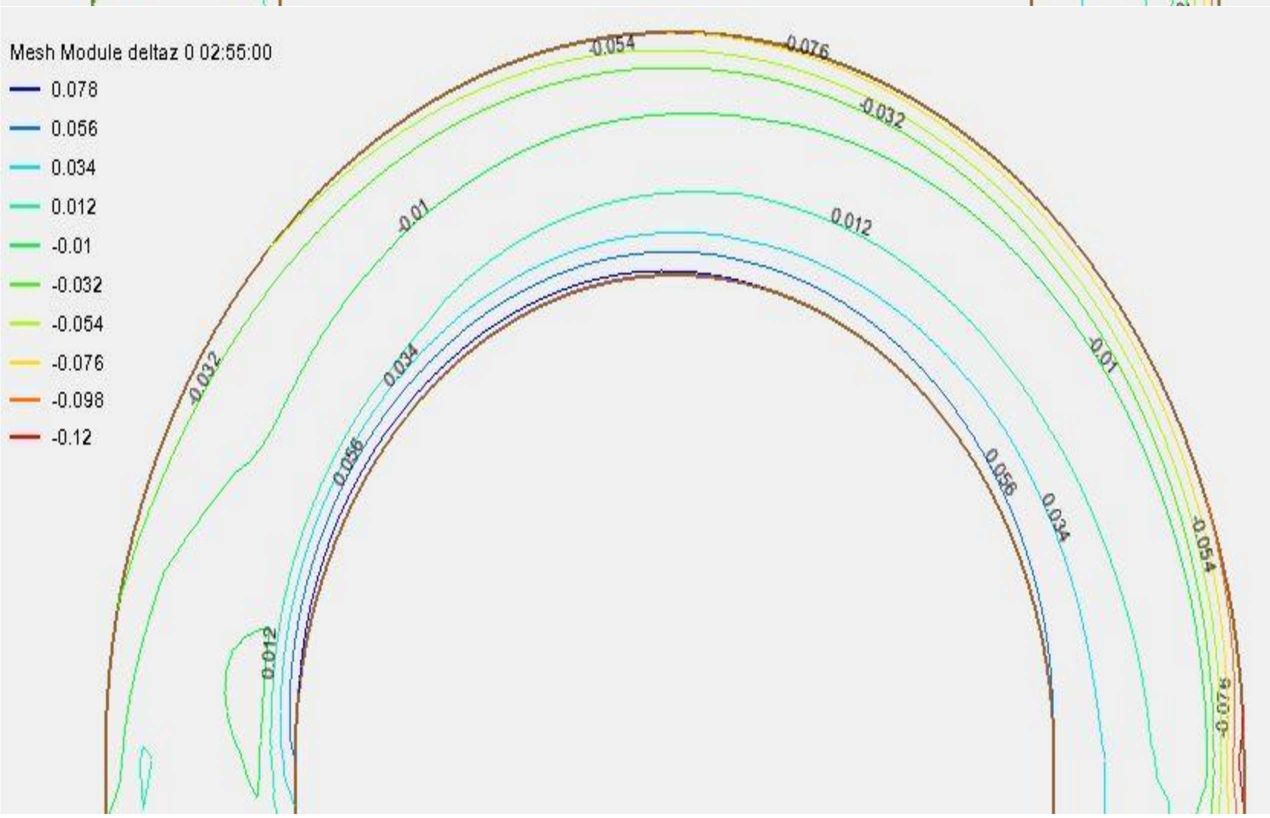
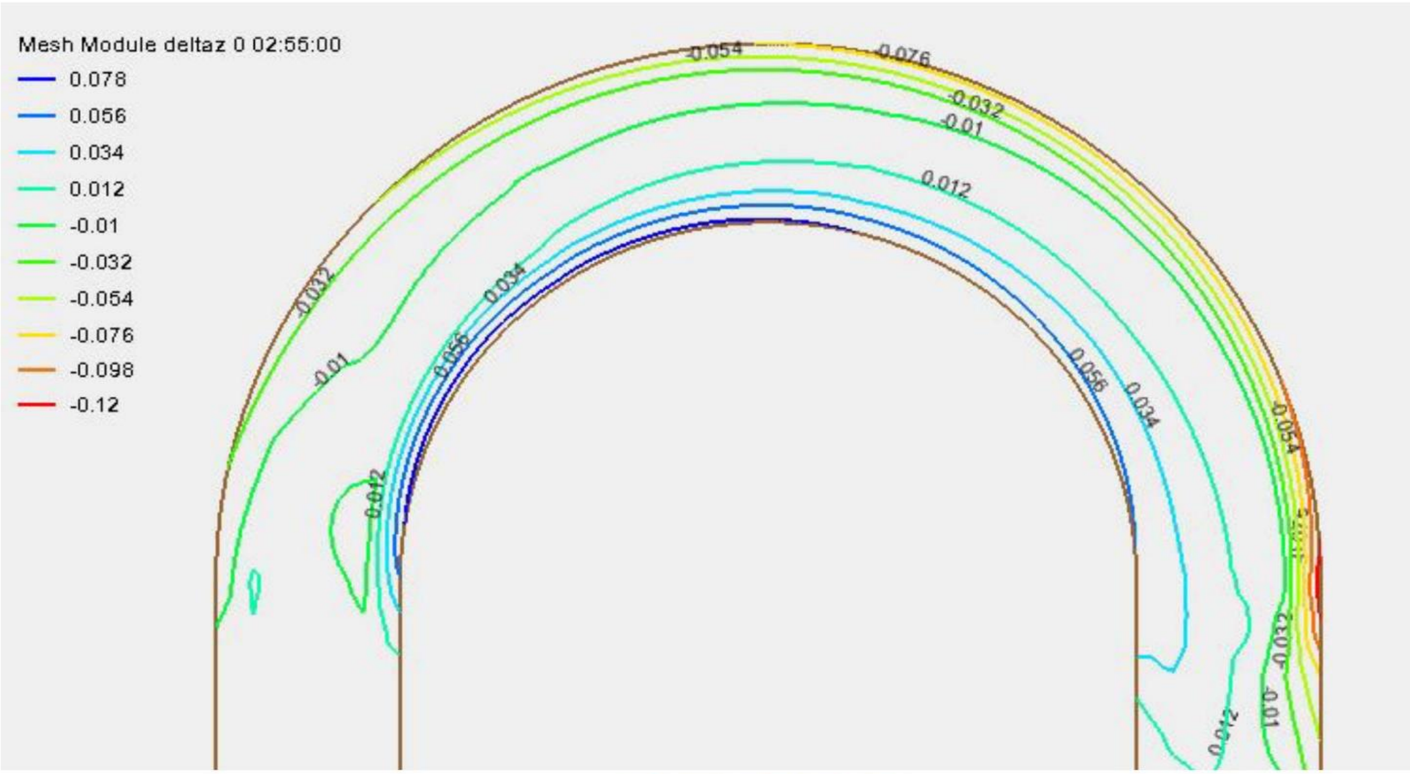


