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JOINT VENTURE TEAM/GAINES

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7. CONCLUSIONS BY ANDY GAINES, MVM

7.1. BACKGROUND

As with any model, the potential for misuse of the results is possible. Prior use of the large-scale physical models (WES, University, or other laboratories) restricted who could conduct model studies because of space, costs, and operational requirements. As a result, model results were produced, processed and analyzed under the direction of persons trained and experienced in physical loose-bed modeling. The advent of micromodels as a viable engineering tool removes much of the restriction to a relatively few individuals/entities because micromodels are relatively small and affordable. Thus, widespread use of these models by inexperienced modelers is a concern. This concern also exists for numerical models. For example, today's availability of inexpensive computers and modeling software provides a means for almost anyone to open shop as an "expert" hydraulic/sedimentation modeler. Yet, simply having a computer and modeling software does not warrant many claims of modeling competence in government, university and private sector arenas. Likewise, having micromodel equipment does not guarantee that model results are obtained and interpreted in an appropriate manner.

While the concern about inappropriate model use is not restricted to micromodels, the avenue for model misapplication by individuals having insufficient training in river hydraulics and sedimentation becomes a distinct likelihood. This is particularly true given the meager cost of setting up a micromodel lab (the 3-D laser scanner, the most expensive component of present micromodel equipment, is considered optional).
Future use of micromodels requires a set of safeguards to ensure that only experienced river and hydraulic/sedimentation engineers (emphasis on both aspects) conduct micromodel studies and interpret micromodel results. Correct application and interpretation of micromodels requires experience grounded in the fundamental mechanics of river morphology, hydraulics, and sediment transport as well as model operational procedures.

The evaluation of any topic raises the specter of criticism. The perceived criticism can be taken as an affront to the method, technique, or capability of a particular approach. There may also be a personal connotation on the part of the one who performed the work whether in large-scale or small-scale loose-bed physical models or numerical models.

Evaluation of a technology must include an assessment of previous works. Because the very nature of a qualitative model or approach indicates a lack of perfect agreement with the real world, the review often identifies some deficit or deviation between the model result and the observed prototype behavior. Such is the case for both large- and small-scale loose-bed models. Neither of these model approaches has claimed to exactly reproduce prototype conditions. As such, a review of previous large- and small-scale models reveals differences between model results and the prototype -- a fact completely expected.

In this context, defining capabilities and limitations for such models must consider the fact that the models (and modelers) were constrained from the onset. Of those model studies included herein, calibration or verification of the model bathymetry served as the sole assessment factor when determining its suitability for alternative testing. The modeler's judgement regarding whether the model was calibrated/verified incorporated both internal and external constraints.

Internal constraints depend upon the physical characteristics of model components at the scale dimensions. A prime example of an internal constraint is the use of water as the fluid in the model, which limits the model's ability to reproduce viscous forces in the correct proportion. Internal constraints cannot be overcome without changing model scales, sediment material characteristics, fluid characteristics, and possibly operational procedures.

External constraints consist of prototype data availability, of funding limitations, of time restrictions, and on the relative degree of answer sought. The latter, relative degree of answer sought, plays a significant role in this process because some models were conducted simply to confirm a design already developed or to provide a visual demonstration of the expected results to other non-technical personnel. External constraints often serve as rigid constraints -- typically, external constraints cannot be avoided or modified without great difficulty.

Statements regarding capabilities and limitations for qualitative models should be tempered by a consideration of both internal and external constraints. Circumstances may exist where a qualitative model result is desired to confirm a technical opinion. In this case, the internal constraints of the model are understood. One acknowledges that the model may not fully depict prototype conditions, but the result aids in confirming (in conjunction with previous experience of similar problems, measured prototype data, or other model studies) that the proposed work will function as desired.

Absolute limitations, therefore, may only exist for individual applications. Ultimately, the person(s) responsible for developing a problem solution makes the decision whether to use a particular engineering tool or not. The present evaluation attempts to identify the principle internal limitations that exist and to describe the possible ramifications of those limitations. With this knowledge, a potential modeler can: 1) assess whether the micromodel provides the level of detail needed to assess the problem at hand, 2) determine whether alternate methods are necessary in lieu of the micromodel, or 3) determine if model efforts (numerical and/or physical) in addition to the micromodel are warranted.

