Physical Modeling of Rivers in the Hydraulics Laboratory

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14. ABSTRACT

Distorted scale physical modeling is an effective means of modeling long stretches of rivers where depths would be too shallow if scaled using an undistorted scale. A distorted scale model uses a different horizontal and vertical scale compared to the prototype. The ratio of horizontal to vertical scaling is known as the distortion ratio. Distorted scale physical models are not frequently used by the Bureau of Reclamation's Hydraulics Laboratory due to the types of model studies typically requested in support of Reclamation's mission. Previous distorted scale models at Reclamation's Hydraulics Laboratory have used a distortion ratio of less than 5 in order to collect quantitative and qualitative model data. Distorted scale models have been used more frequently by the U.S. Army Corps of Engineers (USACE) and other laboratories in academia with distortion ratios of over 20. This study includes a literature review of distorted scale modeling used by other laboratories, the laboratory techniques employed for data collection, and the usability of the results produced at the distorted scale. Results of this scoping study show that distorted scale modeling at distortion ratios up to 10 may be feasible in Reclamation's Hydraulics Laboratory for physical models of rivers with larger spatial extents in future studies.

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Cover Photo: A distorted scale physical model in the Bureau of Reclamation's Hydraulics Laboratory in Denver, CO. (Reclamation/Melissa Shinbein)

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Executive Summary

Distorted scale physical modeling is an effective means of modeling long stretches of rivers where depths would be too shallow if scaled using an undistorted scale. A distorted scale model uses a different horizontal and vertical scale compared to the prototype. The ratio of horizontal to vertical scaling is known as the distortion ratio. Distorted scale physical models are not frequently used by the Bureau of Reclamation's Hydraulics Laboratory due to the types of model studies typically requested in support of Reclamation's mission. Previous distorted scale models at Reclamation's Hydraulics Laboratory have used a distortion ratio of less than 5 in order to collect quantitative and qualitative model data. Distorted scale models have been used more frequently by the U.S. Army Corps of Engineers (USACE) and other laboratories in academia with distortion ratios of over 20. This study includes a literature review of distorted scale modeling used by other laboratories, the laboratory techniques employed for data collection, and the usability of the results produced at the distorted scale. Results of this scoping study show that distorted scale modeling at distortion ratios up to 10 may be feasible in Reclamation's Hydraulics Laboratory for physical models of rivers with larger spatial extents in future studies.

Introduction

The Bureau of Reclamation's Hydraulics Laboratory in Denver, CO provides physical modeling in the area of environmental hydraulics. The Hydraulics Laboratory conducts physical modeling of fish passages, fish protection and screening, river restoration and habitat features, and reservoir and river sedimentation related to hydraulic structures. Demand for physical modeling related to Reclamation's mission has typically focused on structure and near-structure performance in rivers and reservoirs. Recent demand for physical modeling of rivers with larger spatial extents has highlighted the need for better understanding of how to successfully represent these projects at model scale.

Physical modeling of rivers presents a unique set of issues including wide geographic extents, high flows, and shallow depths along with sediment mobility. Distorted scale modeling may be utilized to best represent field characteristics in a laboratory setting. This scoping project will act as an internal guidance document on distorted scale physical models by answering the following questions:

1) How are other hydraulic laboratories conducting distorted scale modeling?
2) What laboratory techniques can be used to collect meaningful data?
3) What are the results of these studies and how are they applicable to the prototype?

To answer these questions, the project team reviewed literature on distorted-scale physical modeling including how sediment movement is affected and how to collect meaningful data in the distorted-scale environment. Other goals of this project were to explore of the limitations of physical modeling of rivers and determining when computational fluid dynamic (CFD) models could be utilized instead. The most effective ways to obtain data in distorted scale models was explored. Finally, the project team suggests future uses for distorted scale models based on Reclamation's needs.

Literature Review

Distorted Scale Models

Distorted scale physical models are generally used for long stretches of watercourses that, if modeled with simple undistorted geometric scaling, would result in water depths too shallow to properly scale without interference from surface tension or tractive forces. A distorted scale model uses a different horizontal and vertical scale compared to the prototype. Typically, the horizontal scale is a much larger number, thus a smaller scale to prototype, than the vertical scale due to the large area covered in the model (Briggs, 2013). The ratio of horizontal to vertical scaling is known as the distortion ratio. In models with large distortion ratios (i.e., horizontal scale significantly larger than vertical scale), velocity directions may not be correctly reproduced, and the distortion may be visibly distracting to observers. Therefore, Reclamation's Hydraulics Laboratory has used distortion ratios less than five to ten per recommendations for collecting quantitative data (Chanson, 1999). Another major drawback to distorted models is as the distortion of a model is linked to a defined variable, such a depth or roughness, the model can only be used to accomplish this objective. Thus, distorted models can only be used when the objective is clearly pre-defined (Bureau of Reclamation, 1980).

