E-9

MAYNORD

CAPABILITIES/LIMITATIONS EVALUATION DRAFT

Evaluation of Capabilities and Limitations of Micro-model
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I. Introduction

The micro-model is an extremely small-scale physical river model having a movable bed and varying discharge. The model is described in Gaines and Maynord (2000) and is most commonly used to address river training activities for purposes of navigation and environmental effects. The model is not used for more rigorous problems like rate of sediment transport. This report presents the results of an evaluation of the micro model.

During this evaluation this writer keeps in mind that someone once said that you should never be afraid to try something new because amateurs built the ark and professionals built the Titanic. This writer also keeps in mind what M.S. Yalin, a recognized expert on physical movable bed models, said upon seeing the micromodel "Just because water runs downhill does not mean that you have a model". When water is run through a movable bed model and the model scours the bed near the outer bank of a bend, the flow crosses over to the opposite side of the channel prior to the following opposite bend, or an obstruction simulating a dike creates scour at the end, those responses should not surprise an observer. The question that must be answered is to what extent does that model replicate the trends, locations, and magnitudes of response that are specific to the prototype reach being simulated. More importantly, how well will the model replicate changes to the system in a model calibrated to existing conditions and used to test alternatives? Evaluators must be open to new ideas while recognizing there are physical laws that govern similarity of flow and sediment transport in rivers.

Throughout this evaluation, the statement has been made that results from the micro model should only be interpreted by someone knowledgeable in river engineering. No one has disputed this often repeated statement and it is most frequently heard when someone raises a question about the veracity of the micro model. That statement does not change the need to test the veracity of results from the micro model when operated according to standard procedures used in the micro model. A concern of proponents of the micro-model is that the model is being subjected to an evaluation which has not been done for many other modeling efforts within the

USACE. While that appears true to this writer, the solution should be evaluation of all modeling approaches rather than no evaluation of the micro-model.

In an evaluation of any engineering material or tool, it is helpful to have (1) a generally accepted test or measure and (2) generally accepted limits or criteria for that test. Item (1) can be stated as "How good is this tool?" Item (2) can be stated as "How good is good enough?" In movable bed models, whether physical or numerical, neither question has been fully answered. The objective of this evaluation of the micro model is to address "How good is this tool?" The complete answer to the second question "How good is good enough?" is beyond the scope of this evaluation. However, an important aspect of the second question is the consequence of the model being wrong. Each of the various uses of the micro model will be evaluated from the standpoint of the consequence of the model being wrong. Coupled with the consequence of the model being wrong is the type of study being conducted. While environmental concerns and navigation are of equal importance, the required accuracy of navigation predictions is generally greater than environmental predictions. For example, environmental studies can be successful by showing the creation of diversity of depth and velocity even if the location is not properly simulated. Navigation studies generally need to be more precise in predicting location in order to achieve safe navigation.

At the beginning of this evaluation, Gary Parker of the University of Minnesota served as a short term consultant to recommend approaches to use in this evaluation. He suggested the micro model be compared to a large model having minimum distortion. Had the evaluation been able to construct and operate a model according to the classical approach of Einstein and Chien (19??) or Yalin (1965), using such a model as a standard of comparison would have been a valuable approach. Lacking such a model, this writer has chosen to base his evaluation on how the micro model compares to the prototype, the effects of deviations of the micro model from currently accepted movable bed modeling criteria, and a series of flume tests to determine the effects of various distortions.

The micro model website states "Micro Modeling is an excellent engineering tool for evaluating and designing structures to improve navigation on the Mississippi River. It provides a means to optimize the design of structures such as dikes, bendway weirs and chevrons to greatly improve navigation conditions, while improving the environment and establishing biological diversity." The statements about optimizing and design suggest the micro model is being used quantitatively. The past use of flow visualization in the micro-model to assess navigation conditions also implies a level of quantitativeness that should be evaluated.

The objective of this evaluation is to determine whether the micro model is a quantitative tool, qualitative tool, or simply a demonstration/education tool and to outline what study types are appropriate for micro-modeling.

II. Historical Perspective on Movable Bed Modeling

General Gaines (2002) provides a summary of previous physical movable bed models (MBM). One item that should be perfectly clear to anyone who has read these previous studies is that strict adherence to similarity criteria is not done in many if not most MBM. Graf (1971) categorizes movable bed models as rational models which are semi-quantitative or empirical models which are qualitative. Graf (1971) places models developed using the regime theory in the qualitative class. Blench (1964) states that the time consuming verification phase can be shortened by application of regime relations.