In a general sense, the present evaluation identifies a need to suggest procedural changes in the application of models (numerical and physical) other than the micromodels as described herein. To the JV team's knowledge, no other model has been subjected to the level of scrutiny currently focused on the micromodels. Other models should be subjected to a similar review in order to determine their areas of applicability and if procedural changes are necessary.

7.2. CONCLUSIONS - ANDY GAINES, MVM

At the beginning of this evaluation there were great expectations for reconciling differences of opinion about the micromodels versus the WES large-scale models. Although there were significant political issues involved, the evaluation was to explore technical issues alone through a joint venture between the Memphis District (MVM), the St. Louis District (MVS), the Engineer Research and Development Center (ERDC) and the Mississippi Valley Division (MVD). The initial charter of the joint venture identified the following scope of study.

> Potential advances in micromodel application are dependent on a basic understanding of micromodel procedures, identification of it's full capabilities and any associated limitations and how well the micromodels reproduce prototype conditions both during calibration and any predicted channel response to alternative structures.
>
> The proposed study will furnish part of the basic knowledge. The study will encompass three major components and will be a joint effort between MVM, MVS, and ERDC, and MVD.

The three components mentioned included a familiarization process (Component A), Flume Studies (Component B), and an evaluation of model scale effect (Component C).

The familiarization process included the use of an active micromodel study to document the micromodel process, a comparison of previous model study results, and a review of available literature on physical sediment modeling. The comparison of previous model study results sought to evaluate models with different scales and scale distortions regarding their ability to reproduce the prototype bathymetry. The flume studies were to provide data to assess the boundary effects (bed and flume wall roughness and sediment characteristics), and the effects of various slopes, scales, and scale distortion ratios. The evaluation of scale effect included micromodels conducted at two scales and the use of two energy conditions in each of these micromodels. The predictive capability of each of the two micromodels was also to be assessed.

7.2.1. Familiarization (Component A)

The Richardson Landing and Kate-Aubrey micromodel studies were utilized in the initial phase of this component. During micromodel calibration, WES personnel participated closely in model operation and setup and gained a basic understanding of the micromodel procedure. A written description of the procedure (at that time) was also prepared. This description of the procedure has been somewhat refined throughout the evaluation study.

Sixteen WES model studies and fourteen micromodel studies were compared to their respective prototypes using morphologic concepts to relate model and prototype bathymetry. These comparisons are presented in a separate document (Gaines, Gordon, and Maynord, 2002). Conclusions derived from bathymetric comparisons are incorporated in the following subsections. A very limited assessment of the flow visualization technique employed in micromodels was also accomplished to assess similarities between the prototype and model surface flow patterns. Conclusions derived from the assessment of flow visualization is also provided in the following subsections.

7.2.1.1 Bathymetry Comparisons between Model and Prototype

All confidence in the WES sand-bed and coal-bed models and the micromodels derives from their ability to reproduce observed prototype bathymetry. Agreement between the WES models and the respective prototypes was achieved through a verification process where a specific time period was simulated in the model to produce a known prototype response. Agreement between the micromodels and the respective prototypes was achieved through a calibration process whereby adjustments in the model are made to produce general bathymetric trends as observed in one or more prototype surveys. The verification and calibration processes involve a detailed focus on bed morphology and not on surface flow patterns or flow distributions, *per se*. Although these verification and calibration processes are different, they both serve as the basis for the modeler's confidence in the model. A poorer agreement between model and prototype should translate into a lesser degree of confidence while a better agreement should translate into a greater degree of confidence.