Fig 4.7(a)(upper) CFL value of 0.3 **Fig 4.7(b)(lower) CFL value of 0.7**



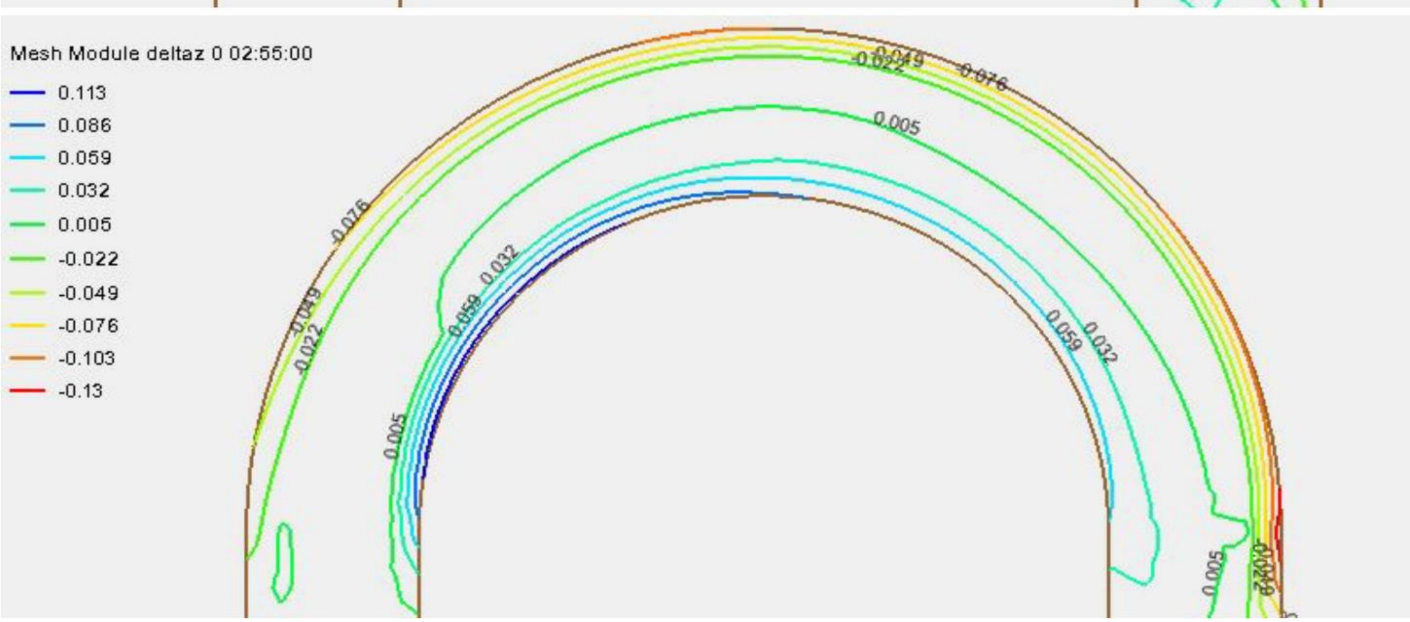


Fig 4.8(a)(upper) Friction value of 50 **Fig 4.8(b)(lower) Friction value of 50**

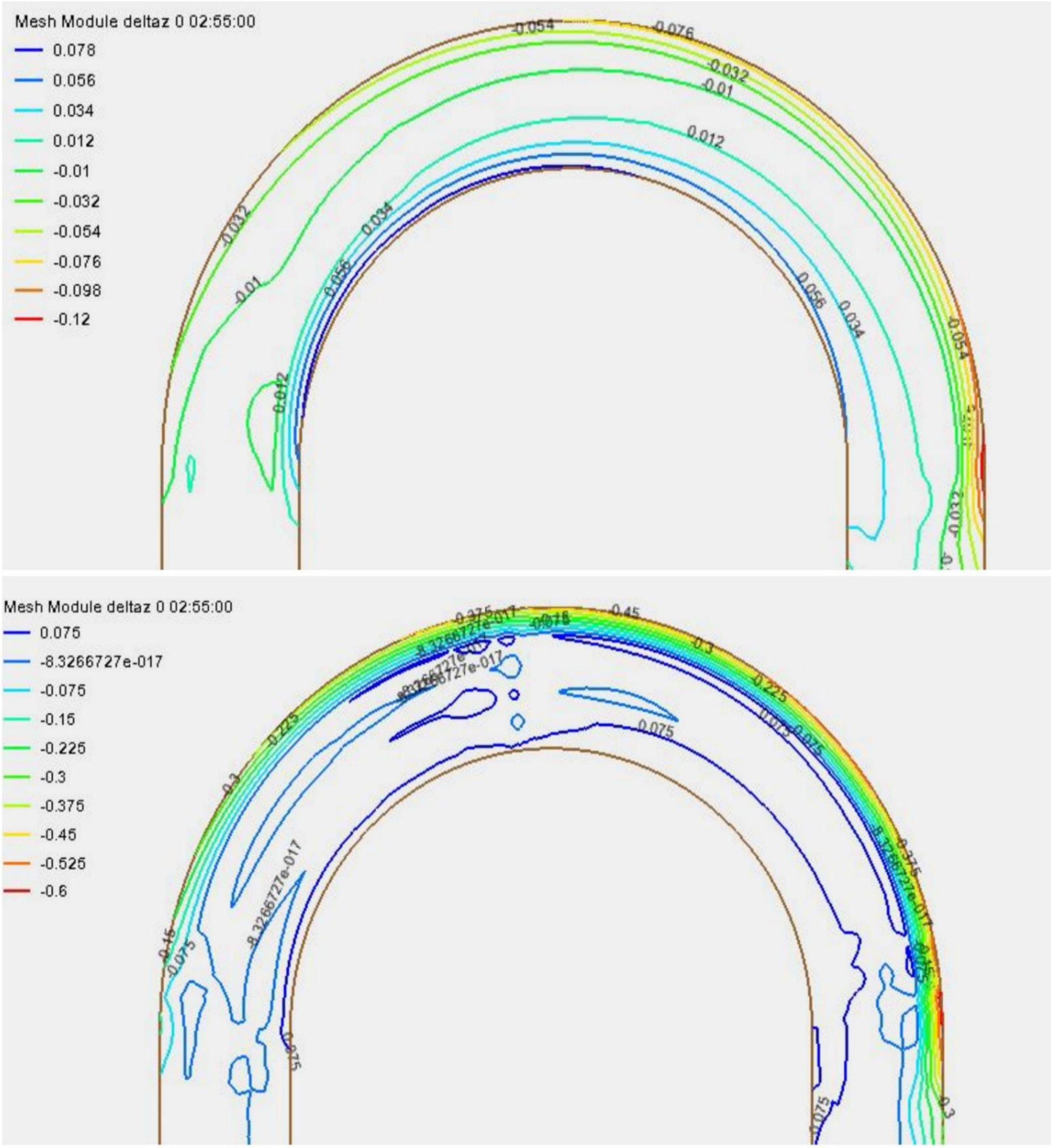


Fig 4.9(a)(upper) ENGULENDHANSEN **Fig 4.9 (b)(lower) MPM**

Table 4.6 Different Parameters for Sensitivity Analysis

S.NO	PARAMETERS	VALUE	VALUE
1	CFL VALUE	0.3	0.7
2	FRICTION VALUE	75	50
3	SEDIMENT TRANSPORT FORMULA	ENGULENDHANSEN	MPM

As we can see from the above comparison of model results of different parameter values with the original model results, we can conclude the most sensitive parameter of our model. The above comparison shows that the most sensitive parameter is the sediment transport formula parameter by changing the sediment transport formula from ENGULENDHANSEN to MPM the results changed.

By changing the CFL value and friction value the results were also changed but in a little quantity and it can be taken as the same values by neglecting the little difference.

The big difference occurred in the results by changing the sediment transport formula parameter and hence we concluded that the sensitive parameter in the BASEMENT model is the sediment transport formula parameter.

4.4 CONCLUSION

A 2D sediment transport model 'Basement' was applied to experimental river sedimentation to simulate deposition and erosion in the river. The results showed that the model is capable to simulate the general behavior of sediment transport, deposition, and erosion phenomenon. The difference between simulated and experimental results is present but up to some ignorable extent because the results are quite similar to experimental results but as you know that model is manmade so there should be the presence of errors also. But overall the accuracy of the model is very good in the simulation of sediment transport, deposition, and erosion phenomenon. Here are some limitations and overestimations that occur in our results as compared to the experimental results.

The model mostly overestimates erosion values and little overestimate the deposition values as compared to experimental erosion and deposition values into simulations in Run 4 and Run 5 in the region of 120^o-150^o and 150^o-180^o.

The deposition values are quite comparable with experimental deposition values they are matching in most of all the simulations which are quite accurate.

The simulated results do not show any deviations from experimental results but in some simulations, the model results are a little bit different in values as we discussed in the upper paragraph these are in an acceptable range. But overall the model capability and accuracy in simulating sediment transport type problems are much acceptable and accurate.

The sensitivity analysis was also done in this research which shows the most sensitive parameter in this model, in comparing three model parameters (CFL value, sediment transport formula, and friction value) the most sensitive parameter is the sediment transport formula parameter.

4.5 RECOMMENDATIONS

1. To enhance accuracy mesh should be dense (finer).
2. For enhancing accuracy CFL value must be nearer to zero.
3. By putting the curvature effect in 3D models will give more accurate results instead of 2D models.
4. These experiments must be simulated by 3D models and then compare their results.

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ANNEXURE A

MODEL CONSTRUCTION AND METHODOLOGY

GENERAL:

Hydraulic modeling of a laboratory channel bend has been carried out by using the Basement model. The basement is free and user-friendly software and easily available on the internet. This model can simulate the sediment transport and sedimentation phenomenon in a river bend. We will compare laboratory results with basement simulated results and will see how much these results are matching with experimental results.

A channel bend having a central angle of 180^0 degrees has been constructed in a laboratory with the dimensions of 4m radius, 1m width. The bend is connected with a stilling, an upstream straight reach of 11.5m, a downstream straight reach of the same length, and a sediment settling tank. A layer of sand around 20cm thick, with d_0=1.0mm and δ=2.5, was placed on the bed before each experiment began.

Different experiments have been performed on this channel bend in a laboratory with different hydrographs, and the results are also changed by the changing of the hydrograph. These results are shown below.

BASEMENT MODEL:

The freeware tool BASEMENT (Basic Simulation Environment for Computation of Environmental Flow and Natural Hazard) developed by the Laboratory of Hydraulics, Hydrology and Glaciology (VAW) at ETH Zurich, was used for the research. The Basement model employs a finite volume technique to solve the governing equation over an unstructured triangular mesh. Almost all grids using triangular cells are unstructured.

The software system BASEMENT "(basic-simulation-environment) shall provide a flexible and functional environment for numerical simulation of alpine rivers and sediment transport involved. The numerical models for the computation of one- and two-dimensional flows with moving boundaries and appropriate models for bedload as well as suspended load are forming the core of the software system.

Basement Capabilities:

- Simulation of flow behavior under steady and unsteady conditions in a channel as well as its transition;
- Simulation of sediment transport (both bedload and suspended load) under steady and unsteady conditions in a channel with arbitrary geometry;
- Simulation of erosion and deposition;
- Choose between different approaches (e. g. choice of problem matched solver-algorithms);

FLOW EQUATIONS:

The basement model uses Shallow Water Equations for simulation of the flow for 2D model problems.

And for the flow of sediment transport problems it uses many types of equations which will be selected on the choice of the user, I used the EngulendHansen formula for sediment transport. Flow equations are given below:

2D shallow water equations for flow:

- The Basement model uses 2D Shallow Water Equations for solving flow problems, which is given below in the vector form:

$$\boldsymbol{U}t + \nabla (\boldsymbol{F}, \boldsymbol{G}) + \boldsymbol{S} = 0 \text{ ………………eq(5)}$$

- where U, $F(U)$, $G(U)$, and S are the vectors of conserved variables, fluxes in the x and y directions and sources respectively.

The complete set of Shallow Water Equations is derived in the form:

$$\frac{\partial h}{\partial t} + \frac{\partial (uh)}{\partial x} + \frac{\partial (vh)}{\partial y} = 0 \text{………………………..…..eq(6)}$$

$$\frac{\partial \bar{u}}{\partial t} + \bar{u}\frac{\partial u}{\partial x} + \tilde{v}\frac{\partial u}{\partial y} + g\frac{\partial h}{\partial x} = -g\frac{\partial zB}{\partial x} - \frac{1}{\rho h}\tau Bx + \frac{1}{\rho h}\frac{\partial[h(\tau\, xx + Dxx)]}{\partial x} + \frac{1}{\rho h}\frac{\partial[h(\tau\, xy + Dyx)]}{\partial y} \text{……..…..eq(7)}$$

$$\frac{\partial \tilde{v}}{\partial t} + \bar{u}\frac{\partial \tilde{v}}{\partial x} + \tilde{v}\frac{\partial \tilde{v}}{\partial y} + g\frac{\partial h}{\partial y} = -g\frac{\partial zB}{\partial y} - \frac{1}{\rho h}\tau By + \frac{1}{\rho h}\frac{\partial[h(\tau\, yx + Dyx)]}{\partial x} + \frac{1}{\rho h}\frac{\partial[h(\tau\, yy + Dyy)]}{\partial y} \text{……….eq(8)}$$

Where,

h [m] water depth

g [$m/s2$] gravity acceleration

P [Pa] pressure
U [m/s] depth averaged velocity in x direction
uS [m/s] velocity in x direction at water surface
u [m/s] velocity in x direction at bottom (usually equal zero)

v [m/s] depth averaged velocity in y direction
vS [m/s] velocity in y direction at water surface
vB [m/s] velocity in y direction at bottom (usually equal zero)
wS [m/s] velocity in z direction at water surface
wB [m/s] velocity in z direction at bottom (usually equal zero)
zB [m] bottom elevation
zS [m] water surface elevation
$\tau Sx, \tau Sy$ [$N/m2$] surface shear stress in x- and y direction (here neglected)
$\tau Bx, \tau By$ [$N/m2$] bed shear stress in x- and y direction
$\tau\, xx, \tau\, xy, \tau\, yx, \tau\, yy$ [$N/m2$] depth averaged viscous and turbulent stresses
Dxx, Dxy, Dyx, Dyy [$N/m2$] momentum dispersion terms

Bedload Transport equations for sediment transport:

Basement model posses different sediment transport formulas for bedload transport, given below are some bedload transport formulas which can be used for simulation purpose on the choice of user.

EngulendHansen:

We have used the EngulendHansen formula for sediment transport which is given below:

$$\boldsymbol{qB = 0.05q((s-1))^{1/2} g\, c^2 f\, \theta^{2.5} df^{1.5}} \text{………..eq(9)}$$

where df denotes the mean fall diameter of the bed material and θ the Shields parameter.

Ashida and Michiue:

The bed load formula for non-uniform sediments according to Ashida and Michiue (Ashida and Michiue, 1971) reads

$$\boldsymbol{qBg = 17\sqrt{(s-1)gd3g}\,(\theta g - \xi g\theta cr, ref)(\sqrt{\theta g} - \sqrt{\xi g\theta cr, ref}\,)} \text{……..}\mathbf{eq(10)}$$

where qBg is the specific bedload transport rate of grain class g, θg is the dimensionless shear stress for grain class g, θcr, *the ref* is the reference critical dimensionless shear stress (Ashida and Michiue (1971) proposed $\theta cr,ref = 0.05$), dg is the diameter of the grain class

g, $s = \rho s/\rho$, g is the gravitational acceleration, and ξg is the hiding function.

Meyer-Peter and Müller (MPM & MPM-Multi):

The bedload transport formula of Meyer-Peter and Muller (Meyer-Peter and Muller, 1948) can be written as follows：

$$qBg = \alpha\sqrt{(s-1)gd3g}(\theta g - \theta cr{,}g)^{m} \text{ ....eq(11)}$$

Herein, α denotes the bed load factor (originally $\alpha = 8$), m the bed load exponent (originally $m = 1.5$), qBg is the specific bedload transport rate of grain class g, θg is the effective dimensionless shear stress for grain class g, $\theta cr,g$ is the critical dimensionless shear stress for grain class g, dg is the diameter of the grain class g, $s = \rho s/\rho$, and g stands for the gravitational acceleration. Note that by adjusting α to 4.93 and m to 1.6, the bed load formula can be adapted according to Wong and Parker (2006).

Meyer-Peter and Muller observed in their experiments that the fist grains moved already for $\theta cr = 0.03$. But as their experiments took place with steady conditions, they used a value for which already 50% of the grains were moving. They proposed a value of 0.047.

However, for very unsteady conditions, one should use values for which the grains start to move (Fah, 1997) like the values given by the shields diagram. The formula of Meyer-Peter and Muller is applicable in particular for coarse sand and gravel with grain diameters above 1 mm (Malcherek, 2001).

The original bedload transport formula is intended for single grain simulations. But an extension of the MPM-Formula for fractional transport is implemented in the program and called MPM-Multi. It uses the hiding function ξg proposed by Ashida and Michiue (1971):

$$\xi g = \begin{cases} \left[\log\frac{19}{}\log\left(\frac{19dg}{dm}\right)\right]2 & \frac{dg}{dm} \geq 0.4 \\ \frac{dm}{dg} & \frac{dg}{dm} < 0.4 \end{cases}$$

dg is the grain size diameter of grain class g and dm the mean diameter of the grain mixture.

The dimensionless critical shear stress of grain class becomes:

$$\theta cr{,}g = \theta cr{,}ref\ \xi g,$$

where $\theta cr, ref$ usually is assigned to a fixed value (e.g. $\theta cr, ref = 0.047$) or the critical Shields parameter of the mean grain size.

Parker

Parker extended his empirical substrate-based bed load relation for gravel mixtures (G. Parker, 1990, Parker et al. (1982)), which was developed solely regarding field data and suitable for near-equilibrium mobile bed conditions, into a surfaced-based relation. The new relation is proper for non-equilibrium processes.

Based on the fact that the rough equality of bedload and substrate size distribution is attained employing selective transport of surface material and the surface material is the source for bedload, Parker has developed the new relation based on the surface material. An important assumption in deriving the new relation is suspension cut-off size. Parker supposes that during flow conditions at which significant amounts of gravel are moved, it is commonly (but not universally) found that the sand moves essentially in suspension (1 to 6 mm). Therefore Parker has excluded sand from his analysis. In his free access Excel file, he has explicitly emphasized that the formula is valid only for the size larger than 2 mm. Regarding the Oak Creek data, the original relation predicted 13% of the bed load as sand. For consistency, it has to be corrected for the exclusion of sand and finer material.

$$W*si = 0.00218G[\xi s\omega\varphi sg0] \;\; ; \quad W*si = \frac{Rgqbi}{(\tau B/\rho)3/2Fi}$$

$$\xi s = \left(\frac{di}{dg}\right)^{-0.0951}; \; \varphi 50 = \frac{\tau*sg}{\tau*rsg0} \;\; ; \; \tau*sg = \frac{\tau B}{\rho Rgdg} \; ; \; \tau*rsg0 = 0.0386$$

$$\omega = 1 + \frac{\sigma}{\sigma 0(\varphi sg0)}[\omega 0(\varphi sg0) - 1]; \; \sigma = \sum Fi\left(\frac{\ln(di/dg)}{\ln(2)}\right)^2 \; ; \; dg = e\sum Fi\ln(di)$$

ξs is a “reduced” hiding function and differs from the one of Einstein. The Einstein hiding factor adjusts the mobility of each grain *di* in a mixture relative to the value that would be realized if the bed was covered with uniform material of size *di*. The new function adjusts the mobility of each grain di relative to the *d*50 or *dg*, where *dg* denotes the surface geometric mean size. Although the above formulation does not contain critical shear stress, the reference shear stress $\tau * rsg0$ makes up for it, in that transport rates are exceedingly small for $\tau * sg < \tau * rsg0$.

Regarding the fact that parker’s relation is based on field data and field, data are often in the case of low flow rates, the relation calculates low bedload rates (Marti, 2006).

Wilcock and Crowe

Wilcock and Crowe developed a sediment transport model for sand/gravel mixtures (Wilcock, 2003), similar to Parker's model (G. Parker, 1990), and it was developed with a large experimental results dataset. It references fractional transport rates to the size distribution of the bed surface, rather than the subsurface, making the model explicit and capable of predicting transient conditions. The hiding function incorporated in the model resolves discrepancies observed among earlier hiding functions implemented in other transport models, such as the Oak Creek and the Cambridge ones (A.J. Parker G.; Sutherland, 1990). Wilcock and Crowe's model

(Wilcock, 2003) uses the full-grain size distribution of the bed surface, including sand, incorporating a non-linear effect of sand content on gravel transport rate.

$$W*si = G(\varphi i)\ ;\ W*si = \frac{Rgqbi}{(\tau B/\rho)3/2Fi}$$

where:

$$G(\phi i) = \begin{cases} 0.002\ \varphi 7.5 & \varphi i < 1.35 \\ 14\left(1 - \frac{0.894}{\varphi i 0.5}\right)4.5 & \varphi i \geq 1.35 \end{cases}$$

And;

$$\Phi i = \frac{\tau * sg\ di - b}{\tau * ssrg\ dg} \quad ; \quad \tau * ssrg = \frac{\tau B}{\rho R g d g}$$

$$\tau * ssrg = 0.021 + 0.015 exp(-20Fs) \quad ; \quad b = \frac{0.67}{1 + \exp\left(1.5\frac{di}{dg}\right)}$$

The non-linear effect of sand content Fs on gravel transport is taken into account in $\tau *ssrg$. Wilcock and Crowe (Wilcock, 2003) have shown that increasing sand content in the bed active layer of a gravel-bed stream increases the surface gravel mobility. This effect is captured in their relationship between $\tau *ssrg$ (a surrogate for a critical Shields number) and the fraction sand in the active layer Fs. Note that $\tau *ssrg$ decreases as Fs increases, causing an increase of φi and in turn of the fraction bedload qbi.

Rickenmann

Experiments for bedload transport in gravel beds were performed at VAW ETH Zurich for bed slopes of 0.0004-0.023 by Meyer-Peter and Muller (1948) and bed slopes of 0.03-0.2 by Smart and Jaeggi (1983) and by Rickenmann (1990). Rickenmann (1991) developed the following bedload transport formula for the entire slope range using 252 of these experiments.

$$\Phi B = 3.1\,\left(\frac{d90}{d30}\right)^{0.2}\ \theta' 0.5(\theta' - \theta cr) Fr 1.1 (s-1)^{-0.5}$$

$$qB = \Phi B((s-1)\,gd3m)\,0.5$$

θ' is the dimensionless shear stress, θcr the dimensionless shear stress at the beginning of bedload transport, $s = \rho s/\rho$ the sediment density coefficient, Fr the Froude number and dm the mean grain size.

Smart and Jäggi (for single grain and multiple grain classes)

Experiments for bedload transport in gravel beds were performed at VAW ETH Zurich for bed slopes of 0.0004-0.023 by Meyer-Peter and Muller (1948) and bed slopes of 0.03-0.2 by Smart and Jaeggi (1983) and by Rickenmann (1990). Smart and Jaggi developed a bedload transport formula for steep channels using their experimental results and the results of Meyer-Peter and Muller.

$$qB = \frac{4}{s-1}\left(\frac{d90}{d30}\right) J 0.6 R u (J - Jcr)$$

where$s$ is the sediment density coefficient ($s = \rho s/\rho$), R is the hydraulic radius, u is the velocity, J is the slope and Jcr is the critical slope for the initiation of the bedload transport, which is calculated as

$$Jcr = \frac{\theta cr (s-1) dm}{R}$$

where θcr is the critical shields parameter (for the initiation of motion) and dm is the mean grain size. To account for the gravitational influence of the local bed slope Smart and Jaeggi (1983) proposed the following reduction of the critical shields parameter:

$$\theta cr = \theta cr, Ref\ (\cos(\arctan J))\left(1 - \frac{J}{\tan\psi}\right)$$

where J is the local bed slope, ψ the angle of repose, and $\theta cr, Ref$ the critical reference shields parameter for the medium grain size defined by the user (Smart and Jaeggi (1983) propose a value of 0.05). The Smart & Jaggi transport formula is extended to multiple grain classes by applying the original equation to the individual grain classes according to the following approach:

$$qB, g = \frac{4}{s-1}\left(\frac{d90}{d30}\right)^{0.2} J\ \mathbf{0.6} Ru(J - Jcr, g)$$

Compared to the original eq. 1.102 the transport rate for each grain class qB, i is calculated with the critical slope Jcr,g for the initiation of motion of the grain class I according to

$$Jcr, g = \frac{\theta cr, g(s-1)di}{R}$$

where $\theta cr,g$ is the critical shields parameter for grain class g, dg is the diameter of the grain class g. With the term $\alpha = (d90/d30)0.2$ the original equation intends to account for the influence of the grain class distribution. According to Smart and Jaeggi (1983), this term is in the range of $1.06 \leq \alpha \leq 1.53$. If this term is to be neglected Smart and Jaeggi (1983) recommend substituting $\alpha = 1.05$. The influence of the grain class distribution is considered in the hiding and exposure approach according to Ashida and Michue (Ashida and Michiue, 1971; Parker, 2008).

$$\zeta g = \begin{cases} 0.85\left(\frac{dg}{dm}\right) - 1 & for\ \frac{dg}{dm} \leq 0.4 \\ \left(\frac{\log(19)}{log19(\frac{dg}{dm})}\right)2 & for\ \frac{dg}{dm} > 0.4 \end{cases}$$

$$\theta\, cr, g = \zeta\, g\, \theta\, cr$$

Wu

Wu et al. (2000) developed a transport formula for graded bed materials based on a new approach for the hiding and exposure mechanism of non-uniform transport. The hiding and exposure factor is assumed to be a function of the hidden and exposed probabilities, which are stochastically related to the size and gradation of bed materials. Based on this concept, formulas to calculate the critical shear stress of incipient motion and the fractional-load transport have been established. Different laboratory and field data sets were used for these derivations. The probabilities of grains dg hidden and exposed by grains di are obtained from

$$phidg = \sum_{i=1}^{ng} \beta i \frac{di}{dg+di}, \qquad pexpg = \sum_{i=1}^{ng} \beta i \frac{dg}{dg+di}$$

The critical dimensionless shields parameter for each grain class g can be calculated with the hiding and exposure factor ηg and the shields parameter of the mean grain size θcrm as

$$\theta crg = \theta crm \frac{\left(\frac{pexpg}{phidg}\right) m}{\eta g}$$

The transport capacity now can be determined with Wu's formula in dimensionless form as

$$\Phi Bg = 0.0053 \left(\frac{\theta'}{\theta crg} - 1\right)^{2.2}$$

Finally, the bedload transport rates calculated for each grain fraction as

$$qbg = \beta g((s-1))^{1/2} gd3g \; \Phi Bg$$

As results of their data analysis the authors recommend to set $m = -0.6$ and $\theta crm = 0.03$ to obtain the best results. If this transport formula is used in combination with a local slope correction of the critical shear stress (see Section 1.2.1.1.2) attention must be paid that θcrg may not become too small or even zero. Since this critical dimensionless shear stress is in the denominator of the transport formula, such situations may lead to numerical instabilities. To avoid these problems a minimum value for θcrg is enforced.

$$\theta crg = min(\theta mincr, \; \theta crg)$$

Van Rijn

van Rijn (1984a) developed a bed load formula for grain sizes between 0.2 and 2 mm

$$qB = 0.053((s-1)g)^{1/2} \frac{(d50)1.5T2.1}{D*0.3}$$

Here $D*$ is the dimensionless grain diameter according to eq. 1.53 and T is the non-dimensional excess bed shear stress or the transport stage number, defined as

$$T = (u*/u*cr)^2 - 1$$

where $u*$ is the effective bed shear velocity determined as

$$u* = u\sqrt{g}/C'h$$

with $C'h = 18 \log (4h/d90)$.

$u*cr$ is the critical bed shear velocity, u is the mean flow velocity, h is the water depth, $d50$ and $d90$ is characteristic grain diameters of the bed material.

CURVATURE TRANSPORT FACTOR:

Normally, a 2D model cannot reproduce a bend because it cannot simulate secondary currents. However, due to the Engelund approach, a 2D model can sedimentation at a channel bend.

Engelund (1974) proposed an approach in which the curvature effect is taken into account, where the deviation angle φ_b from the main flow is determined as

$$\tan \varphi_b = N_* \, h/R$$

where h denotes water depth, N_* denotes a curvature factor, and R denotes the radius of the river bend. The curvature factor mainly depends on bed roughness. Therefore, $N_* = 7$ for natural streams (Engelund, 1974), and values up $N_* = 11$ for laboratory channels (Rozovskii, 1957).

Due to (Engelund's,1974) approach, the model can simulate a bend. The desired behavior is erosion on the outside and deposition at the inside of the bend.

MODEL CONSTRUCTION:

The following are the main steps of constructing a model in the Basement model.

1) 2D Mesh Generation
2) Material indices for 2D mesh
3) Hydraulic Data
4) Morphological Data
5) Timestep
6) Output

2D MESH GENERATION:

There are many ways for generating a mesh that is used in the basement model but the Base mesh is a plugin that is used for mesh generation in QGIS software. Basemesh is a plugin for the free and open-source geographic information system (GIS) software Quantum GIS (QGIS). Basemesh plugin is capable of generating TRIANGULAR meshes as well as QUADRILATERAL meshes also, both these types of meshes are acceptable in basement software for simulation purposes.

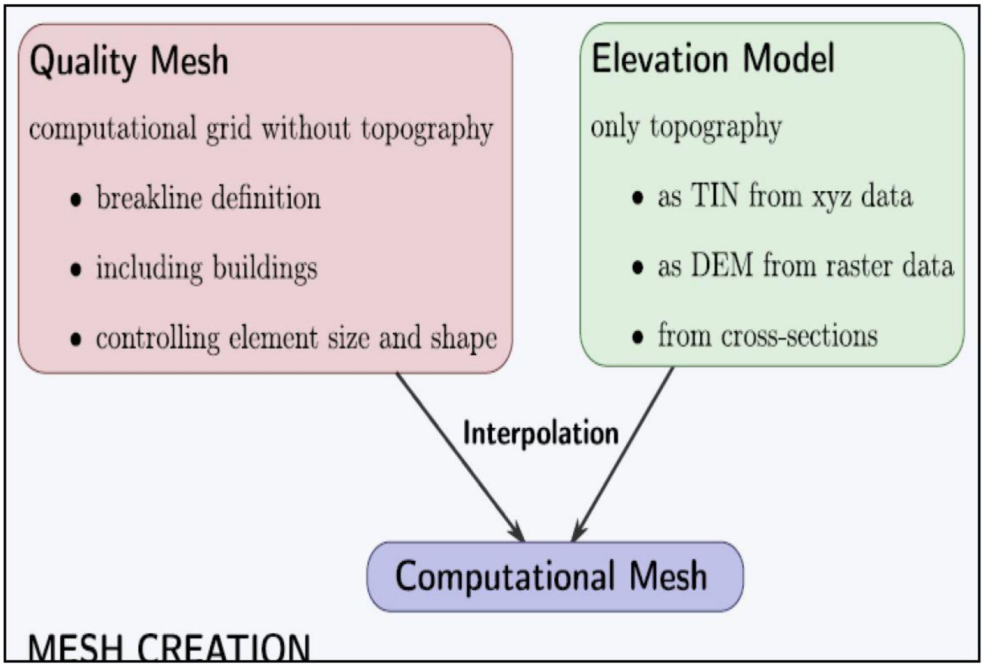

Figure 3.5: Mesh Generation in BASEmesh

Figure 1A

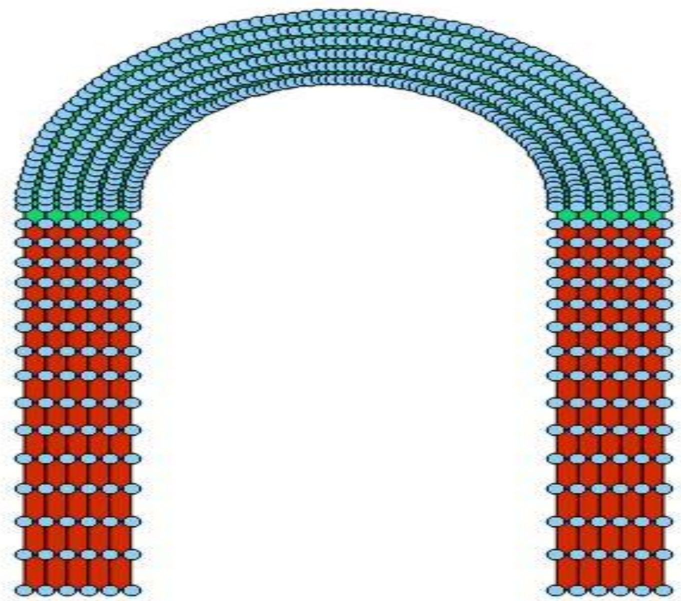

Figure 2A. 2D MESH

MATERIAL INDICES FOR 2D MESH:

There are different areas in rivers that have different characteristics than others, so in generating 2D mesh we will define different characteristics of every region in our channel bend with the help of material indices. We will apply different value in mesh to those regions which have different characteristics for example (friction values or soil parameters) etc.

In this case, only two indices are used; one for the straight zone and the other for the central curved zone.

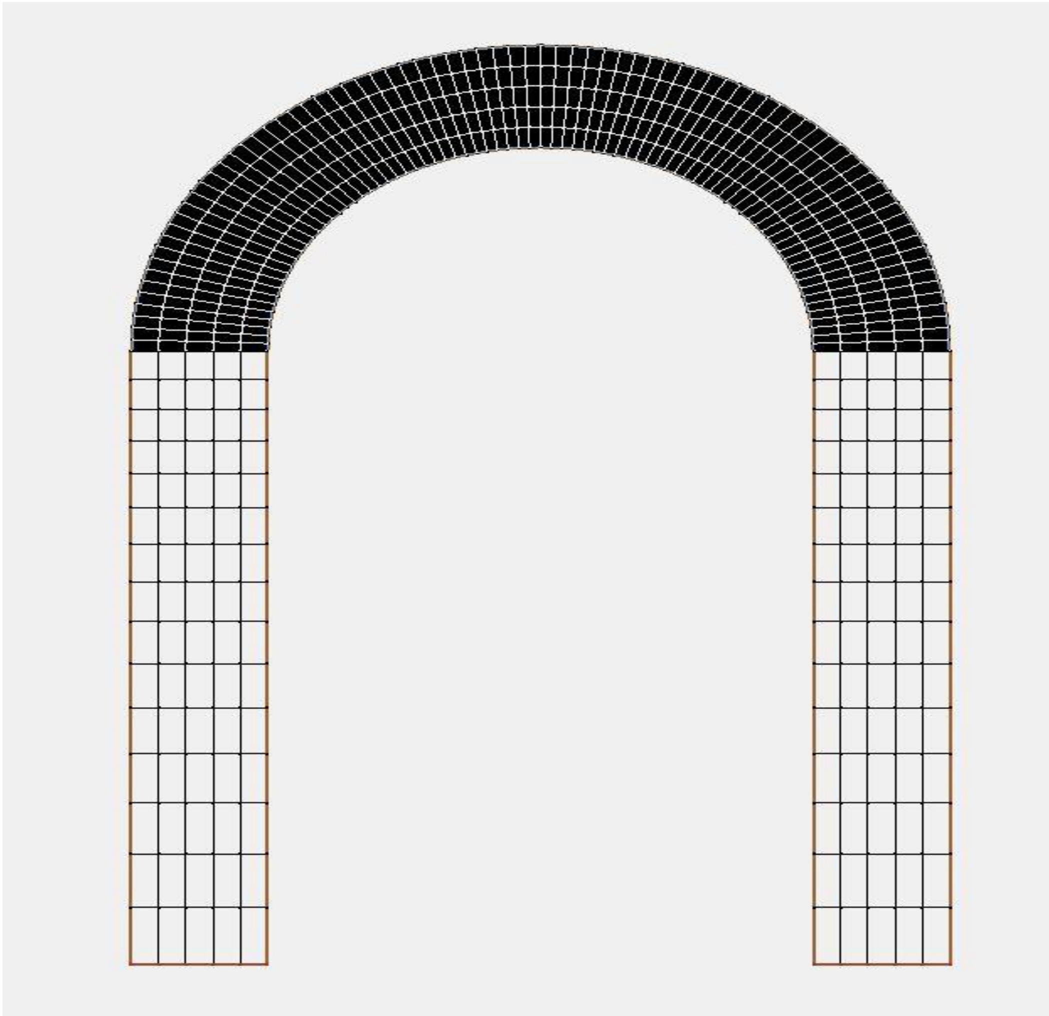

Figure 3A. GRIDS OF 2D MESH

The black-colored region in the upper figure shows different characteristics than the straight white region and assigned different indices to those regions.

HYDRAULIC DATA:

The main portion of the Basement software is of Hydraulic portion which includes many sensitive parameters that can change your results by changing these parameter values infractions. That's why the data should be entered correctly.

Hydraulic data includes Boundary conditions, initial conditions, friction type and values, parameter, and turbulence model. The main subcategories in the hydraulic portion are inflow boundary condition, outflow boundary condition, slope, minimum water depth, simulation scheme, and Riemann solver, etc.

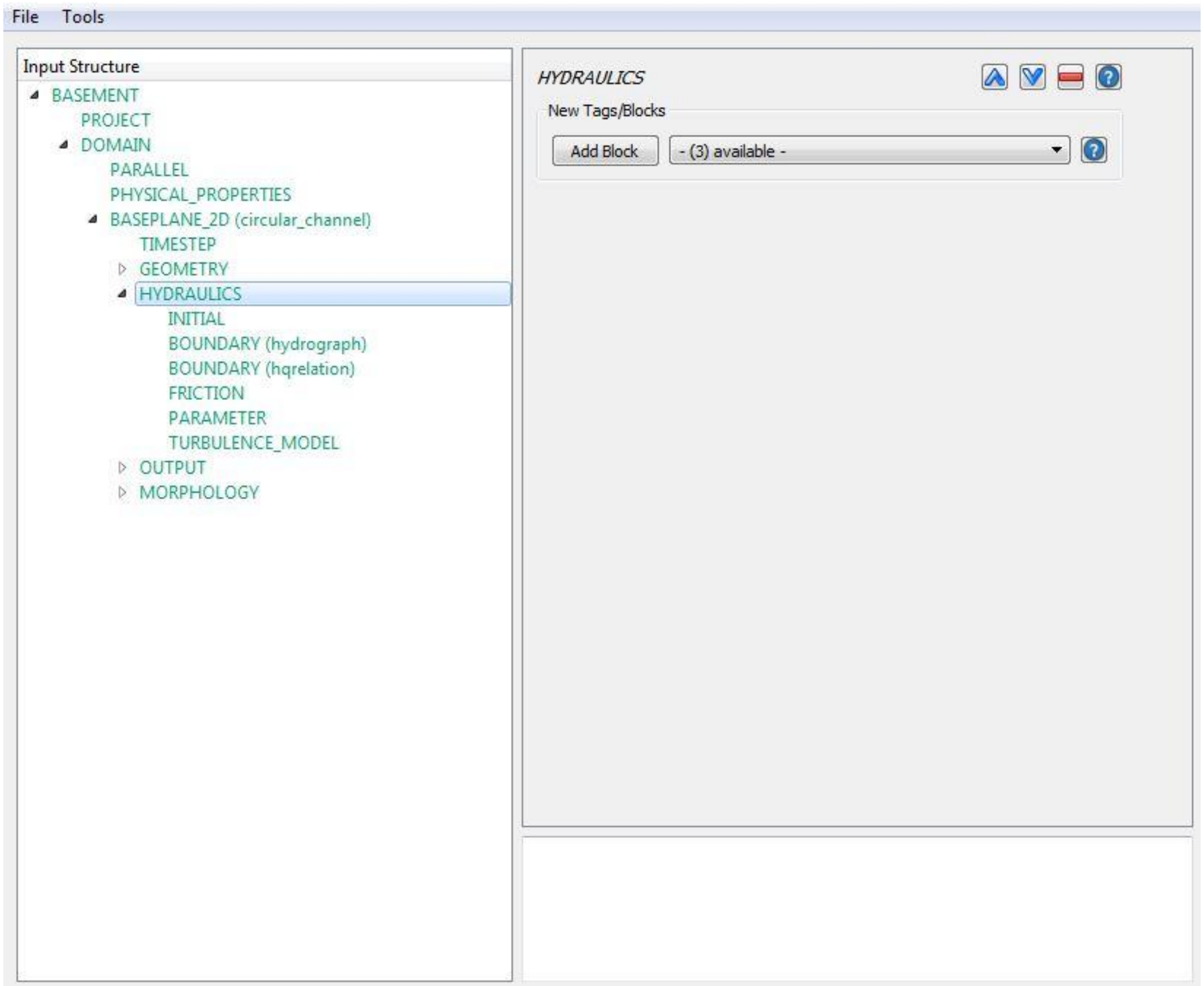

Figure 4A. Hydraulic block in Basement window

INITIAL:

The initial condition is set to dry because the simulation is started from the beginning (zero).

BOUNDARY (INFLOW):

The inflow boundary condition is inserted in text format in the form of a hydrograph which is given below.

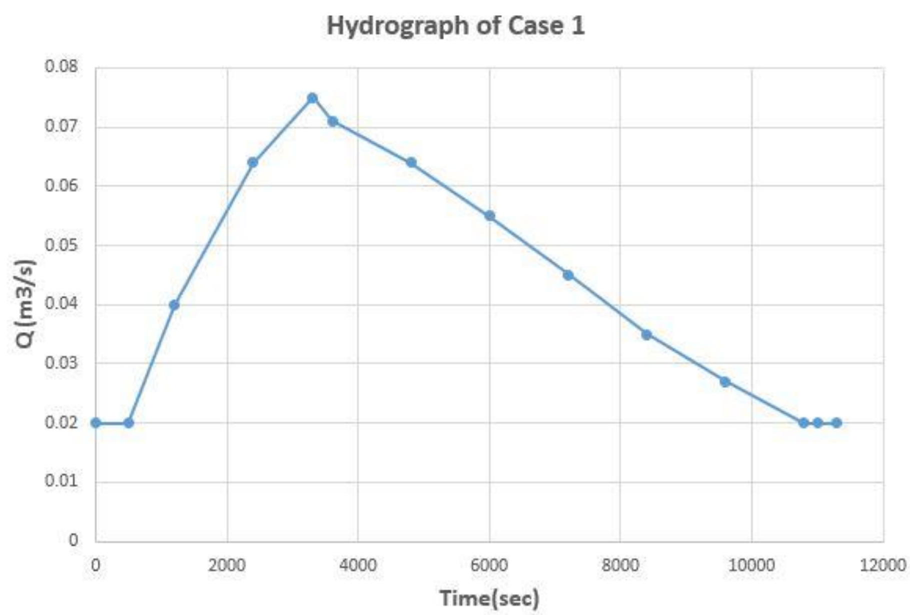

Figure 5A. Hydrograph of case 1

BOUNDARY (OUTFLOW):

The outflow boundary condition is given as a type HQ-Relation and having a slope value of 1.

FRICTION:

The stickler friction type is selected and given a ‘k’ value of 75 for the laboratory channel.

PARAMETER:

The simulation scheme is explicit and Riemann solver is exact, and the minimum water depth has a selected value of 0.00001.

MORPHOLOGICAL DATA:

The morphological is subcategorized in different portions which are given below.

i) Parameter
ii) Bed material
iii) Initial
iv) Bedload

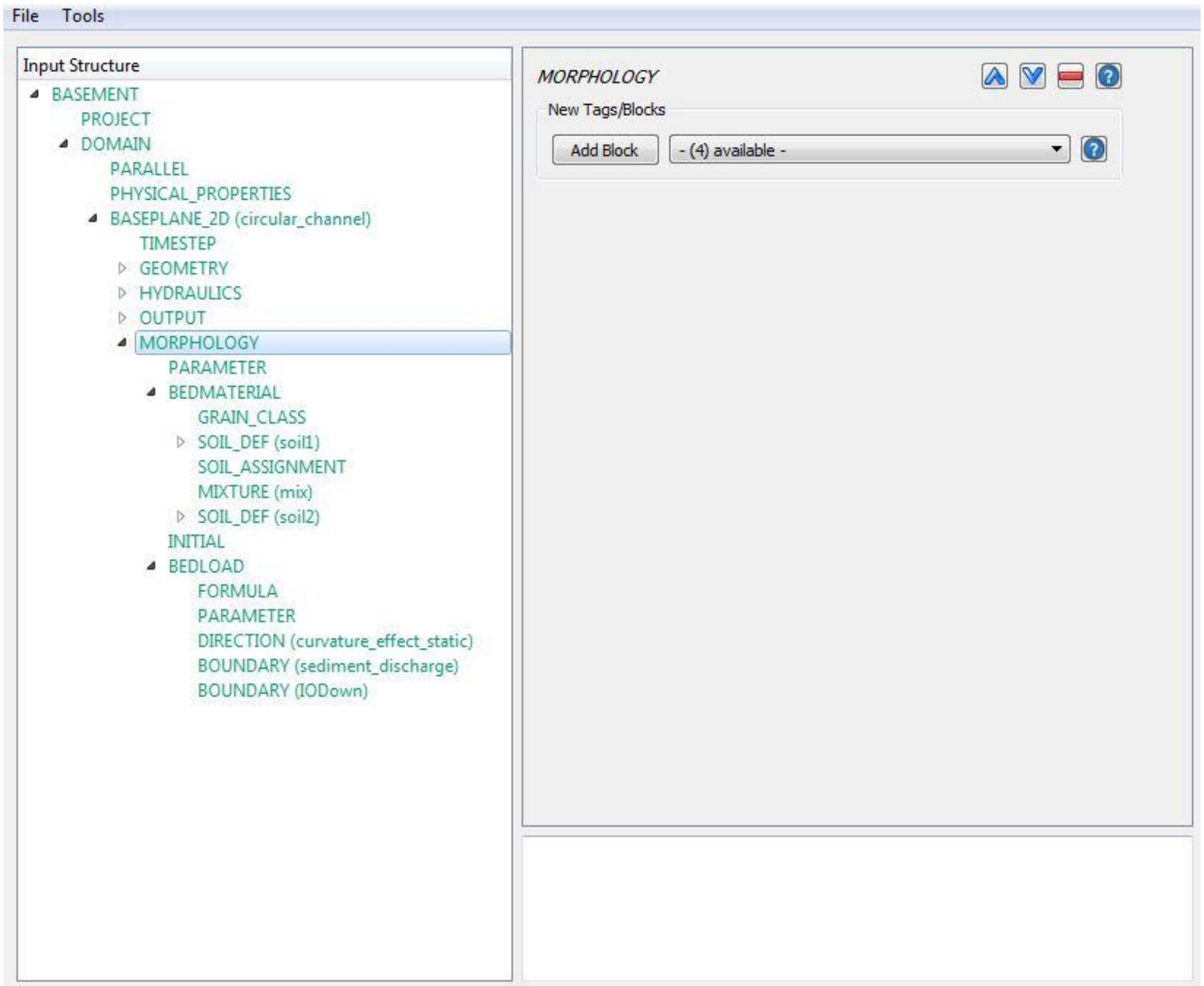

Figure 6A. Morphological data window

The next important step of our model is the morphological data portion. In this portion, we will identify all the information about the bed material size, properties, and its transport formula based on which it flows in a mesh file from inflow to outflow portion.

PARAMETER:

First of all the general parameters data is needed like porosity and density. The selected bed material is sand so the porosity will be 40% and the density by default in the basement is 2650kg/m^3.

BED MATERIAL:

Now the next step is the diameter of the bed material which is 1mm. As we know that our mesh contains two indices so we should be given two soils for example soil 1 and soil 2 having the same

properties and in the same proportion to the indices 1 and 2. There is only one material and the volume fraction will be 100.

INITIAL:

This block defines the initial conditions for morphological data hence we don't have the initial data that's why we will choose the initial mesh.

BEDLOAD:

Now the last and most important step in our model morphological data portion is bedload. If there is no bedload segment is defined then there will be no bedload transport in the simulation.

This portion is consists of the following parameters which are given below.

i) Formula
ii) Boundary
iii) Direction

FORMULA:

First of all, in this portion, we will define our bedload formula according to our current situation. There are many bedload formulas present but we will select that formula that is suitable for our modeling. We have only one bedload material that's why we will select the

ENGULENDHANSEN formula because it better describes bedload transport in laboratory bend channels.

BOUNDARY (INFLOW):

The inflow boundary condition is needed for bedload in the text file format. So we have no inflow sediment discharge required that's why we added a text file in this block having zero sediment discharge values and string name sediment discharge.

BOUNDARY (OUTFLOW):

The outflow boundary condition is required for the bedload and we selected the type IOdown for our outflow boundary condition having string name outflow.

DIRECTION:

The last and most important step in the direction block. In this block, you will provide information about the direction in which the bedload material will flow. We have circular bend mesh then we have to specify the lateral transport type as a curvature effect static condition.

The main reason for selecting curvature effect static is the fixed bend, our bend will remain fixed over the entire simulation. This type of direction is only applicable in bends cases. We have specified the bend in our mesh by giving the indices value 2 in the lateral index.

The next important factor in the direction block is the curvature transport factor. (Rozvskii, 1961) proposed a value of 11 for laboratory channels.

The last tag is radius-static which is defined as -4, the negative sign represents the clockwise direction.

We will incorporate the EngulendHansen approach in our basement model because without incorporating this approach we cannot catch our desired condition and our desired condition is erosion on the outside of the river bank and deposition on the inside of the river bank.

Engelund (1974) proposed an approach in which curvature effect is taken into account, where the deviation angle φ_b from the main flow is determined as

$$\tan \varphi_b = N_* h/R$$

where h denotes water depth, N_* denotes a curvature factor, and R denotes the radius of the river bend. The curvature factor mainly depends on bed roughness. Therefore, $N_* = 7$ for natural streams (Engelund, 1974), and values up $N_* = 11$ for laboratory channels (Rozovskii, 1957).

Due to (Engelund's,1974) approach, the model can simulate a bend. The desired behavior is erosion on the outside and deposition at the inside of the bend.

TIMESTEP:

This block is used for assigning values to CFL, total run time, minimum time step, and start time.

The courant-Friedrichs-Lewy number is selected 0.5 because smaller values near zero will take more simulation time.

The total runtime of our experiment in case 1 is 10800 sec.

The minimum time step and start time values are assigned by default values.

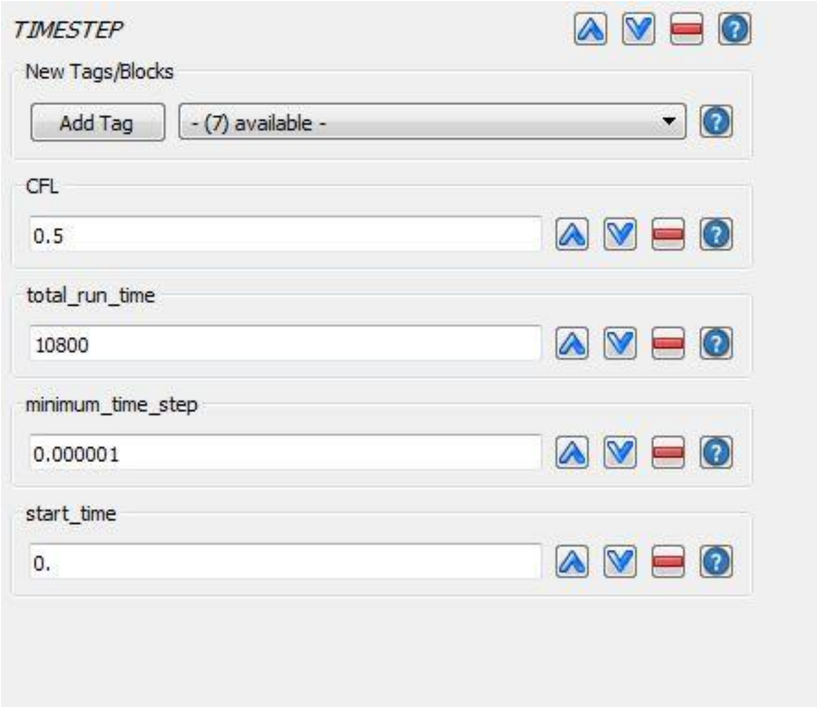

Figure 7A. Timestep window

OUTPUT:

The last block in basement software is output. In this block, we have to specify our required data from our experiment. We will specify it further in the subcategories of the output block.

The output block further consists of a type, output timestep, values, and format.

In type, we have selected node centered.

The output time step is selected 700 secs.

The values are deltaz, depth, velocity, and WSE. We only need deltaz values for our research but the other values are only selected for informational purposes.

The last step 'format' is defined as 'SMS' because we will visualize our results in contours form which will be easily visualized in SMS software.

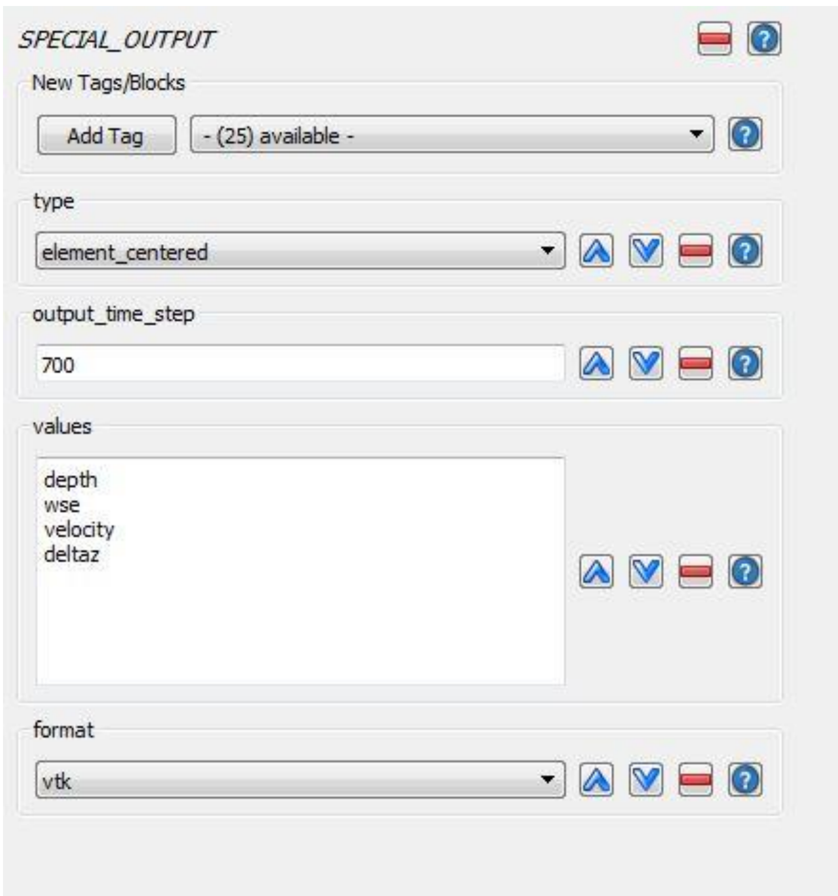

Figure 8A. Output window