Rational MBM Graf credits Einstein and Chien (1954) with development of the rational method of MBM. Yalin (196?) and the Delft Hydraulics Laboratory also developed methods that fall under Graf's category of a rational MBM. The rational method is simply a more rigorous adherence to similarity criteria and generally requires large models to apply the method. Rational models are characterized by low vertical scale distortion, low Froude number exaggeration, and equality of Shields parameter in model and prototype.

Qualitative MBM Qualitative models place less reliance on similarity requirements. Warnock (1949) states "Instead of arranging the various hydraulic forces involved to meet definite requirements laid down in any law of similitude, the successful prosecution of a movable-bed model study requires that the combined action of the hydraulic forces bring about similitude with respect to the all-important phenomenon of bed movement, which is the essence of this type of model study." Warnock (1949) also states that the verification of a qualitative MBM is the basis for most of the confidence in the model. Davinroy (1994), who developed the micro model, uses morphological similarity in overall bed configuration which is similar to Warnock (1949). Although less rigorous that rational MBM, most qualitative models attempt to limit vertical scale distortion and Froude number exaggeration. Qualitative MBM have Shields parameter that is less than the prototype. Based on this authors evaluation of the literature, the civil engineering profession has accepted the qualitative MBM as a useful tool in river engineering. Parker, in consulting on this evaluation, stated "In process models precise similitude is not sought. Rather, the model is adjusted so that the processes and patterns of morphology, such as the pattern of scour and fill, are reproduced as faithfully as possible. Because the same physical phenomenon are represented in the model as in the prototype, the model is still useful as a diagnostic tool." Parker also stated "They (process models) provide a tool for a comparative evaluation of various river countermeasures."

Other MBM Freeman (1929) discusses early studies by Reynolds and Vernon-Harcourt which were similar to the qualitative model but used Froude scale velocities in models with huge vertical scale distortions. Vernon-Harcourt conducted a study of the Mersey estuary in England in a model with a distortion of 60. Vernon-Harcourt discusses a verification process which is a 3 step process which differs from the 2 step process used in the micro model and most MBM. In most MBM, the model is adjusted until it can reproduce a certain prototype condition and then it is declared ready for prediction. Vernon-Harcourt adjusted his qualitative model until it reproduces a known prototype condition as in other MBM. He then tests the model against a different set of changes in the prototype to see if it can reproduce these known changes. If satisfactory in this hindcast, he then declares the model ready for prediction.

III. Pertinent Features of the Micro model

While similarity laws are not followed closely in qualitative models, there are definite differences between the micro model and most previous qualitative models as follows:

1) Small size- The micro model is one to two orders of magnitude smaller than most qualitative models. Minimum channel width is on the order of 3 cm with horizontal scales of up to 1:20000. Model depths as low as 1 cm are an order of magnitude less than the minimum of 10 cm recommended in Gujar (1981). No requirements for minimum Reynolds number are used in the micro-model. The small model depths result in extreme distortion of relative roughness.
2) Large vertical scale distortion- With a few exceptions, distortion ratios used in the micro model are about twice that in most qualitative models. Micro models commonly use distortions of 8-15. Distortion effects will be discussed in detail subsequently.
3) Vertical scale and vertical datum determined as part of the calibration/verification rather than in model design. The reader should pause and understand the implications of this difference. In converting model bed elevations to the prototype after a verification test, various vertical scales and vertical datums are tried in the micro model until the bed configuration most closely matches the prototype. This adjustment can be done in the micro model because of the following item.
4) No correspondence of stage and discharge in micro model and prototype- Most qualitative models relate stage and discharge to a corresponding stage and discharge in the prototype.
5) Low stages run in micro model- Typical alluvial streams have dominant or channel forming discharges that are roughly at a bankfull stage. Maximum stages in the micro model are about 2/3 of bankfull. One positive feature of the low stages is that it reduces distortion effects.
6) Verification of micro model based on equilibrium bed- Previous qualitative models conduct verification by starting with a known bed configuration, running the subsequent hydrograph, and comparing the ending bed topography in model and prototype. The micro model starts with an unmolded bed, runs a generic hydrograph for many repetitions until the bed reaches equilibrium, and compares the equilibrium bed to as many prototype hydrographic surveys as possible to see if the correct trends are reproduced.