Comparisons made between 16 WES models and 14 micromodels suggested some slight differences between the large-scale model and micromodel morphologic similarity. In this writer's opinion, the large-scale models had better agreement in the width/depth ratio between model and prototype than did the micromodels, although there was only a marginal difference. Analysis of the remaining four morphologic parameters of area, width, depth, and thalweg position indicated that model to prototype trends were similar between the micromodels and the WES models. Because each model result varied in the level of accuracy achieved in reproducing prototype bathymetric trends[1], the comparison analysis yielded no definitive conclusions regarding whether the large-scale models reproduced overall bathymetric trends better or worse than did the micromodels. However, there is significance in the results being similar for both the WES models and the micromodels, and one could conclude that if the WES models proved sufficient in reproducing prototype bed morphology, then the micromodels seem to do likewise.

There is an inherent danger in making this assumption, however. Basing micromodel acceptability on the WES models assumes that those models can be held as the benchmark--they were correct in all regards. What has not been answered is whether the WES models proved sufficient in replicating the respective prototype bathymetry. This issue is even more relevant concerning the flow visualization technique used in some WES model studies and in some micromodel studies. In the end, assessment of model suitability must always be based upon its representation of the prototype conditions and not on other models.

While this evaluation pertains to micromodels, there was no analysis of the WES models in order to enumerate their limitations, though they do exist. Because some of the evaluation team consider the WES models as the "Holy Grail"[1], there is a need to address how they have been used to achieve desirable prototype response. This will be partly addressed in subsequent paragraphs.

7.2.1.2 Bathymetry Comparisons: Model Predictions versus Observed Prototype Response

Dogtooth Bend: Davinroy (Appendix E) presents data from the Dogtooth Bend model study conducted at WES during the 1980's and 1990's as compared to the predicted and observed prototype bed response. For this model study, the model base test bathymetry showed greater widths and depths in Dogtooth Bend than present in the 1983 prototype survey. Therefore, alternative testing was adversely affected in terms of the model's ability to predict actual prototype bed response. Interpretation of model results had to consider this discrepancy which most likely resulted from distortions in the model. Vertical scale distortion, the most obvious distortion, plays a major role in flow field development, which in-turn affects bed morphology. The effect is most prevalent in sharp bends as documented by numerous authors and investigators.

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[1] In fact each model study had to be considered on it's own merit -- how well each individual model reproduced the prototype bathymetry.

According to data presented by Davinroy, the structure dimensions tested in the Dogtooth Bend model were too long and bendway weir lengths were shortened considerably for actual prototype construction. Based on the relatively poor representation of the prototype bathymetry by the base test for elevations below -10, one would expect a similar result for the bathymetric response predicted by the model under plan conditions. Cross-section plots by Davinroy show this tendency between the predicted model bathymetry and the 2000 prototype post-construction survey. However, it should be noted that the majority of cross-sections shown have differences of less than approximately 10 feet in depth between micromodel plan and the 2000 prototype bathymetric surfaces. This represents about a 10-20 percent difference in depth compared to the range of elevations shown for the model cross-sections.

Experience from the prototype after construction of the model plan has been favorable. Dredging in the reach has been eliminated and response from the towing industry is good. Accidents have been virtually eliminated. How did a model that failed to reproduce general bathymetric trends in the base test configuration yield such positive results? The answer does not lie solely in the model's ability to reproduce the prototype, but in the river engineering process that utilizes those model results along with prototype data and experience provided by the team of experts engaging the problem. The models are simply used as a diagnostic tool.

The phased construction of bendway weirs from the recommended model plan serves as an illustration of the emphasis given to the model result. In essence, a phased construction process is an experiment in the prototype with the number of variables reduced by screening of alternatives in the model. Through the phased construction approach, the modeler and designer acknowledged their lack of total confidence in the model. The model was only used to screen various alternatives thereby reducing the amount of experimentation required in the prototype.

Kate Aubrey Reach: Data from the 1:8,000 and 1:16,000 Kate Aubrey micromodels permitted an assessment of the predictive capability of the micromodels. Both micromodels were calibrated to the 1975-1976 prototype condition. Micromodel bathymetry at calibration provided a reasonable representation of the prototype condition for both micromodels. However, neither the 1:8,000 nor 1:16,000 model of the plan condition compared well with the 1998 prototype survey. Both micromodels failed to represent cross-section area and channel width and depth as observed in the prototype. Thalweg location was predicted fairly well except between ranges 29 to 51 and ranges 55 to 64. Depths were generally overestimated by 10 feet which represents about 10-20 percent of the maximum depths in the prototype.