Distorted scale physical modeling has been used since Osbourne Reynolds used a distortion ratio of 33 to study a movable bed model of the River Mersey estuary in 1887. However, the validity of these studies was not assessed until 1955 when Einstein and Chien derived similarity conditions via theoretical and empirical equations for the hydraulic and sediment transport of distorted scale rivers. These equations were then applied to a numerical example to confirm that distorted scale modeling can be an "acceptable compromise permitting the solution of certain problems which otherwise cannot be solved except by experimentation" (Einstein and Chien, 1955).

These methods of similitude can be broken down into three main requirements (Hughes and Pizzo, 2003):

1) Geometric similitude- ratios linearly correspond to prototype;
2) Kinematic similitude- ratios of vectoral motions for all particles correspond to prototype;
3) Dynamic similitude- ratios of all vectoral forces correspond to prototype.

Generally speaking, most distorted models are distorted with respect to geometric similitude. However, there will inadvertently be distortion of turbulence in physical models, disrupting kinematic and dynamic similitude.

The U.S. Army Corps of Engineers (USACE) has worked with distorted scale physical models extensively due to their agency's interest in large waterway projects, large river systems, and coastal environments. Because of this, USACE has conducted research on gauging the applicability of qualitative and quantitative results in distorted scale models. These models use a distortion ratio of up to 32.6, far exceeding the normally recommended distortion ratio limit of 10. Furthermore, USACE considers a "large scale" model to be a horizontal scale < 600 compared to prototype with a 1 to 10 distortion ratio. A "small scale" model are horizontal scales > 3600 compared to prototype with a 6 to 22 distortion ratio (Davinroy, 2011). Please see Table 1 for a breakdown of these models used by USACE, their distortion ratios, methods for collecting data, and results with respect to impacts of distortion.

Table 1 US Army Corps of Engineers Distorted Scale Models. WSE stands for water surface elevation, ADV stands for Acoustic Doppler Velocimeter, PIV stands for Particle Image Velocimetry, LSPIV stands for large-scale Particle Image Velocimetry, ERDC stands for USACE Engineer Research and Development Center. Due to the number of iterations performed during the Cook Inlet study, this has been broken into two separate rows. For more information on these studies, please see Appendix A.

Prototype Location	**Distortion Ratio**	**Methods for Data Collection**	**Results with respect to impacts of distortion**	**Citation**
Cook Inlet, Alaska	Large-Scale: 32.6 Small-Scale: 24.6	Dyes and tracers; WSE compared to bathymetry	Idealized bathymetry prevented vertical mixing between layers. Upstream boundary conditions are important to modeling and limit usability of small-scale model.	Hughes and Pizzo, 2003
Cook Inlet, Alaska	Additional Study: 1-6	Superimposed velocity maps from PIV	Bottom roughness is critical for similitude of river bend flows. Steeper slopes in distorted models will generate less vertical fluid motion but this effect lessens towards the surface at free flow.	Hughes and Pizzo, 2003
Micro-modeling at ERDC	6 to 22	WSE compared to bathymetry; LSPIV	Can duplicate bathymetry with high levels of accuracy (10% error) but models need to be calibrated to prototype	Davinroy, 2011
Los Angeles and Long Beach, California	4	Water level sensors and wave generation.	Model has been used since 1973. McGehee: maximum uncertainty 5% for waves. Seabergh: adjustments to wave generator position can be made to correctly reproduce refraction.	McGehee, 2001 and Seabergh, 1993
Port of Anchorage, Alaska	4 and 2	Dyes and tracers; WSE compared to bathymetry; ADV	Good comparison during calibration between model and prototype. Injected dye into specific areas of interest for flow visualization.	Hughes, 2010

These USACE models emphasize the importance of calibration to prototype for sediment transport and flow patterns. However, once the model is calibrated, it can provide useful quantitative data for distortion ratios under 10. Should the distortion ratio exceed 10, vertical mixing becomes an issue, but these models can still be used for impacts to water surface elevation and qualitative flow patterns. In Hughes and Pizzo (2003), the impacts of the distortion on turbulence were studied extensively with 3 different distortion ratios (2, 4, and 6) at 4 different configurations compared to a non-distorted scale model of the same prototype. The four different configurations were: unconstrained flow separation (free jet), constrained flow at a vertical edge (constrained jet), a sloped edge at three different angles, and a vertical step. Velocity fields from each distortion ratio were the compared to the undistorted model for each configuration. Results from this study for each configuration are:

1) Free jet: no substantial difference between the distorted and undistorted as turbulence is mainly manifested in the horizontal plane;
2) Constrained jet: good correspondence between the model and the prototype indicate turbulent fluctuations in the vertical direction are weak compared to the horizontal plane, thus distortion does not have a major impact on turbulence;
3) Sloped edge: flow separation exhibited a scale effect which was strongest near the bottom and lessened closer to the free surface. This impact also decreased further downstream, away from the jet boundary;
4) Vertical step: turbulence is generated primarily in the vertical plane and is not impacted by the distorted geometry.