7) The small size of the micro model and the relatively heavy (heavy for plastic) bed material (SG=1.47) results in steep slopes in the micro model. Water surface slopes of the few micro models that have been measured are about 0.01 ft/ft. This translates to about 53 ft / mile which is about 100 times the slope of the Mississippi River. Steep slopes result in significant exaggeration of the Froude number which will be discussed in detail subsequently. Recent studies in the micro model have experimented with material having SG = 1.2-1.3 which should reduce this problem.
8) The small model size and thus larger vertical scale ratio means that model sediment, when scaled to prototype dimensions using typical vertical scale, is 2-4 ft in diameter. As stated previously, the small depths result in extreme exaggeration of the relative roughness.
9) No similarity of friction in the micro model.
10) Micro model uses porous dikes to solve exaggerated scour problems around dikes that occur in distorted models.

The micro model is totally empirical. Similitude considerations do not influence design and operation of the model. Although previous qualitative models do not follow rigorous similarity criteria, large departures from similarity criteria are avoided. The two most obvious examples are large vertical scale distortion and large Froude number/slope distortion. These differences place the micro model in a category by itself which is best described as "totally empirical". The question that must be answered is to what extent do these differences between the micro model and qualitative models affect the results from the micro model?

IV. Application of Movable Bed Models

One of the complexities of this evaluation results from the method in which movable bed models are often applied. Testing in all MBM start with a verification phase. In most previous MBM, the model is verified by molding the bed to a beginning prototype bed survey, running the hydrograph that occurred after the beginning prototype survey, and comparing the ending bed topography in model and prototype. If the comparison is satisfactory, the model is deemed ready for conducting a base test which will be described shortly. If the comparison is not satisfactory, adjustments are made to the model and the process is repeated until the model is satisfactory. In the micro model the verification phase consists of no bed molding and a generic hydrograph is run until an equilibrium bed topography is reached in the model. The equilibrium bed topography is compared to as many hydrographs that are available that represent similar conditions and the model trends are compared to the prototype trends. If the comparison is satisfactory, the model is deemed ready for testing different alternatives because in the micro model the base test and the verification test are the same test. In the verification phase, the modeler notes all deviations of the model from the prototype because these deviations are critical to evaluating the success of alternatives. In qualitative models like the ERDC coal bed models, the base test is a separate test from the verification test and is run for existing conditions using an average or representative hydrograph and is the bed topography used to compare against all alternatives. In both models all alternative tests are compared, not to the prototype topography but, to the model base test. Stated again for emphasis, alternatives are compared to the base test, not to the prototype. This provides a relaxation in the required quality of the verification if the model is being used as a tool to screen alternatives. At the end of the day, this evaluation reduces to the question "How good does a verification test have to be for the model to be used as a screening tool?" This writer believes the answer depends on the rigor of the model. For a rational model by Einstein and Chien (1954) or Yalin, the verification could be less than optimum but the strong amount of physics underlying the model would make it suitable as a screening tool. For a qualitative model where vertical scale distortion and Froude number exaggeration are greater than a rational model but still limited, the verification would have to be better than the rational model to use it as a screening tool because the model has less physical basis in its design and/or operation. For a totally empirical MBM like the micro model where distortion of vertical scale and Froude number are large and water surface and discharge are not reproduced, the verification for use as a screening tool would have to be better than in a qualitative model. A better verification could use the 3 step process of Vernon-Harcourt.

V. Similarity requirements for MBM and Previously Used Deviations from Similarity

General Ettema (1999) presents the dimensionless parameters associated with flow of water and sediment in channels with a bed of cohesionless particles as

$$\Pi_A = f_A\left\{D\left(\frac{g(\rho_s-\rho)}{\rho\nu^2}\right)^{1/3}, \frac{\rho Ri}{D(\rho_s-\rho)}, \frac{\rho_s}{\rho}, \frac{D}{R}, \frac{B}{R}, \frac{\sigma}{\rho giR^2}\right\} \quad (1)$$