Several factors may have affected prototype response, most notably the large quantity of dredging that occurred at intervals between 1976 and 1998. The micromodels made no provisions for dredging. The impacts of dredging in the prototype (versus no dredging in the micromodel) on channel development are not known. However, adjustments made in the micromodel during the calibration process are more likely to have had an adverse affect the model's predictive ability. Non-erodible materials were placed along the left descending bank and in the channel bed of the micromodels to achieve a model bed that reproduced prototype bathymetric trends in the mid-1970s. These adjustments coupled with distortions in the micromodel adversely affected the ability of the model to accurately predict observed prototype behavior.

The question of how Kate Aubrey micromodel results were used in developing prototype plans is not relevant for the 1:8,000 and 1:16,000 models because these model studies were conducted exclusively for the present evaluation effort. There were no other alternatives tested in these micromodels.

Based upon the poor replication of prototype response induced by plan changes, these micromodels did not adequately predict prototype conditions.

7.2.1.3 Flow Visualization: Model versus Prototype Surface Flow Patterns

One area of great concern to the original panel of consultants related to the use of flow visualization, confetti streaks, to assess navigability, especially in localized areas such as approaches to locks and dams. The problem with using flow visualization in the micromodel arises primarily from the high degree of Froude number distortion. Because Froude number similitude reflects the reproduction of gravitational forces in the model, a high degree of distortion in model Froude number creates differences in flow distributions and surface flow patterns.

Gravitational forces play significant roles in flow characteristics where rapid changes in current direction occur. Therefore, gravitational forces have their greatest impact on velocity directions in sharp bends or in the proximity rapid changes in bank alignment such as rock outcrops. Gravitational forces also are of significance in the vicinity of training structures or where other hydraulic structures (e.g. lock chambers, water intakes, or bridge piers) exist in the waterway.

The effects of Froude number exaggeration can be seen in the Vicksburg Front micromodel flow visualization results. Flow traces from the micromodel contrasted with prototype GPS float data reveal significant differences in the distribution of flow between model and prototype. The White River

Prudent use of flow visualization using confetti traces should therefore be restricted to cases where prototype data are available to confirm that model flow patterns reproduce prototype flow patterns.

7.2.2. Flume Studies (Component B)

7.2.3. Model Scale Studies (Component C)

7.2.4. Similitude Considerations

Morphologic parameters calculated for the comparison of the 16 WES and 14 micromodel studies were also used in assessing similitude criteria. Because actual slope and discharge data were not known for all models, scale ratios were approximated from the morphologic parameters of area, width, and depth based upon the horizontal and vertical scales. The approximation derives from and an assumed similitude in Froude number. While neither the WES models nor the micromodels are Froude models, the scale ratio analysis provides a means for investigating the effects of scale on important physical characteristics that describe flow, velocity, boundary influences and sediment mobility.

The WES models generally had a higher degree of similitude in friction, slope, and Froude number than existed in the micromodels included in the evaluation. The higher degree of similitude was evident from graphs of the various similitude parameters where the WES models plotted closer to a value of one than did the micromodels. A value of one represents ideal similarity between the physical phenomena at prototype scale and the analogous phenomena at model scale. In some cases, the WES models were one order of magnitude (one logarithmic cycle) closer to ideal similarity than were the micromodels. Examples of this are the hydraulic and sedimentation time scale ratios and the particle Reynolds number.

7.3. MICROMODEL CAPABILITIES AND LIMITATIONS

The remaining conclusions stated herein focus on the micromodels and only minor inferences are made regarding the previous sand-bed and coal-bed model studies conducted at WES as applicable.