Thus, if turbulence is dominated by either the horizontal or vertical plane, not a combination of the two, the impacts of distortion on model results are limited.

Table 2 Selection of distorted physical models used in academia. WSE stands for water surface elevation, HGL stands for Hydraulic Grade Line, LSPIV stands for Large Scale Particle Image Velocimetry. For more information on these studies, please see Appendix A.

Prototype Location	Distortion Ratio	Methods for Data Collection	Results with respect to impacts of distortion	Citation
Mississippi River Delta, Louisiana	15	Dye Injections; PIV and PIVLab	Average 10% difference of velocity data from theoretical values.	Scott, 2019
Mississippi River Delta, Louisiana	24	HGL; WSE; HEC-RAS for comparison	WSE was 1-2 ft higher in model where the difference increased the further downstream. Good comparison to HEC-RAS but meant to guide additional studies, not a stand-alone result.	Waldron, 2008
Yellow River, China	Transverse: 28 Longitude: 560	WSE	Consistent trend between prototype and model with R^2=0.83. Because measuring for bankfull distribution, did not need as many adjustments to flow field for slope.	Zhang, 2019
Pacific Northwest, Washington	13	ADV and WinADV, LSPIV	Friction factors were not attainable. The results are considered generic only for rivers and structures similar to the prototype as model was only for straight lengths of channel.	Fox, 2005

Distorted scale models are also used in academia, with select models designed at a higher distortion ratio than used by USACE for quantitative analysis. These projects allowed higher distortion ratios because the variables of interest were often narrowly defined. While USACE often assessed wave action with a particular interest in flow distribution, select projects in academia were interested in one or two specific variables. Consistent trends and relatively low error occurred for distortion ratios far exceeding 10. This was especially true if field data from prototype was available for calibration of the physical model. Table 2 showcases a selection of articles reviewed. For more information, please see Appendix A.

These models, whether government or academia, tend to focus on the same variables of interest and use the same methods for data analysis. The most common variables of interest are flow patterns or velocities, sediment transport and deposition, water surface elevation, and impacts of turbulence. For single point velocities, an Acoustic Doppler Velocimeter (ADV) can be reliably used to collect velocities in the distorted scale. Field measurements often use a 3- or 5- point method to average velocities in a single water column. However, due to distortion impacts on the boundaries, a single velocity point at 0.6 times the water depth can be used to accurately collect velocity data within a 5%

margin of error (Zhao, 2013). Large Scale Particle Image Velocimetry (LSPIV) is normally used to collect surface velocities and flow patterns along the model. For distorted scale models, LSPIV can be utilized with an average percent variation of 10% (Scott, 2019). LSPIV can also be used in specific "blind spots" or locations with limited flow due to structures such as barbs or boulders. This method requires the tracer particles used in the assessment of LSPIV data to be inserted into the flow path in the desired area (Fox, 2005).

In all, the key to the success of these distorted scale models lies in the availability of prototype data for model calibration. Since dynamic and kinematic similitude cannot be strictly adhered to during geometric distortion, calibration with prototype data can be used to verify model performance (Gallisdorfer, 2014).

Sediment Distorted Scale Models

Sediment scaling presents a complex problem when sediment needs to be distorted and is often a crucial variable for distorted scale models. In physical scale modeling, loss of similitude between prototype and the model can be caused by friction forces, flow divided into multiple channels, sediment loading, and settling velocity (Einstein and Chein, 1955). Often, to account for these factors, a different scaling is used for sediment from the rest of the physical model. Some methods commonly used are Shields function and Taylor modification.

The Shields function is a dimensionless diagram that relates shear to a boundary Reynolds number (Pugh and Dodge, 1991). The curve is then used to define the threshold for sediment movement and other sediment transport parameters. Per Pugh and Dodge (1991), the Taylor modification is a "dimensionless sediment discharge parameter, which provides nesting curves that parallel Shields' incipient motion curve at constant values of dimensionless sediment discharge". The Taylor modification allows adjustments to sediment discharge to best scale sediment diameter and specific gravity and is most applicable to sand or smaller-grain materials. Afterwards, the Reynolds number is used to relate the Shields function to the Froude scaling used in the rest of the model (Pugh and Dodge, 1991).