The dependent variable A in Π_A might be flow resistance, thalweg sinuosity, sediment transport, or some other variable in alluvial channels. Scale distortions arise when these dimensionless parameters are not the same in model and prototype. However, some of the dimensionless ratios do not cause significant effects under certain conditions. For example, in a large enough model, the last parameter on the right side of equation 1 will not be the same in model and prototype but the effects of differences in surface tension in model and prototype will be negligible. It remains to be determined if the surface tension term can be neglected in a micro model. The first term on the right hand side is a particle density term which shows that if a light weight material is used, the particle size in the model will be larger than in the prototype. The second term is the Shields parameter that is present in almost all MBM criteria. The third term ρ_s/ρ is often ignored because density effects are addressed in the 1st and 2nd terms of the right side of the equation. The fourth term on the right hand side D/R is the relative roughness which is almost never equal in model and prototype of sand bed streams and is often assumed to have negligible effects on results. However, Ettema et al has shown significant scale effects of D/R on bridge pier scour. The micro model has an extreme distortion of D/R which can be as low as 1/6 whereas the prototype is 2 to 4 orders of magnitude less. The 5th term on the right side is the aspect ratio which is another term which can rarely be maintained the same in model and prototype of sand bed rivers. As stated previously, the micro model distortion of vertical scale and thus B/R is about twice as large as most previous MBM.

After reading many of the literally hundreds of references on MBM, guidance for design and operation of MBM consists of similar sediment mobility and flow patterns yielding similar bed configuration. As will be discussed subsequently, some of the techniques for insuring similar sediment mobility can adversely affect reproduction of flow patterns and thus bed configuration. These potential adverse effects on flow patterns are one of the central issues in this writers evaluation of the micro model.

Roughness in Micro Model In the list of differences between the micro model and previous qualitative MBMs, relatively low stages run in the micro model was listed as one of the differences. Based on flume tests by Gaines (2002), micro model sediment has for typical depths in the micro model an average Darcy f of 0.11 that is equal to a Chezy C of 27 $m^{1/2}$/sec. This value is consistent with values for model C presented in Gujar (1981) who found C = 25-30 $m^{1/2}$/sec for fine and coarse sand, 20-25 $m^{1/2}$/sec for fine bakelite, and 25-35 $m^{1/2}$/sec for coarse bakelite. The micro model value can be compared to typical Mississippi River values of C = 50 $m^{1/2}$/sec. With a distorted Froude model, achieving the correct friction requires the ratio of C in prototype to model be equal to the square root of the distortion. With a typical distortion of 11 and a prototype C = 50 $m^{1/2}$/sec, model C would have to be 15 $m^{1/2}$/sec. While we know the micro model is not a Froude model, these values show that the micro model, having a typical C of about 27 $m^{1/2}$/sec, is too smooth which is generally the case with distorted models. The model smoothness issue is a possible explanation of why high stages are difficult to run in the micro model and maximum stage is limited to about +20 LWRP in Mississippi River channels where bankfull is about +30 to +35 LWRP. At higher stages, velocity becomes too great in the model. Similarity of friction is also important in simulating flow in bends. Although the micro model has an extreme exaggeration of relative roughness, the model is too smooth because of the large vertical scale distortion.

Equal Shields Parameter in Model and Prototype Sediment mobility is quantified in most MBM guidance by the second parameter on the right hand side of Equation 1, the Shields parameter, which is the ratio of the forces tending to move the sediment to the ratio of the forces tending to keep the sediment at rest. As stated previously, the rational methods of Einstein and Chien (19??) and Yalin (1965) include the requirement that the Shields parameter be equal in model and prototype. Einstein and Chien (19??) state "no deviation from this equation is usually desired." Yalin (1965) states that the the Shields parameter "is therefore the most important variable from point of view of movement of bed material." Zwamborn (1966) notes that the rational approach "generally lead to completely impractical model scales." In Yalin (1971), an example using the Mississippi River and the classical approach yielded a model width of 10.25

m. This example was based on using the lightest possible sediment which would result in the smallest channel width.

Three techniques have been used to increase sediment mobility in the model to achieve equal Shields parameter in model and prototype. In the Shields parameter, the water density ρ is fixed, prototype ρ_s is relatively constant, and the model particle size D can not be scaled down due to particle cohesion problems and will be roughly the same in model and prototype when dealing with sand bed alluvial streams. Therefore, if the model Shields parameter is to be increased or made equal to the prototype, the only parmeters that can be varied in the model are ρ_s, R, and i. Adjustment of these three parameters have led to three techniques often used jointly in MBM as follows:

1) Lightweight sediment- Typical minimum specific gravity of model sediment has been about 1.05 but sediment this light has to be carefully handled and model flooding and startup are difficult. Walnut shells having a specific gravity of 1.3 have been used. Coal having a specific gravity of 1.3 is common. The plastic used in the micro model having specific gravity of 1.48 is relatively heavy compared to other lightweight materials in use. The use of lightweight sediment has little direct effect on flow patterns but particle size is important in several aspects of model similarity. The model ratio of particle size to depth is larger than the prototype in all MBM and Ettema (19??) has shown that non-similarity of this ratio can lead to problems with scour reproduction in models. Particle size also affects resistance which is important in reproducing correct water levels and flow patterns, particularly in bends.
2) Vertical scale distortion- Vertical scale distortion is the second technique used to achieve correct sediment movement. Horizontal scale/ vertical scale is referred to as distortion and values of up to 33 were used by Reynolds as reported in Freeman (1929). Vertical scale distortion results in attempting to model a prototype channel with a model that has an aspect ratio (width/depth) that is much less than the prototype. Knauss (1980) recommends distortion should not exceed 0.1* aspect ratio which is one of the more lenient recommendations for distortion. This limit of 0.1* aspect ratio is based on maintaining a wide central region in model that is not dominated by bank effects. For a typical Mississippi River section having an aspect ratio of 100, distortion would be limited to 10. This

0.1*aspect ratio limit does not address the dynamics of flow in bends which the literature suggests are most affected by distortion. Jaeggi (19??) concludes that morphological processes are highly dependent on width / depth and that a distorted model should be avoided. Glazik (1984) stated that distortion should be avoided in movable bed river models but that a value of 1.5 provided suitable results. Suga and Baba (1971) conducted bed evolution tests in a movable bed bend with distortions of 1, 3, and 5. The plotted profiles for distortions of 3 and 5 departed from the case with no distortion and did not vary in a consistent manner. Suga (1973) reports that distortions used in his lab's MBM studies were 5 or less and concludes that distortion should not be used when scour depth and location are the main subjects. Foster (1975) presented cross section plots of velocity from a model with a distortion of 3 and an undistorted model of the St. Lawrence River. Foster concluded "The velocities in the distorted model shifted several hundred feet toward the outside of the bend from those in the undistorted model." Channel width in this reach was 1200-1500 ft. Zimmerman and Kennedy (1978) conducted research on curved channels to determine the transverse bed slope in bends and concluded distorted models can be used if distortion is limited to no more than 2 or 3. Chitale (19??) recommends limiting distortion to 6 or less. While these previous studies have recommended limitations on distortion, the regime theory requires distortion of models according to the equation

$$h_r^{\,3} = L_r^{\,2} \qquad \textbf{Equation 2}$$

Using equation 2 and a typical micro model Lr = 10000 in the micro model results in hr = 464 or a distortion of 21.5 which is generally greater than used in the micro model. Note that as Lr increases, so does the distortion. Limits of applicability for equation 2 are unknown but no examples are found in the literature where regime theory has been applied in model design for scale ratios typically used in the micro model. While no one would dispute that small channels generally have lower aspect ratios than large channels, what is not obvious to this writer is the subsequent conclusion that a model of a large channel must have a lower aspect ratio. A large channel often has multiple secondary current cells affecting flow and bed topography. A smaller channel or a distorted model of a larger channel may have only one much stronger cell affecting flow and bed topography, particularly in bends.

The rational approach of Yalin (1971) is based on the equality of Shields parameter and grain Reynolds number in model and prototype and results in

$$h_r^{3} = \Delta\rho_r \, L_r^{3/2}$$ **Equation 3**

The rational approach also shows increasing distortion with increasing Lr. For typical minimum model depths and thus h_r recommended in the rational approach, equation 3 results in small allowable distortions.

The criteria for distortion fall into two categories of 1) distortion should be minimized and less than some value that ranges from 1.5 – 6 or 2) regime theory requires distortion but none of the applications of regime theory in the literature deal with Lr = 10000 typical of the micro model. Studies of distortion in bends show pronounced effects.