7.3.1. Capabilities

1. **Micromodels can be used effectively to demonstrate and communicate complex hydraulic and sedimentation issues (level 1).** Demonstration of hydraulic and sedimentation principles in gross terms requires no specific model design. Simply having a flume with flowing water and sediment serves to illustrate many basic principles. The addition of a model insert that represents a particular prototype reach only enhances the demonstration effect. The visual nature of the micromodel allows scientists that are not familiar with hydraulic or sedimentation phenomena to "see" how water and sediments interact within the channel.

2. **Micromodels provide an opportunity to educate various audiences (level 1).** This follows directly from the demonstration and communication aspects of micromodel capabilities. Often, local sponsors and other non-technical individuals have a vested interest in river processes. Use of the micromodel to help these individuals understand

the complexities of river hydraulics provides a mechanism to arrive at desired project outcomes.

3. **Micromodels provide a means to qualitatively compare relative bed changes between alternative modification plans.** Past experience with micromodels indicates that after a period of calibration (where the model is adjusted to reproduce observed prototype conditions), various alternatives can be analyzed. This analysis involves a relative comparison between alternatives and the model base test in a qualitative manner to aid in selection of a recommended plan of modification. The screening of alternatives in this way helps engineers and other scientists assess which alternatives provide the desired channel response. The relative comparisons are not used (and cannot be used) to indicate absolute elevations or dimensions in the prototype. Specification of absolute elevations and/or dimensions requires quantitative analysis beyond the scope of present micromodel methodologies. Qualitative comparisons are consistent with levels 1) and 2).

4. **Micromodels identify general scour and depositional trends.** The qualitative application of micromodels identifies overall behavior of the channel bed in response to various alternatives relative to the model base test. Scour and depositional trends identified through the micromodel cannot be transferred directly to the prototype. The inability to directly transfer model results to the prototype is due to effects that result from model distortions, from differences between the model base test and prototype bathymetry, from differences in boundary conditions, and from differences in hydrographic inputs. The qualitative nature of general scour and depositional trends is consistent with level 2.

5. **Micromodels provide supplemental information for use in other models** (e.g. numerical or larger physical models).

7.3.2. Limitations

1. **Unknown discharges used in the micromodel** - Prior to starting the JV evaluation, flows were largely unknown in the micromodel. A few exceptions where timed volumetric measurements were made are the cases where model discharge was known. Model discharge was established by a visual assessment of the state of sediment mobility yet the discharge rate was unknown. The shape of the actual hydrograph was also unknown because control of model discharge was accomplished by specifying a valve opening, not a discharge rate. Implementation of flow meters in routine micromodel operation alleviated these limitations. However, micromodels continue to be operated based upon valve opening. Future enhancements in micromodel operation could be achieved if hydrograph simulation was based on discharge rates instead of valve openings.

Davinroy (1994) utilized a model-prototype discharge scale relation in operating the Dogtooth Bend micromodel. This approach appears to be an essential part of operating and interpreting micromodels. However, subsequent micromodel efforts fail to follow this approach. Future micromodel studies should attempt to establish a discharge relationship between the micromodel and prototype to aid in interpreting model results.

2. **Operational sensitivity to position of by-pass line** - Prior to the JV evaluation, a by-pass in the delivery piping provided for adjustment of water delivered from the pump to the micromodel headbay. Micromodels typically used flexible piping to convey water and sediment and any movement of the piping changed the distribution of flow between the by-pass line and the primary line leading to the model headbay. Changes in this distribution produced fluctuations in the amount of water and sediment delivered to the model. The primary concern with the by-pass occurred when sediment lodged in the pump intake requiring removal of the pump. After the pump intake was opened, replacing all of the flexible piping in the original positions was extremely difficult. Therefore, discharges delivered to the model were altered slightly. Because slight adjustments in any model operational parameter potentially causes significant changes in model bed response, a stable discharge was crucial to achieving model calibration. Implementation of a constant-head assembly in the micromodel procedures alleviated this limitation.

3. **Micromodels do not reproduce prototype stages**. Stages directly impact the amount of energy in the model. Stages that are too low (using a stage of +20 LWRP in model to represent a stage of +30 in prototype) produce different velocity and sediment distributions within the channel cross-section. As a result, the ability of the thalweg to adjust laterally is restricted. Observations in both micromodels and loose-bed flume studies support this. Additional problems arising from incorrect stage pertain to overtopping of training structures. Where stages are too low, structure elevations must be adjusted vertically to achieve the "appropriate" level of overtopping flow. Such adjustments are necessary to obtain a desired lateral velocity distribution in the model channel. These adjustments lead to the possibility for misinterpreting model data when converting to prototype scales.

Simulation of incorrect stages in the micromodels coupled with vertical scale distortion leads to a velocity distribution associated with a narrow-deep channel (model) as opposed to a wide relatively shallow channel (prototype). Therefore, model shear and velocity distributions do not represent prototype conditions. The narrow and deep channel that exists in the micromodels precludes full development of 2-dimensional and 3-dimensional velocity distributions. Micromodels have an overly restricted thalweg -- the model thalweg cannot adjust laterally within the cross-section with the same degree of flexibility that occurs in the prototype. Narrower channels and increased vertical distortion produces a larger deviation in velocity and shear distributions from prototype conditions. Inadequate representation of stages limits micromodels to levels 1) and 2).

4. **Micromodels do not represent prototype discharges**. Current operation of micromodels using a cyclic hydrograph touts the claim that "model hydrographs mimic the average annual response of the prototype." However, adoption of flow meters into routine model operation revealed that the cyclic hydrograph provides only a limited representation of a true hydrograph cycle. The problem with the cycle lies in the control valve hardware -- the valve provides insufficient resolution and control to obtain the desired hydrograph cycle. Present discharge hydrographs in the model vary on rising and falling limbs due to the valve operating characteristics. Lack of control near minimum

and maximum flow settings result in operation of the model at minimum/maximum flows for a disproportionate period of time. Improvements in the valve hardware are essential to provide consistent and predictable control of model discharges. Such improvements provide the capability to develop design hydrographs that more closely mimic prototype discharge trends.

Current discharge control limits micromodels to levels 1) and 2) because the variable discharge drives development of desired bathymetry. The model hydrograph should provide a representation of prototype discharge characteristics. Achievement of more consistent control of discharge does not translate to the use of micromodels in levels 3) and 4). Other factors play a more significant role in expanding the use of micromodels to these levels.

5. **Micromodels have exaggerated Froude numbers**. Exaggeration of Froude number in loose-bed models results from efforts to obtain similar sediment mobility between the model and the prototype. The exaggeration in Froude number results from velocities that are higher than required for Froude similitude. The higher velocities are required to produce the dynamic similitude prescribed by u_*/u_{*c}. Accordingly, flow parameters influenced by mean stream velocity (V or V^2) are likewise exaggerated. Ettema argues additional points on the effect of exaggerated velocity head ($V^2/2g$).

A simplified consideration of the energy equation demonstrates the effect of exaggerated velocity head.

$$\frac{P_1}{\gamma} + Z_1 + \frac{V_1^2}{2g} = \frac{P_2}{\gamma} + Z_2 + \frac{V_2^2}{2g} + \text{Losses}$$

where, P is pressure, Z is elevation, V is mean stream velocity, g is the unit weight of water, g is the gravitational constant, the subscript 1 denotes an upstream location, the subscript 2 denotes a downstream condition, Losses represent all energy losses between location 1 and 2. Losses include frictional/roughness losses, form losses, and contraction losses among others. Losses are generally a function of V^2. Therefore, exaggeration of velocity significantly impacts the energy relationship. Contraction losses represent the effects of dikes and related training structures. Exaggerated velocities have a negative impact on flow patterns and flow/velocity distributions, particularly in the vicinity of training structures (Ettema's report and observations from micromodels and UMR flume work further support the theory here). A similar negative impact occurs in channels with pronounced curvature (e.g., sharp bends).