In addition to the Shields function and Taylor modification, slope in the physical model can be distorted to a different scale than the rest of the geometric distortion, interfering with mixing and sediment transport. This may happen when the model is not large enough to overcome scaling effects for sediment (Gill and Pugh, 2010). The solution to this is often to not follow Froude and Reynolds scale distortion as strictly and to calibrate the model to known field data (Gill and Pugh, 2009). When field data is not available for calibration, results are often not quantifiable but can still produce qualitative data for velocity profiles (Mefford, 2004). Furthermore, scour is often overestimated in the model due to lack of cohesive forces when scaling sediment, presenting a worst-case scenario. Results from these studies can be used to determine where erosion is most likely to occur (Abderrezak, 2013).

Table 3 Selection of distorted scale physical models with respect to sediment. WSE stands for water surface elevation, LSPIV stands for Large Scale Particle Image Velocimetry.

Prototype Location	Distortion Ratio	Methods for Data Collection	Results with respect to impacts of distortion	Citation
Missouri River	Slope: 2.4; Shields diagram and Taylor modification for sediment design	Expands methodology for sediment transport including incipient motion.	Model would align to prototype by distorting the slope separately from other geometric properties during calibration.	Gill and Pugh, 2009 and 2010
Elwha River	Shields diagram and Taylor modification for sediment design, scale ratio of 3; time scale adjustment for sedimentation process ratio 32.8	WSE, velocity vectors/profiles	Not many quantifiable numbers as there was no prototype model to compare to. Thus, all results were qualitative.	Mefford, 2004
Old Rhine River	Shields diagram for sediment design- each grain size has a different geometric scale (page 101 for breakdown); time scale of 6	LSPIV	Used smaller scale sediment particles, thus less scour anticipated in the prototype (more shear required to move heavier sediment) with qualitative results focused on where erosion was most likely to occur.	Abderrezzak, 2013

Numerical versus Physical Distorted Scale Models

As limitations for a particular physical model increases, numerical models are often suggested as an alternative solution. However, numerical models come with their own limitations. Numerical models are often less expensive and less time-consuming than physical models. However, physical models, even when distorted, are often more accurate at modeling sediment transport and air-entrainment. Thus, it is worth comparing the pros and cons of each before selecting an approach. Both distorted physical models and numerical models require calibration from field data to perform accurately.

Distorted physical models can accurately provide quantitative results for most typical variables for a distortion ratio of less than 10. Examples of these variables include WSE, field flows and velocities, and sediment transport. Once the distortion ratio exceeds 10, physical model results become more qualitative. However, for less common variables of interest such as average cross-sectional velocity, distortion can largely impact the results (Fang, 2008). Additionally, distorted scale models tend to underestimate impacts from vertical mixing (Hughes and Pizzo, 2003). While these impacts of distorted scale modeling can negatively affect sediment transport, numerical models have difficulty computing kinematic behavior of cohesive and non-Newtonian fluid at this time (Huang, 2018). Sediment transport is also a three-dimensional phenomenon. Three-dimensional modeling is more expensive and time consuming than 1- or 2-dimensional numerical modeling. The trade-off between accuracy in sediment transport and time/cost must also be considered for the selection of numerical modeling. Therefore, the selection of a numerical versus a distorted physical model depends on the distortion ratio that would be needed to construct the model, the variables of interest, and the type of data, qualitative or quantitative, needed.

Table 4 Numerical models that were compared to distorted-scale physical model studies. For more information on these studies, please see Appendix A.

Prototype Location	**Distortion Ratio**	**Methods for Data Collection**	**Results with respect to impacts of distortion**	**Citation**
Tributaries to Three Gorges Dam, China	2, 5, 10	Mathematical modeling compared to previous physical models and field data	The distorted scale strongly affects the velocity field in the cross-sectional and vertical directions. However, the error factor along the direction of the flow was small (<12%).	Fang, 2008
Wushe Reservoir, Taiwan	10	Storage capacity of reservoir compared to physical model and field data	Qualitative comparison between field, physical model, and numerical model show good agreement (no numbers provided for deviations between models).	Huang, 2018

Future Distorted Scale Project Ideas

Reclamation's Environmental Roadmap provides a guide for research needs within the Science and Technology Program in the fields of river restoration and sedimentation modeling, among others. A list of future potential research projects was developed for which distorted scale physical modeling may be utilized. These areas of study include:

1) Improving fish screens;
2) Modeling complex river systems (multi-channel) for sediment patterns;
3) Restoration projects with sediment dynamics;
4) Lateral habitat features at low flows;
5) Habitat availability function of floodplain;
6) Spatial and temporal scale modeling for optimizing river restoration budgets;
7) Features with sustainability in floodplain;
8) Reservoir sediment patterns;
9) Dam removal with sediment sluicing;
10) Debris movement;
11) Rock ramp designs.

Reclamation may also have new opportunities for distorted scale physical modeling in support of other Department of Interior agencies such as the National Park Service.

Conclusions and Recommendations

This scoping level study shows that physical hydraulic modeling with a distorted scale is feasible for Reclamation's Hydraulics Laboratory for quantitative results up to a distortion ratio of 10 and qualitative results for larger distortion ratios. The key to successful distorted scale modeling lies in reliable prototype field data for physical model calibration, especially if sediment transport or scour are variables of interest. Other agencies such as USACE and academic institutions have been successfully using distorted scale models since the 1970s. Results from these studies show the range of applicability of distorted scale physical models to the type of work requested in Reclamation's Hydraulics Laboratory.

Data collection techniques such as LSPIV, ADV, and WSE measurements are directly applicable to distorted scale models and can provide reliable quantitative analysis when applied appropriately. For models involving sediment transport, the results tend to be qualitative and overestimate scour. Furthermore, distorted scale models can often produce comparable results for numerical models.

Future work may include using distorted scale modeling to meet the needs of Reclamation projects, especially for rivers with larger spatial extents. Depending on the specifics of the project, a higher distortion ratio may be considered to produce valuable results. As the physical model is constructed, other laboratories and agencies mentioned in previous sections can be contacted for discussion of distorted scale modeling techniques. To apply the techniques described in this scoping-level project, a Science and Technology Program project with a distorted scale will be submitted during a the FY22 call for proposals.

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Appendix A: Literature for Distorted Models

Author	**Title**	**Distortion Ratio**	**Variables of Distortion**	**Variables of Interest**	**Laboratory Technique**	**Results**	**Limitations**
Bureau of Reclamation	Hydraulic Laboratory Techniques	N/A	N/A	N/A	Reference for laboratory techniques. Pages 52-55, 106-113.	N/A	N/A
Chang-Chia Huang	Physical Model-Based Investigation of Reservoir Sedimentation Process	10	Geometric	Storage capacity of reservoir	Qualitatively compared the physical model to the numerical model to see when the sediment elevation would reach critical level	Determine when the reservoir hits critical capacity and needs to be dredged. Physical model is preferred, even if distorted, for sediment assessment in the short term.	Discusses limitations of distorted scale models versus numerical models for sediment (page 3).

Author	**Title**	**Distortion Ratio**	**Variables of Distortion**	**Variables of Interest**	**Laboratory Technique**	**Results**	**Limitations**
David D. McGehee	Estimating Overtopping Impacts in Los Angeles/Long Beach Harbors with a Distorted-Scale Physical Model	4	Geometric	1) Change in energy; 2) low frequency wave energy as a function of breakwater crest elevation	1) wave generation; 2) manually adjust crest elevation to overtopping conditions with concrete and clay.	Non-dimensional comparison of total energy at two sites. Results appear to be within 10% of what is expected in prototype.	Lower limit of wave periods for high wave energy appear to develop too quickly for field thus harbor energy needed to be normalized by incident energy (as with wind waves). Upper limit at low frequency transmit much more energy than wind of same height thus focuses on effect of crest elevation.
Einstein and Chien	Similarity of distorted river models with movable bed	Varied; defined here as h_r	1) Vertical distortion: horizontal lengths are independent of h_r; 2) Grain size ratio (D_r) on length scale with a separate second distortion; 3) slope ratio (S_r) independent of other ratios, model is assumed tilted in addition to distorted; 4) ratio of	N/A	1) Friction Criterion-frictional similarity is based on the behavior of the entire section for which it assumes the form of a rating curve (generalized Manning equation) (page 443), 2) Froude scale; 3) Sediment Transport: focus on intensity of transport	Delta values in table 1 can be used to assess impacts of deviation from the other variables listed (p454). Shows the validity of distorted scale models and has a key advantage in that it "permits the prediction of its reliability at least in a qualitative way... and even gives such deviations quantitatively " (page 454)	"It is impossible, however, to introduce only one distortion. This fact is apparent in the case of side slopes distorted in the same manner as vertical heights… in the case of a sediment-carrying stream still more distortions must be introduced. " (page 441)

Author	Title	Distortion Ratio	Variables of Distortion	Variables of Interest	Laboratory Technique	Results	Limitations
			effective densities can represent a 4th distortion; 5) 5th distortion for hydraulic time ratio (t_r) ; 6) bed-load ratio (q_b) and total-load-rate ratio (q_T); 7) settling velocity		and shear between model and prototype; 4) Zero Sed Load: the sediment begins moving at a similar flow in the model and prototype; 5) Laminar-sublayer: function of grain size		
Gensheng Zhao	Similarity of the velocity profile in geometrically distorted flow model	4	Chezy coefficient	Depth-averaged horizontal velocity (0.6 times the water depth below WSE); Chezy coefficient	Chezy coefficient deduced for vertical velocity; 1-, 3-, 5- point Measurement methods for velocity	1 point. method for collecting horizontal velocity okay to use; point velocities at bed are smaller than prototype; point velocity at free surface larger than prototype	This was only tested for one model; should reapply methods at other distortion ratios

Author	**Title**	**Distortion Ratio**	**Variables of Distortion**	**Variables of Interest**	**Laboratory Technique**	**Results**	**Limitations**
Hongwei Fang	3D Numerical Investigation of Distorted Scale in Hydraulic Physical Model Experiments	1, 2, 5, 10	Geometric distortion; sediment settling and sediment concentration	Flow and sediment movement	3D numerical modeling of an original physical model completed in 1986.	1. Flow- more deviation at higher levels of distortion, however still close at cross sections; 2a. Sand settling- starts off well and further downstream gets almost perpendicular (page 49); 2b. Sediment concentration- trend is similar to (2a) but much larger deviation values	The issue with distortion is selecting sediment that will be represented properly in the physical model. This study does not consider the issues with physical modeling and instead directly compares numerical modeling.
James F. Fox	Fluid-sediment dynamics around a barb: an experimental case study of a hydraulic structure for the Pacific Northwest	13	Geometric; Sediment (Shields)	(1) flow redistribution experiment, (2) sediment movement experiments, and (3) streambank protection	ADV; LSPIV; Scour	LSPIV dead zone immediately downstream of barbs; used ADV for quantitative data; usable PIV results for quantitative data.	Due to distortion, similitude of the friction factor was not attainable.

Author	Title	Distortion Ratio	Variables of Distortion	Variables of Interest	Laboratory Technique	Results	Limitations
Michael J Briggs	Basics of Physical Modeling in Coastal and Hydraulic Engineering	2; 4	Geometric distortion	Los Angeles and Long Beach model and Estuarine Experiment flume - models previously completed and presented as case studies	Not listed	This Technical note aims to provide an overview of physical laboratory modeling performed by Army Corps of Engineers and thus does not discuss specific study results but rather an assessment of pros and cons of different types of physical models.	Waves may have multidirectional characteristics with frequency and directional spreading that are not always possible to simulate as accurately in the laboratory. These limitations are compounded in the distorted scale as the horizontal and vertical scale are different.
Patrick Scott	Qualitative and Quantitative Flow Visualization Studies on a Distorted Hydraulic Physical Model	15	Geometric; dynamic; sediment; time (page 11-13)	1. Qualitative Interests: Determine if flow in the model is Reynolds independent; 2. Quantitative Interests: Hydrodynamic patterns	1. Qualitative: fluorescent dye 2. Quantitative: PIV (and PIVLab) for surface velocity; mobile bed	1. Qualitative- mixing in the model to examine Reynolds number independence was met. Plumes would flow into the walls sooner in the bends and hug outside banks of curve with increasing sharpness of curvature, helical and secondary mixing were more easily observed in sharper bends (page 33). 2. Quantitative- used PIVLab successfully	Scale effects in turbulence; see page 52 for full list of limitations and Appendix C/D for setup and how to keep seeding constant between trials

Author	Title	Distortion Ratio	Variables of Distortion	Variables of Interest	Laboratory Technique	Results	Limitations
Robert D. Davinroy	Hydraulic Sediment Response (HSR) Modeling, Replication Accuracy to the River	6 to 22	Linearly for bed movement	bed movement; channel forming bed response/discharge response that best develops the observed bed response of the river	Polyurethane foam for bed; granular plastic and urea for sediment; lasers for bathymetry to normalize velocity (compare to ADCP field data); high definition cameras for flow visualization and general model observation; galvanized steel mesh for solid structures	Small scale has a smaller mean square error at the thalweg but more variation of WSE at the cross-section. Case Study 1 (page 8) distortion ratio 11, model variance from bathymetry 6.6%. Case Study 2 (page 12), distortion ratio 21.5, variance 14.2-16% (mostly due to dredging at site)	HSR models rely on hydrodynamic and sediment transport to develop equilibrium bed response and resultant 3D bed configuration within the channel (use calibration parameters to make repeatable). When modeling response of bed around structures, often overestimates scour.
Ryan L. Waldron	Physical Modeling of Flow and Sediment Using Distorted Models	24	Geometric; Sediment (Shields)	Quantify impacts of scaling on results (replicate prototype sand transport and WSE and velocity data)	Hydraulic grade line for comparison of gradient (p29) can use gradient to indicate if distortion impacting WSE; used HEC-RAS for numerical modeling	1) WSE: stage 1-2 ft higher in model, differential increase further downstream; 2) HEC-RAS is similar to WSE produced in model	Model is scaled to 1994 gauge data, prototype seems to no longer match; model impacted by hysteresis (governed by headwaters); model was not designed for quantitative studies, only qualitative of sediment transport