3) Increase model slope- Increased model slope is the third technique used to achieve correct sediment movement. This leads to a Froude number in the model that is greater than the prototype which also raises concerns about the ability of the model to reproduce flow patterns. Increased model slope is achieved by an increase in model discharge. ERDC coal bed models had discharge ratios (and Froude numbers) that were exaggerated at low flows but close to the flow required by equality of Froude number at high flows. In the Dogtooth bend micro model at mid-bank flow, Davinroy (1994) reports that the Froude number in the micro model was 6 times the Froude number in the prototype. Einstein and Chien (19??) allow some exaggeration of model Froude number but do not recommend a limit. In an example presented by Gujar (1981), a Froude number distortion of Fm/Fp = 2.5 was classified as large whereas 1.67 was classified as acceptable. Qingshen et al (1986) recommends a Froude number distortion of less than 2. Latteux (1986) reported a Froude number exaggeration of 2.5 was unsatisfactory but 2.2 provided acceptable results. Vollmers (1986) used Froude number exxageration of 1.4 in the MBM of the Elbe estuary which had a distortion of 8. The earlier models of Reynolds in which distortions of up to 33 were conducted with tidal periods according to the Froude criteria which would result in no distortion of the Froude number in the model, which is required in tidal

models. Without Froude number exaggeration, the Reynolds' model was slow with one simulation in the 0.6 m wide by 2 m long model lasting 3 weeks. Froude number exaggeration is based on the concept that Froude number has limited significance for low values typical of alluvial streams. A problem arises when the Froude number is exaggerated to the point where it is no longer insignificant in the model. Froude number distortion should be limited by not getting anywhere close to critical conditions at a Froude number of 1.0. For example, a prototype Froude number of 0.5 and a Froude number distortion of 2.0 would result in a model Froude number of 1.0 and clearly be unacceptable. Sherenkov (1984) evaluated similarity of the recirculation zone below an abrupt channel expansion as a function of Froude number in a fixed-bed channel. Froude number effects were small, but not insignificant, up to a Froude number of 0.66. The length of the recirculation zone varied increased by about 25% from a Froude number of 0.1 to 0.66. Between data points at a Froude number of 0.66 and 0.90, the recirculation length changed significantly. Sherenkov's best fit line started rapidly changing at a Froude number of about 0.75. Summarizing these findings, Froude number exaggeration has generally been limited to 2.0 or less and model Froude number, if exaggerated, should not exceed somewhere in the range of 0.66-0.75.

Model Shields Parameter Less than Prototype As stated previously, Graf's category of empirical or qualitative MBM has model Shields parameter less than the prototype. Qualitative MBM also use lightweight sediments, vertical scale distortion, and slope increase but only to achieve an acceptable level of sediment transport. Glazik and Schinke (1986) describe MBM experience using a model Shields parameter significantly less than the prototype. As quoted in Glazik and Schinke (1986), results from Liebs (1942) and the assumption of a specific gravity of 2.65 results in a Shields parameter of 0.030 that represents "initial movement of single grains", 0.047 represents "initial, though slow, transformation of the bed", and 0.076 represents "beginning of vivid bed material movement". Model design and operation in Glazik and Schinke (1986) is based on a model Shields parameter of about 0.061. The prototype in their report, for which a model study case history was presented, had a prototype Shields parameter of 0.51 which shows that using 0.061 in the model is a significant relaxation. The Mississippi River and other major alluvial rivers often have Shields parameter in excess of 1.0. Hecker and

White (1989) describe a MBM used on the Arkansas River where the Shields Parameter was less than the prototype. Based on personnel communication with Tom Pokrefke and Charles Nickles who conducted ERDC coal bed MBMs, "beginning of vivid bed material movement", or a Shields parameter of 0.076, best described the techniques used at ERDC. Although actual depths and slopes used on the coal bed models suggest a Shields parameter that is closer to 0.061, either 0.061 or 0.076 show a significant reduction of Shields parameter was used in the ERDC models. Chitale ((19??) states that movable bed model design is based on "adequate tractive force to ensure satisfactory bed movement". Shen (1990) states that if the rate of sediment movement is not an issue and the only need is to create a movable bed, a Shields parameter need only be greater than the critical value. The use of MBM for bed similarity studies without having equality of Shields parameter is consistent with Laursen and Alawi (1989) conclusions on the effects of velocity on scour in which they found that scour was independent of shear/critical shear ratios greater than about 3-4.