Froude number (and velocity) exaggeration limits micromodel usefulness to levels 1) and 2). Use of micromodels should be restricted to these levels based upon current micromodel approaches. Where required to provide a demonstration tool for levels 3) and 4), micromodels may be used with extreme caution, but only in conjunction with other model results and adequate explanation by experienced personnel. Future developments in the micromodel may enhance model capabilities by reducing velocity and Froude number exaggeration. Recent use of a lighter weight sediment material, a Polyester PlastiGrit Type I, tends to reduce the slope required to achieve sediment mobility which in turn reduces the Froude number exaggeration. The reduced slope and Froude number exaggeration achieves favorable model response as compared to models using the heavier Urea PlastiGrit Type II. Micromodels having lower distortion ratios have achieved a favorable model response when compared to micromodels having a higher vertical scale distortion. The lower vertical scale distortion also helps reduce slope distortion and Froude number exaggeration in the micromodels.

6. **Surface velocity patterns are adversely affected by model distortions and exaggeration of Froude Number.** Increased distortion of the vertical scale results in model channels having smaller width divided by depth ratios, B/y, than found in the prototype channel. Circulation in channels with small B/y ratios is stronger as evidenced by observations in the laboratory and in small streams. As one example, Davinroy (1994) presents corroborating isovelocity data for prototype and model at a cross-section in the Dogtooth Bend reach of the Mississippi River (Davinroy, 1994, Figures 33 and 34, respectively). Davinroy's figures depicting isovelocity contours indicate a somewhat stronger circulation pattern in the micromodel than found in the prototype. Although there are similarities between the prototype and the model in that both exhibit several higher velocity cells across the channel width, the lateral distribution is different in the

micromodel than shown in the prototype. The prototype data show the highest thread of velocity located approximately 250 feet from the left bank position while the micromodel data show the highest thread of velocity at a distance of 400 feet, a difference of 150 feet. The difference of 150 feet between these locations may appear minor. However, this represents approximately 10 percent of the total channel width.

In situations where even a 10 percent error exists in surface flow pattern location (e.g. an approach to a lock and dam or similar hydraulic structure), scale effects and distortion effects on model outputs must be clearly understood. Calibration of micromodel surface velocity patterns to observed prototype surface flow patterns should be included when flow visualization is a part of the model study. Prototype surface flow patterns could be obtained from LSPIV, point velocity measurements over an extended period of time, or other similar methods. Use of the micromodels even as a diagnostic tool in categories 3 or 4 should be avoided.

7. **Roughness characteristics in the micromodel are not adequately scaled.** The lack of appropriate roughness in micromodels is closely associated with their inability to reproduce prototype stages. Estimates of friction factors and roughness coefficients for micromodel sediments and flow conditions indicate that roughness is too low in micromodel channels. In other words, the model bed is too smooth.

Because stages (and depths) are not correctly reproduced in micromodels, surface flow patterns are not correct. Surface flow patterns have greater errors for prototype reaches containing a high degree of flexibility in thalweg position (not laterally constrained) and/or having high sinuosity (sharp bends).

Based on flume tests by Gaines (2002) using flow depths typical in micromodels, micromodel sediment has 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 micromodel 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 micromodel is not a Froude model, these values show that the micromodel, 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 provides a partial explanation of why high stages are difficult to run in the micromodel 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 - the energy is excessive and increases the exaggeration of scour depths.

Similarity of friction is also important in simulating flow in bends. Although the micromodel has an extreme exaggeration of relative roughness, the model is too smooth because of the large vertical scale distortion and the sediments used.

9. Model Shields Parameter Less than Prototype - Graf's (1971) category of empirical or qualitative loose-bed models has model Shields parameter less than the prototype. Qualitative loose-bed models also use lightweight sediments, vertical scale distortion, and increased slope, but only to achieve an acceptable level of sediment transport. Glazik and Schinke (1986) describe loose-bed model 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 loose-bed model 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 loose-bed models, "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 shows a significant reduction of Shields parameter was used in the ERDC models.

Chitale 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 loose-bed models for bed similarity studies without having equality of Shields parameter is consistent with conclusions by Laursen and Alawi (1989) regarding the effects of velocity on scour. Laursen and Alawi (1989) found that scour was independent of shear/critical shear ratios greater than about three to four.