Author	Title	Distortion Ratio	Variables of Distortion	Variables of Interest	Laboratory Technique	Results	Limitations
Steven A. Hughes and Gian-Marco Pizzo	Flow Table Study of Cook Inlet, Alaska	Large Scale: 32.6 (15,625 horizontal/ 480 vertical); Small Scale: 24.6 (11,306 horizontal/ 480 vertical)	Geometric distortion (turbulence scale effects)	1. large-scale flow patterns; 2. small-scale flow patterns; 3. turbulence scale effects in distorted physical model; 4. sloping transitions; 5. 3-D flow model of inlet	Two Models: 1) Large and small scale- dyes and tracers for complex flow; 2) turbulence (page 29)- stress does not exhibit similitude	Results showed qualitative location of gyres and eddies	Idealized bathymetry prevented vertical mixing between layers; upstream boundary conditions important to modeling and limit usability of small-scale model. Distortion does not work well for a jet (page 31) where vertical velocities exceed horizontal velocities. Similarly seen at flow around a bend (page 32).
Steven A. Hughes and Gian-Marco Pizzo	Flow Table Study of Cook Inlet, Alaska (same as above)	1-6 (p43 and 64 for full list of distortion scale factors)	Turbulence	1. Unconstrained flow separation at vertical edge; 2. Constrained vertical edge; 3. flow separation at sloped edge (prototype slope is 45°); 4. flow separation at vertical step	Velocity measurements using laser doppler velocimeter throughout area of interest which was adjusted due to distortion (page 40). Comparison made by superimposing distorted velocity map onto image of distorted model.	1. 12 tests (3 distortions, 4 velocities)- similar agreement on all levels of distortion; 2. same as 1, implying vertical turbulence very small compared to horizontal; 3. Distorted slopes of 63°, 75°, and 80°. "Some of the turbulent structure geometry will be incorrect, but the distorted model should reproduce somewhat similar dominant flow patterns associated with flow separation with velocity magnitudes nearly correct" (page 60); 4. Good similitude (page 65 for more discussion)	"In all cases the impact of model distortion was evaluated by comparing the measured velocity fields of the prototype experiment with the velocity fields of the distorted models scaled to prototype size using appropriate scale ratios. Judging whether or not good similitude existed between model and prototype was subjective, and good correspondence was noted where variations between vector fields were thought to be small enough to have been caused by measurement error or small misalignment of boundary geometry between experiments." (page 66)

Author	**Title**	**Distortion Ratio**	**Variables of Distortion**	**Variables of Interest**	**Laboratory Technique**	**Results**	**Limitations**
Steven Hughes	Physical Model of Knik Arm and the Port of Anchorage, Alaska	4 and 2 (Large-Area Model and Small-Area Model)	Geometric	1) Flow velocity and water level (large model); 2) Tidal cycle; 3) Boundary Conditions	ESTEX Flume (60 ft wide and 420 ft long); bathymetry and topography for model construction; wave gauges (p50-51); Sontek ADV; dye tracer for boundary condition and baby powder for ice floes (p53)	Good comparison of the calibration gauges to the previous calibration run was an indication that the new reference velocity signal was valid. Comparisons of velocities made between the pre-expansion Port and the completed Port expansion revealed only a slight increase in maximum velocity magnitudes at locations along the future dock face	Discussion of scale effects on p31

Author	**Title**	**Distortion Ratio**	**Variables of Distortion**	**Variables of Interest**	**Laboratory Technique**	**Results**	**Limitations**
William C Seabergh	Los Angeles and Long Beach Harbors Model Enhancement Program, Improved Physical Model Harbor Resonance Methodology	4	Geometric; wave timescale	long period waves caused by an offshore oil platform	1) Wave generator; 2) Data acquisition: ADACS (p15) water level sensor	"A comparison of model and prototype data indicated good correlation." (p32)	Wave refraction and diffraction govern how wave energy is distributed along the coast and throughout the harbors. Both cannot be scaled simultaneously in distorted model; a solution can be found for exact scaling of diffraction and refraction to the wave period (long-wave), below which adjustments to wave generator position can be made to correctly reproduce refraction (p13)
Xue Zhang	The Use of a Microscale Physical Model to Simulate Bankfull Discharge in the Lower Reaches of the Yellow River	28 (transverse) 560 (longitude)	Geometric distortion; model slopes	WSE: 1) bankfull discharge versus prototype; 2) impacts of 3D distortion; 3) bankfull discharge versus numerical model	water level: needle gauge at tailwater, radar gauge in model	1. Consistent trend between prototype and model for bankfull discharge; 2. Relationship $R^2=0.83$; 3. close to numerical model as well	Appears to have different slope adjustments at different points along the model. This model is distorted in the 3D scale, but because analyzing for bankfull distribution, do not need as many adjustments to the flow field for slope