In the micro model, the few slope measurements taken have shown a slope of about 0.01. At a maximum stage in the micro model of +20 LWRP, the hydraulic depth is about 35 ft in typical Mississippi River applications. The hydraulic radius is about 83% of the hydraulic depth for a distortion of 11 which is an average distortion value used in micro models. Using a typical vertical scale of 1:800 results in a model hydraulic radius of 0.036 ft. Using a specific gravity of 1.47 and a model D_{50} of 1.0 mm, results in a typical Shields parameter used in the micro model of 0.23. This value is compared to prototype values on the Mississippi River that are typically greater than 1.0. The micro model Shields parameter is closer to the prototype than in both the model by Glazik and Schenke (1986) and the coal bed models at ERDC. Because of the importance given to the Shields parameter in the rational approaches of Yalin and Einstein and Chien, some might be tempted to conclude this is a favorable feature of the micro model. However, it happens in the micro model because of the large vertical scale distortion in conjunction with the large Froude number distortion. The experience of previous qualitative models by Glazik and Schenke (1986) and the ERDC coal bed models is toward a significantly lesser Shields parameter resulting in general bed movement. This approach allows the modeler to minimize vertical scale distortion and Froude number exaggeration.

At the risk of being repetitive, the primary advantage of smaller Shields parameter in the model than in the prototype, and almost certainly the reason its use has evolved, is that distortions in Froude number and vertical scale can be reduced, which should result in improved reproduction of the flow field and thus improved reproduction of the bed morphology. Another factor concerning the Shields parameter is its effect on the time scale for sediment movement. Small models having large Shields parameters will respond extremely fast. Such rapid response reduces testing time but was intentionally avoided in the ERDC coal bed models.

Ackers (1987) poses the question that remains today when discussing the rational approach requiring equality of Shields parameter and other criteria stating "Yet many apparently successful models have been made of sand bed rivers and estuaries which did not follow those rules. Were those modelers deluding themselves as to the degree of simulation achieved, or is the academic approach to scale selection unnecessarily restrictive or even misleading?" Vollmers (1989) classification of modelers addressed this same concept in a slightly facetious manner at a 1987 NATO workshop (Shen 1990). He grouped the workshop participants into two groups: 1) Theoreticians having published similarity laws but never run a movable bed model; and 2) practicians using similarity laws to obtain initial data for their models, but who later on during the experiments are forced to accept numerous compromises that cannot be explained physically. If one concludes that only those studies having equal Shields parameter in model and prototype are valid, then the micro model is not valid. As stated previously, this writer concludes that valid studies have been conducted where the Shields parameter was significantly less in the model than in the prototype.

VI. Model Comparisons- Site specific studies conducted as part of this evaluation Two reaches of the Mississippi River, Kate Aubrey and Vicksburg, were studied in detail as part of this evaluation. Details are presented in the following paragraphs.

Kate Aubrey Comparison The Kate Aubrey reach experienced shoaling problems that required repeated dredging. The reach in several surveys from the late 1960's to 1976 exhibits a consistent upstream to downstream trend of left bank- right bank – left bank – right bank location of the thalweg. This thalweg pattern was agreed to be an essential element of any verified movable bed model. Kate Aubrey was studied in an earlier 1980's ERDC coal bed model and as part of this evaluation in a traditional micro model and a larger micro model having a horizontal scale ½ the scale of the traditional micro model. The larger micro model was referred to as the 2X micro model. The traditional model was 1:16000 horizontal scale and 1:900 vertical whereas the 2x model was 1:8000 horizontal and 1:600 vertical. One concern of the traditional Kate Aubrey micro model was the use of features in the model such as isolated areas of larger bank roughness to achieve correct bathymetry that had no physical counterpart in the river. Using Froude criteria for distorted models, scaled maximum flowrate in the 1X and 2X models was 1444000 and 1048000 cfs, respectively. The larger 2x micro model required less exaggeration of the discharge, which was expected. Both models exhibit the lack of similarity of friction (model too smooth) discussed above since 1000000 cfs in the prototype produces a stage of approximately +30 LWRP compared to the +20 LWRP stage in the micro model. Both micro models were verified to the 1975 and 1976 bathymetry (referred to as base conditions). The 1975 prototype survey is shown in **Figure 1** along with range numbers throughout the reach. Base/verification test results from 5 runs from the traditional micro model, 1 run from the 2X micro model, and 2 prototype surveys are shown in **Figures** 2 to 8 for every 5th range through the problem dredging reach. After verification, all dikes present in 2000 (referred to as "plan" conditions) were placed in both the traditional and 2X micro models and compared to 1998, 1999, 2000, and 2001 bathymetry. Plan test results from a single run from the traditional micro model, a single run from the 2X micro model, and 4 prototype surveys are shown in Figures 9 to 15. Comparison of the base/verification and the plan tests results in the following conclusions: