Simulation of Suspended Sediments for Physical Model Studies

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Abstract: *Physical Hydraulic Model Studies are essential especially when sediment transport is involved. There are many mathematical model studies to assess the sediment deposition and transport of material in a hydraulic system. The present set of equations that are used in available models have limitations as three-dimensional flow pattern involving sediment transport has not been fully understood and therefore at present, average solution over space and time are used in these mathematical models. In order to have better insight into the hydraulic system carrying sediments, a physical model on a suitable scale can be certainly useful. However, for these model studies simulation of sediment to model scale becomes very critical. For, the simulation of sediment, one has to consider specific gravity of the material used in physical model. Once material with specific gravity is known, then further analysis needs to be carried out so that the fall velocity of the various particle sizes needs to be simulated converted from prototype. The size of sediment for the lower part of gradation curve becomes too small to be practically used in a hydraulic model. In practice, most of the time, coal ash and walnut shell powder having specific gravities of around 1.6 have been used almost all over the world. In recent times, plastic balls having specific gravity more than 1 have been fabricated and used in many laboratories. However, this also has limitations as the size becomes further smaller. In view of this, extensive studies were conducted in our laboratory – InfraPlan Hydraulic Laboratory in Pune, India. These studies concluded that coconut shell powder having specific gravity of 1.2 was most effective and is also easily available in a crushed form having various particle sizes. The coconut shell powder has been used in our laboratory successfully for many studies in Indian as well as foreign projects. The coconut shell powder was effectively used to assess the performance of the desilting basins to arrive at efficient design of the overall system. The coconut shell powder has also been used to assess sediment deposition patterns along the river for various flood events. The present paper highlights the evolution of coconut shell powder for hydraulic model studies and its application. The studies conducted on desilting basin and river morphology studies using coconut shell powder have been described in the paper.*

Keywords: *Sediment transport, sediment deposition, physical model studies, flushing, desilting, river morphology*

1. Introduction

Typical river flows in the upper reaches through the hilly and mountainous terrain, the middle reaches are mainly composed of floodplains and the lower reaches covers the delta regions and tidal portions. The mountainous rivers typically have steep slopes and high velocities and are of predominantly degrading nature. Catchment denudation and soil erosion causes high sediment load to enter the river. Usually, the riverbed and banks in the upper reaches are usually highly resistant to erosion. In the middle reaches the rivers are often characterized by meandering nature. Successive erosion and deposition occur on the river banks depending on the location and flow regime. Here, the erosion of banks, the path of bedload movement and the location of deposits, change significantly with change in stage of the river. During high floods these rivers may inundate very large areas. In the end reaches the rivers are mainly of aggrading type. The bedload which it carries is deposited near the river mouth which causes the delta formation. It may be mentioned here that the dams and other hydraulic structures along the river also affect the sediment movement significantly.

Some of the important sediment properties required for any kind of analysis are sediment size, nominal diameter, fall velocity, particle size distribution, porosity, and sediment load. The sediment load is classified as contact load (the material rolled or slide along the bed), saltation load (the material bouncing along the bed), bed load (the material transported along the bed) and suspended load (the material moving in suspension). The sediment transport causes different bed forms such as ripples, bars, dunes, antidunes, which changes over time and space. Various empirical approaches and equations are available for estimation of sediment transport, based on the river geometry, sediment classification and sediment size. For estimation of bed load, Mayer-Peter and Muller's equation is commonly used, whereas Einstein's method is used for estimation of total sediment load, by computing bed load and suspended load separately. Furthermore, critical velocity approach and critical tractive force approach is used to analyze the sediment movement. The critical tractive force approach was first introduced by Shields in which sediment movement is represented by the average bed shear stress.

Hydraulic models are essential to reproduce various hydraulic parameters for different types of hydraulic structures. Physical models scale down the dynamic phenomena whereas the mathematical models reproduce various parameters numerically. Both physical as well as mathematical models are used to reproduce and execute the different kinds of sedimentation studies. The simulation or reproduction of sediment transport in any kind of model is a critical task. The various modeling techniques as well as the different materials used for physical hydraulic models have been discussed here.