Appendix B: Literature for Sediment Distorted Models

Author	Title	Distortion Ratio	Variables of Distortion	Variables of Interest	Laboratory Techniques	Results	Limitations
Brent Mefford	Elwha River Surface-Water Intake Structure	Shields diagram and Taylor modification for sediment design, scale ratio of 3; time scale adjustment for sedimentation process ratio 32.8 See pages 5-7 for discussion on scaling process	Sediment	Sediment entrainment/exclusion and fish passage/protection specifically of sand and gravel	Sediment scaling using Shields parameter for settling velocity; coal for bed	1. Steady state- could not use quantifiable numbers as there was nothing to calibrate to; 2. Flood hydrograph- visual observation of flow separation and sediment patterns; 3. Intake modifications- quantitative data for velocity measurements; 4. Rock ramp- visualization of how boulders should be placed	Standard technique for calibrating model is comparing prototype and model results for sediment, which was not available for this model. Silt and clay not represented.
C.A. Pugh and R.A. Dodge	Design of Sediment Models	N/A	Shields function with Taylor modification	Lateral scour of fuse plug	Shields and prototype comparison	Within 2.5% of field test.	N/A

Author	**Title**	**Distortion Ratio**	**Variables of Distortion**	**Variables of Interest**	**Laboratory Techniques**	**Results**	**Limitations**
Dale Lentz	Blue River Fish Barrier Hydraulic Model Study	N/A	N/A	Fish barrier study: Scour erosion	Sediment modeling; Sontek ADV; contour mapping; WSE	Scour wall recommended for sediment deposition along banks of river	Scour erosion in prototype is expected to be less severe than model due to conservative simplifications in model design and operations
Kamal El Kadi Abderrezzak	A physical, movable-bed model for non-uniform sediment transport, fluvial erosion and bank failure in rivers	Each grain size has a different geometrical scale (page 101 for formula, page 100 for chart)	Shields function; Reynolds number	Bank erosion	LSPIV	Erred on the side of smaller sediment particles, thus less scour anticipated in the field (more shear required to move heavier sediment). Qualitative (indicates where erosion is most likely to occur).	Tests use constant flow rates (not hydrograph). No prototype erosion data to calibrate to. Shields parameter not preserved.
R.A. Dodge	Model Similitude-Extended for Active Sediment Transport	N/A	Shields function with Taylor modification	Background information on scaling sedimentation using the Shields function with Taylor modification.	Scaling sedimentation	Taylor's transport function most important for cohesive materials	N/A

Author	**Title**	**Distortion Ratio**	**Variables of Distortion**	**Variables of Interest**	**Laboratory Techniques**	**Results**	**Limitations**
Thomas W. Gill and Clifford A. Pugh	Sediment Transport Similitude for Scaled Physical Hydraulic Modeling	1:24 geometric scale; 6.5:1 bed slope exaggeration	Sediment and Transport	Design of movable bed physical scale models based on dimensionless bed shear (Shields parameter); dimensionless unit sediment transport (Taylor's function).	Incipient motion calculation for Shields (Page 2); see page 4-6 on how calculation was selected; attempt to make shields parameter parallel between model and prototype.	Model aligned well enough to prototype by distorting the slope separately from other geometric properties.	Cannot reduce particle size according to geometric model scale because of cohesiveness. To compensate, may need to decrease density of bed material, increase model slope, or combine density and slope adjustment to produce transport mechanics similar to prototype.
Thomas W. Gill and Clifford A. Pugh	Physical Hydraulic Model Proposal for US Army Corps of Engineers Missouri River Bend Model	2.4 for slope exaggeration	Model slope	Sediment transport, shallow water habitat	Recirculation, sediment modeling	Model not constructed.	Required high flows exceeding flow capacity of Reclamation's Hydraulics Laboratory

Author	Title	Distortion Ratio	Variables of Distortion	Variables of Interest	Laboratory Techniques	Results	Limitations
Tommy Ekamitra Sutarto	Application of large-scale particle image velocimetry (LSPIV) to identify flow pattern in a channel	N/A	N/A	PIV Application: 1) map flow structure; 2) sensitivity of LSPIV to parameters; 3) capability in complex flow structure	LSPIV; trapezoidal model with sudden expansion-constriction shape and sandy bed	The LSPIV method has successfully predicted the flow structure in the wall-expansion area. The velocity vector and the flow streamline developed by LSPIV could depict the core flow and swirling flow occurred near the left and right bank.	The best tilting angle of the camera is 90 degrees, in other words, the optical axis is perpendicular to the flow. Small tilting angle results in highly distorted images which are difficult to correct with the image transformation algorithm.