2. Model Studies for Sediment Transport

2.1. Mathematical Models

A wide range of computer programs are available for mathematical or numerical simulation using hydrodynamic equations and highspeed digital computers. Many software packages are available for simulation of sediment transport which can be categorized as 1D, 2D or 3D based on analysis method and the consideration of various system parameters. It's worth noting that sediment transport modeling is complex task and requires certain assumptions in numerical methods, fluid dynamics, and sediment transport processes. Depending on the specific objectives and complexity of the problem, specialized software packages are employed to perform the simulations efficiently. Boundary conditions and initial conditions have to be assumed and defined in the model to establish the model limits. Additionally, model calibration and experimental validation of the model results is crucial to ensure its accuracy and reliability.

In general, the one-dimensional differential equations of gradually varied unsteady flow in movable bed channels are extensions of the Saint-Venant equations for rigid boundary channels. They are the equation of continuity for sediment, the equation of continuity for water, and the equation of motion for the water-sediment mixture developed by Chen (1973). Certain assumptions are made while deriving these equations. Furthermore, there is no generally accepted set of governing equations for the bed and near-bed processes. The formulations of these equations, even though not so different, may still vary depending on the bed and near-bed layer concept, or simply depending on the approach. A number of two-dimensional models, often including corrections for three-dimensional effects, have recently been developed to be used for specific applications. In contrast to the bed and near-bed processes, modeling of suspended-material processes is practically always based on the sediment-transport or advection-diffusion equation with an additional fall-velocity advection term, which are derived from two-phase flow equations or using continuum approach. Even after required simplifications are made, the development of two-dimensional and three-dimensional flow and sediment models is constrained by the available computing resources. Due to the complexity of the problem and the typical need for long-term simulations, flow and sediment modeling can be expensive in terms of CPU time. Therefore, many flow and sediment models adopt further simplification. Because the bed-load flux is a vector parallel to the bed surface, the bed-load transport is essentially two-dimensional. But the flow and the suspended-sediment transport are fully three-dimensional processes. Therefore, two-dimensional flow and suspended-sediment transport models may have limited applicability. The present set of equations that are used in available models have limitations as three-dimensional flow pattern involving sediment transport has not been fully understood and therefore at present, average solution over space and time are used in these mathematical models.

2.2. Physical Models

Physical hydraulic models can be broadly classified as 'Geometrically similar models' in which all model parameters exhibit a certain relationship to the corresponding parameters in nature, and 'Distorted models' for which this requirement is partially fulfilled. Geometrically similar models are typically used for modeling spillways, intakes, harbors, and break water models. The distorted models are specifically used in many cases, for example where size of the stream to be modeled is very small. By choosing the different depth scale, accuracy in vertical measurements may be increased. Distorted models are also used to reproduce the bed movement adequately by achieving the higher velocities and higher turbulence in the vertically exaggerated models.

The physical models can be rigid, semi-rigid or mobile based on the reproduction of riverbed. Rigid bed models are generally used for studies of flood levels, in which the riverbed is constructed with rigid materials and the sediments are reproduced. In semi-rigid models the sides or parts of the bed are made rigid and the riverbed is made up of erodible material. In case of movable or mobile bed models both riverbed and side banks are erodible. The scale of the physical model would depend upon the nature of the study and experiments to be carried out. While choosing the scale for river models, various parameters would have to be considered such as the widths and the flow depth shall not be too low to avoid scale effects due to excessive friction, the model scale should ensure a sufficiently high Reynold's number and thus ensure turbulent flow for the lowest discharge. The magnitude of critical tractive force for various particle sizes in the model would affect the bedload movement and sediment simulation becomes a challenging task.

3. Sediment Simulation in Physical Models

In order to have better insight into the hydraulic system carrying sediments, a physical model on a suitable scale can be certainly useful. However, for these model studies simulation of sediment to model scale becomes very critical. The sediment particle size gradation and sediment load are the important parameters for reproduction in physical scale models. Along with this, appropriate bed movement in the model is crucial in deciding the choice of the material. The
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active bed movement in the prototype for certain flow regime should be reproduced in the model. Since the downscaling of the model dimensions the materials required for sediment reproduction are excessively fine and tend to float on the water surface due to surface tension. Due to fineness of material the cohesiveness of particles is increased and higher velocities are required to move such materials. To avoid this, the lighter materials are used in the models having lesser specific gravity than the natural sand or silt.

3.1. Materials used for sediment simulation

The choice of the material depends upon various factors, such as sediment gradation, particle sizes, sediment load and whether the bedload or suspended load is to be reproduced. Generally, sediments are reproduced in the physical model using suitable material such as sawdust, coal powder, pumice crush powder or walnut shell powder. A natural sand may also be used depending on its suitability. The following section briefly describes the various materials used for sediment simulation.

- Coal Powder: Coal dust particles share some similarities with natural sediment particles, making them suitable for modeling sediment behavior under certain conditions. The average specific gravity of coal dust varies from 1.4 to 1.5 and it forms an excellent bed material. However, getting a uniform size of material is a difficult task.
- Saw Dust: It can be used to simulate the suspended sediments. It can float in water and when it is wet it slowly settles in the water. However, it is difficult to have different size of particles in a large quantity.
- Pumice Stone: It has the specific gravity of 1.4 to 1.7 and grain particle sizes can be from 1mm to 3mm.
- Plastic Balls: Small plastic balls or beads having a specific gravity to nearabout 1.2 may be used to simulate suspended sediment particles, particularly in studies for evaluating the particle movement neglecting their cohesive properties. Plastic beads are typically uniform in size and shape, which makes them easier for operation and measurement during experimentation.
- Walnut shell powder: It has a specific gravity of 1.4 to 1.6 and it can be crushed to various particle sizes as per the requirement. This makes it popular material for model studies in India, however due to its growing applications in cosmetics and other fields, its availability and cost are a major concern as of now.
- Sand: In some of the physical model studies, natural sediments of specific size range may be chosen based on the scale and objectives of the study. Behavior of sand particles in water is affected by factors such as particle size, shape, density, and settling velocity. The movement and transport of sand particles can be studied to understand sediment dynamics, erosion, sedimentation patterns, and the formation of bedforms. Sand generally has a specific gravity ranging from 2.5 to 2.7, which influences how sediment particles settle or float in water and how they interact with the flow.

In view of the above discussion, there is a need to evolve a more suitable alternative for the sediment simulation, in form of the material which would be suitable and readily available. In this connection, the coconut shell powder was successfully used to reproduce the suspended sediments for some of the projects carried out at InfraPlan Hydraulic Laboratory, Pune.

3.2. Sediment Modeling Approaches

The geometrically similar Froudian model is scaled so that the Froud number is kept constant for the model and prototype. Froude scale models do not necessarily simulate the tractive forces and sediment erosion accurately as the viscous forces are not reproduced proportionally. However, sediment sizes can be adjusted in some Froude scale models. Therefore, the model sediment should be adjusted to properly simulate sediment transport in view of the geometrical scaling. A diagram of settling velocity of sand and silt particles in water illustrates that small particle <1 mm in diameter, settle at progressively lower velocities as the particles become smaller. For particle diameters larger than 1 mm. the settling velocity is a function of the particle diameter (d) to the 1/2 power. By increasing the size of a model sediment grain, the settling velocity can be corrected to the proper value for Froude scaling in the model.

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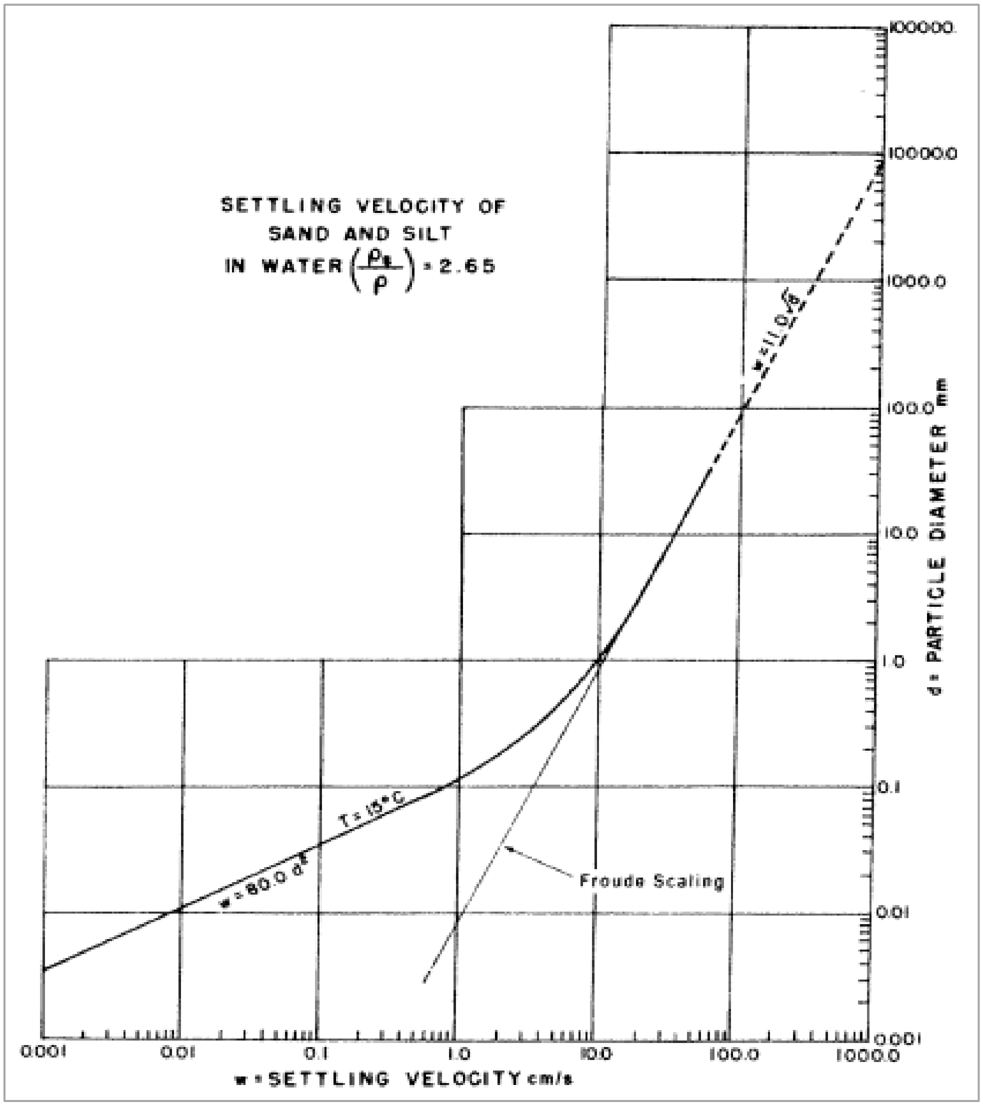

Figure 1. Settling velocity of sand and silt in 15^0 C water

Various similarity laws and approaches have been developed by multiple researchers for sediment movement based on flow and sediment dynamics. These sediment similarity laws are far from unanimous. To achieve exact quantitative similarity, theoretically all the dimensionless parameters should be matched for prototype and model. However, this seems to be difficult without distorting the model changing the sediment density, are any such modification. In view of this criteria for similarity of some the parameters must be relaxed. As such the modelers choose some of the key parameters which are essential to establish the similarity. The important parameters generally looked into are shields number, particle Reynolds number and particle fall velocity. It may not be possible to establish similarity for all the parameters simultaneously. As such the sediment simulation becomes a qualitative process and a proper care has to be taken while deviating from similarity some of the dimensionless parameters.

4. Case Studies

Various sedimentation studies for different kind of hydraulic structures such as desilting basin, tailrace tunnel, spillways as well as river diversion works, estuaries have been carried out on physical scale models at InfraPlan Hydraulic Laboratory, Pune. Two representative case studies have been presented hare with respect to sediment simulation.

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4.1. Case Study 1 - Physical model studies for Desilting Basin

A physical hydraulic model was constructed for one of the hydropower project in Laos. The desilting basin was reproduced on a geometrically similar scale of 1:16. The proposed project is run-off-river type having a power intake located on the right bank of the river at a height on 10 m above riverbed. The model studies were conducted for assessing the geometrical configuration sediment settling efficiency, sediment carrying capacity and efficiency of desilting basin. The data for sediment gradation as well as sediment load was provided by the project authorities. The anticipated sediment sizes were ranging from 0.001 mm to 1 mm. 100% of suspended sediments were below 0.2 mm size. In view of this the geometrical scaling of sediments would lead to very fine sediment size which would not be possible. As such, coconut shell powder having low specific gravity of 1.2 was chosen so that the model particle sizes would be larger.

The fall velocities of the particles were simulated, to reproduce the sediment deposition in the desilting basin using following equation developed by rouse was used.

$$\frac{Cy}{Ca} = \left(\frac{\frac{d-y}{y} * a}{d-a} \right)^{z} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots . Equation\ 1$$

Where,

Cy = Concentration at depth "y" above bed level
Ca = Concentration at 0.05d above bed level
d = Depth of flow
y = Depth at which concentration Cy is to be calculated
a = 0.05d

$$Z = \frac{w}{k * \sqrt{(g * d * s)}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots . Equation\ 2$$

Where,

W = Fall velocity of particles
K = Von Karman constant
g = Acceleration due to gravity
s = water surface slope

Thus, for the proper simulation of the distribution of sediments on a vertical 'Z_p' in model should be equal to 'Z_m' in prototype for corresponding diameter of the sediment. Hence, the following relationship is established for the geometrically similar models.

$$w_p = w_m \sqrt{\frac{d_p}{d_m}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots . Equation\ 3$$

Thus, a relationship between the diameter of low specific gravity material used in the model and that of the sediments in prototype can be worked out using above equation. Following Figure 2, the fall velocities for the different sizes of particles.

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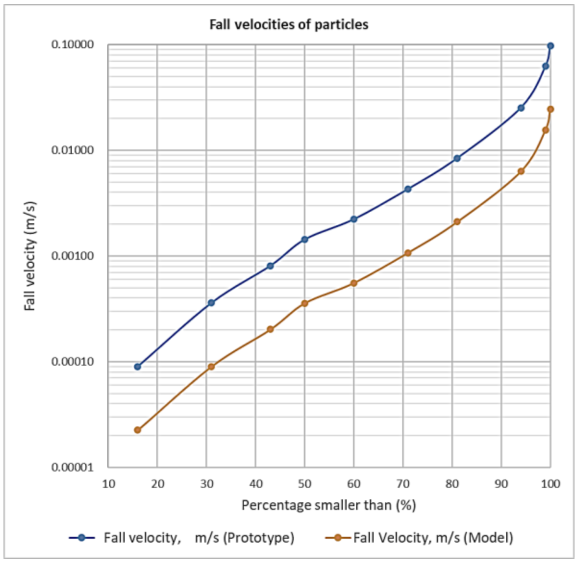

Figure 2. Fall velocities of the Particles

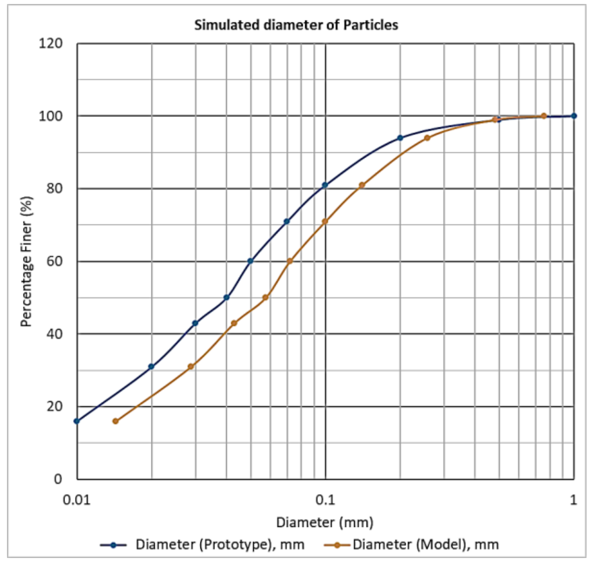

Figure 3. Simulated Diameter of Particles

The Figure 3 shows simulated diameters of the particles in model against prototype diameters. This is the sediment gradation curve used for the model. The coconut shell powder is crushed and sieved according to the gradation and used for the experiments as the suspended sediment load. The suspended sediment load for the diversion river for 1-in-10-year flood event is given as 8,500 mg/l by weight. This sediment load is converted to sediment load by volume as 7,083 ppm and the experiments were carried out by injecting the materials at inlet channel, upstream of desilting basin. Following Table 1 presents the fall velocities for the different sizes of prototype as well as model particles.

Table 1. Fall velocities and simulated particle sizes

Sr. No.	Diameter (Prototype), mm	Percentage of Sediments %	Percent smaller than %	Fall velocity, m/s (Prototype)	Fall Velocity, m/s (Model)	Diameter (Model), mm
1	0.010	16	16	0.00009	0.00002	0.014
2	0.020	15	31	0.00036	0.00009	0.029
3	0.030	12	43	0.00081	0.00020	0.043
4	0.040	7	50	0.00143	0.00036	0.058
5	0.050	10	60	0.00223	0.00056	0.072
6	0.070	11	71	0.00430	0.00108	0.100
7	0.100	10	81	0.00841	0.00210	0.141
8	0.200	13	94	0.02531	0.00633	0.257
9	0.500	5	99	0.06245	0.01561	0.483
10	1.000	1	100	0.09808	0.02452	0.757

Model studies were conducted using coconut shell powder as a sediment and various experiments were carried out for a combination of discharges and sediment concentration. Sediment deposition was observed and settling efficiency of the desilting basin was evaluated. It was found out that overall settling efficiency was 40% in view of the very fine particle size of prototype sediments. Furthermore, the experiments were carried out for effective flushing of the sediments to optimize flushing operation. This desilting basin has to be flushed with intermittent drawdown flushing and it takes little under 10 minutes for complete flushing of one unit of desilting basin. Photographs 1 to 4 shows the sediment deposition and flushing in a model.

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Photograph 1. Typical pattern of deposition inside the desander basin

Photograph 2. Drawdown flushing under progress (desander basin)

Photograph 3. Flushing in progress after closure of inlet gate

Photograph 4. After complete flushing is achieved

4.2. Case Study 2 – Physical model studies for River diversion and sediment deposition

A physical hydraulic model study for one of the river meeting Black Sea was conducted at InfraPlan Hydraulic Laboratory, Pune, to assess the hydraulic performance and sediment movement near the river mouth. Part of the coast near the river mouth is eroding for last few decades the erosion. It was decided to construct a geometrically similar physical model on a scale of 1:50 confirming to Froundian Similitude. The main objective of physical model was to analyze the behavior of river mouth in the normal flow conditions and flood events as well as to understand the capacity of river to provide sediment supply for the shores and highlight possible interventions. It was proposed to divert the river towards North side so as to enable the sediment deposition along the coast to improve sediment deposition. The sediment gradation indicates the sediment sizes ranging from below 16 mm to

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0.05 mm. The following approach was adopted to simulate the sediments based on the suggestions and recommendations by Hunter Rouse and C. A. Pugh. The fall velocity for actual prototype sediments was calculated and scaled down to model velocities. The model particle diameters were chosen so as to reproduce the required fall velocities in the model. Two different materials were compared for sediment simulation. Primarily the sand having specific gravity of 2.65 is used to simulate the required fall velocity. Alternatively, the coconut shell powder having specific gravity of 1.2 was used. The following Table 2 shows the required particle sizes of the sand as well as coconut shell powder.

Table 2. Sediment diameter simulation for sand and coconut shell powder

Sr. No.	Diameter (Prototype), mm	% Finer Gradation	% Finer	Fall velocity, m/s (Prototype)	Fall Velocity, m/s (Model)	Model Particle Dia (mm) (Using sand with Sp.Gr 2.65)	Model Particle Dia (mm) (Using Coconut Shell powder Sp.Gr 1.2)
1	16	100	50	0.415	0.058	0.46	3.00
2	8	44	22	0.293	0.041	0.31	1.50
3	4	15	8	0.206	0.029	0.22	1.00
4	2	13	6	0.144	0.020	0.17	0.063
5	1	12	6	0.098	0.014	0.13	0.50
6	0.6	6	3	0.071	0.010	0.11	0.35
7	0.2	5	3	0.025	0.004	0.06	0.20
8	0.1	1	1	0.008	0.001	0.04	0.10
9	0.05	0.20	0.11	0.002	0.0003	0.02	0.06

Extensive studies have been carried out to find the suitability of material and the coconut shell powder was found out to be the best option for simulation as suspended sediments. Detailed studies conducted for using Coconut Shell Powder and results were very promising. To evaluate the sediment movement following parameters namely; Critical boundary shear stress, shear velocity and dimensionless parameters, Grain Reynold number and Shield's parameter were evaluated for prototype as well as model grain sizes. As the bed shear stress, i.e., tractive force in the stream becomes higher than the critical stress of the particle, the sediment movement occurs. The particle movement in the model was evaluated against the prototype, the sediment diameters that can be moved at various flow conditions were evaluated. It was observed that, similar sediment movement as reported in prototype was occurring in the model. The detailed experiments were carried out further. It was observed that the sediment material sizes proposed in the model were appropriate to suite the required sediment properties. The prototype and model sediment gradation curves are shown in Figure 4. The studies conducted with this gradation curve indicated that the sediment deposition was adequately simulated in the model. It may be mentioned here that simulation is very qualitative in nature. However, they are very good for assessing the efficacy of the alternatives that were studied on the model.

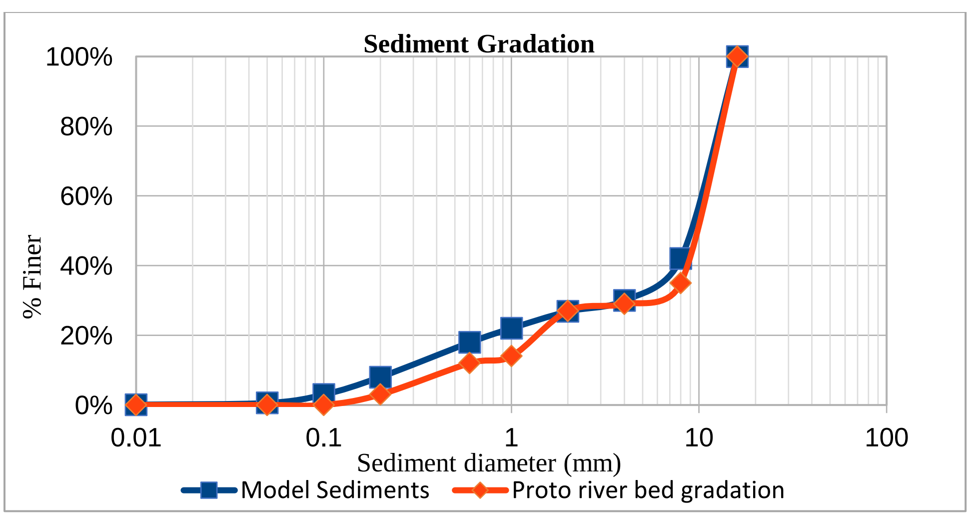

Figure 4. Critical Shield's Curve for prototype and Model Particles

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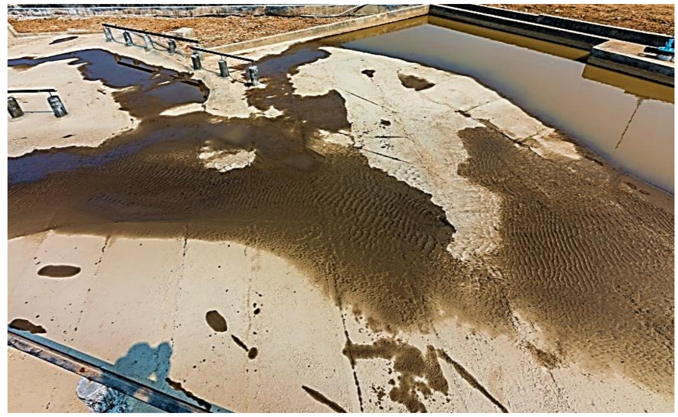
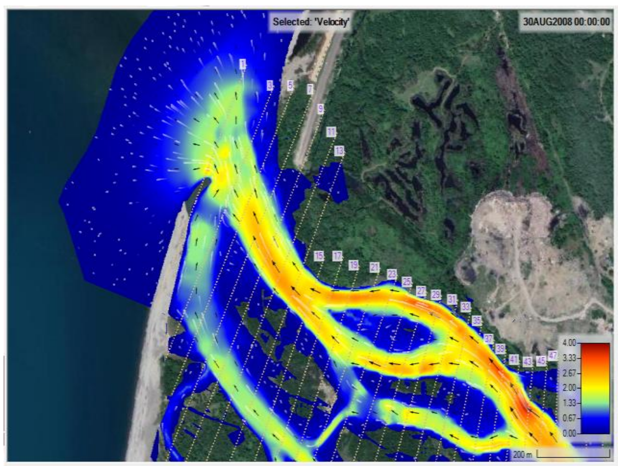
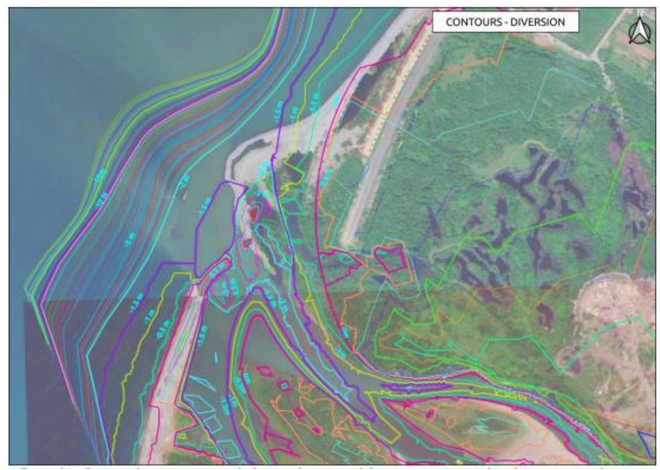
Photograph 5. Before Diversion (Existing Situation)



Photograph 6. After Diversion Scenario



Photograph 7. Velocity distribution after diversion



Photograph 8. Proposed Diversion of river based on model studies

Photograph 9. Aerial view showing river model

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5. Results and Discussions

The geometrically similar rigid bed physical hydraulic model on the scale of 1:50 confirming to Froudian similitude, provided good insight in assessing the hydraulic performance and sediment movement near river mouth. All the studies were carried out for steady state condition. Water surface profiles, velocities were measured and sediment deposition pattern was observed and reported. Mathematical model in Hec-RAS was prepared for the reach of 3 km from river mouth. The mathematical model was used to arrive and compare the water surface profiles and Manning's n values in various sections of river reach. The results of mathematical and physical model were in close agreement. The overall flow conditions at the river mouth were predominantly smooth and steady over entire range of discharges. High velocity flow is observed at certain reaches along the main stream (right end stream) for the flood discharges. The water surface profiles were plotted for various discharges. The upstream water elevations varied from 3 m to 5.5 m at 2500 m upstream. The depth of flow varied from 1 m to 5 m in the river reach over the entire range of discharges. The velocities varied from 0.5 m/s to 4.5 m/s. The sediment deposition was observed for various discharges. Sediment load of 5,000 ppm was considered for studies. Studies were also conducted for sediment load of 10,000 ppm. It was observed that the sediments of sizes 16 mm and above were not movable in this reach of river. The sediments of size less than 0.05 mm were getting flushed entirely into the sea as suspended load. The sediment of size varying from 0.05 to 16 mm got deposited in the various reaches of the river. The sediment deposition was in the order of only 10% to 20% of entire sediment load injected for discharges of 650, 1085 and 1340 m^3/s. The sediments that were washed out into the sea were of the order of 30% to 40%. The sediment deposition near the mouth was very negligible for existing situation and observed along the flow lines. Almost entire sediments near mouth were flown straight into the depth of canyon beyond bed elevation of -10 m.

The Diversion of river mouth was found feasible by bodily shifting the cross sections from 400m upstream of river mouth towards the north side. As observed from the 2D mathematical Hec-RAS model, almost around 66% of the flow was flowing towards north side after the diversion compared to previous around 40%, for a discharge of 650 m^3/s. Flow conditions in the physical model indicated, that the flow was getting diverted smoothly towards the north direction. Sediment deposition pattern near the mouth was considerably improved with respect to its location and extent. The more sediment deposition is observed near the right side of flow along the beach across the seabed. This can be seen from various photographs. It may be noted here that, the sediment deposition will occur slowly over the years and will get deposited towards the north side.

Model studies for diversion concluded that, appropriately designed guide bunds along with proper protection works designed for maximum velocities are required on the left bank of main stream as well as connecting stream. The maximum velocities for the design of guide bunds are to be arrived by extrapolating the observed maximum velocities in the channel (suggested at least factor of 1.5 to account for the fluctuations due to high velocities and turbulence). The seaward area of connecting stream, where the current depth is higher, needs to be filled after the diversion. The excavated material can be used for this filling. The construction of guide bunds along with the protection works should be completed within one working season. After the construction of guide bunds, its performance shall be monitored continuously for scouring, if any. Proper precautions to be taken up periodically so as to protect the guide bund. The sediment gradation data of the particles supplied for the river indicated lack of the particle size of 1 to 4 mm, which attributed less deposition of sediments at the river mouth.

This is a typical gravel bed river where all the fractions of the bed material move only for few flows in a year. As there is intermittent sediment supply from the upstream due to series of dams, the river bed surface gets progressively coarser due to transportation of fine sediments, for the entire range of discharges. Overall sediment deposition pattern shows typical ripples and large bed features such as bars, transverse and diagonal bars, riffles and pools, and transverse deposition of coarse material, etc. It can be inferred that transport of coarser material does not take place on continuous basis. The materials entering into the stream may get temporarily stored in the channel in the form of bars and will be released during the floods. Due to combination of these factors, it can be inferred that the sediment transport is very unsteady and non-uniform. It would be appropriate here to mention that, there are several uncertainties always involved in the model studies, with respect to sediment simulation, sediment movement, flow conditions, scouring and deposition. Yet the model provides good conformity with the overall behavior and relative effect of the intervention measure to be applied. The results should be qualitatively judged while planning the implementation measures. The model studies indicated that the coconut shell powder was suitable for simulating the particle movement in the model.

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6. Acknowledgement

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