The few slope measurements taken in the micromodel have shown a slope of about 0.01. At a maximum stage in the micromodel 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 micromodels. 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 micromodel of 0.23. This value is compared to prototype values on the Mississippi River that are typically greater than 1.0.

The micromodel 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 micromodel. However, it happens in the micromodel because of the large vertical scale distortion in conjunction with a 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.

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.

10. Slope distortion in the micromodels is too high. Slopes in the micromodels are highly tilted to achieve a desired state of sediment mobility using the PlastiGrit Type II sediment material. Exaggeration of model slope tends to restrict thalweg adjustment laterally within the channel. This results from exaggerated velocities and from a prototype channel represented as a narrow and deep cross-section. The latter results primarily from the vertical scale distortion. Distortion of model slope produces velocities that are not necessarily reproduced correctly in terms of magnitude and direction. Incorrect reproduction of velocity magnitude and direction leads to incorrect reproduction of flow details (e.g. the flow hydrodynamics). Current slope distortions used in micromodels limit applications to levels 1) and 2).

Slope distortion plays a major role in all facets of model operation and interpretation of model results because of its influence on flow hydrodynamics in the model. Additionally, determination of scale effects (an objective stated for the current evaluation effort) requires that model slope be known. However, slope is not reported in any published micromodel reports. Ironically, Davinroy (1994) determined a slope for the Dogtooth Bend micromodel. Davinroy (1994) also alluded to the fact that slope should be determined and analyzed because it

> "...may be used as a guide for future micromodel studies, although only by conducting a number of studies will more exact model to prototype slope relationships and model slope to model distortion relationships be more fully know."

Subsequent micromodel studies failed to document slope, which was a major disadvantage for the present evaluation. Documentation of slope should be a integral part of the micromodel procedure. Both micromodel and prototype slopes at analogous water levels should be included in study reports and operational logs.

11. **Micromodels operate on a sediment equilibrium principle.** Use of the equilibrium concept for micromodel operation becomes a limitation only if prototype bathymetry results from a non-equilibrium condition. Where the prototype undergoes constant changes in boundary conditions (bankline migration, rapid scour or deposition trends, etc.), the equilibrium approach may lead to incorrect model results. The potential for incorrect model predictions increases as the rate and magnitude of the non-equilibrium condition in the prototype increases. Micromodel use is restricted to problems where prototype banks do not change appreciably over time and where the prototype exhibits no long-term aggradation-degradation trends.

12. **Sediment materials used in micromodels limit their application to sand- or gravel-bed streams with active bed transport.** The PlastiGrit sediment material behaves in a similar manner to sand. Simulation of bed response with a cohesive bed is beyond the capability of existing physical and numerical models. The mechanics of cohesive material erosion and transport is not understood and no empirical methods exist to simulate channel adjustment.

13. **Tributary and divided channels impose requirements to ensure adequate representation of flow and sediment distributions between the respective channels.**

14. **Adequate documentation of micromodel operational and design parameters facilitates a better understanding of how the model represented the prototype.**

15. **Availability of prototype data limits understanding of some boundary conditions.**

16. **Suspended sediments cannot be modeled using micromodel techniques.** Sediment material characteristics change appreciably when sizes are in the clay and silt range. Suspended sediments at prototype scale typically fall in the silt/clay particle sizes with some suspended sediments being as large as sand sizes. However, cohesionless materials in the prototype having a median particle size of even 1.0 mm would require model sediments in the clay sizes if the correct horizontal and vertical model scales are used. At such reduced sizes otherwise cohesionless materials exhibit cohesive characteristics. Therefore, model sediment sizes are distorted in order to maintain cohensionless bed transport. The sediment sizes thus used in models do not provide any mechanism for simulating suspended sediments in the prototype. This is evident from the Shields Regime diagram (Figure 3-5).

17. **Inability to achieve good verification in some previous micro model tests**

18. **Conclusions from consultant on applicability to only laterally constrained reaches**

19. **Differences in Kate Aubrey plan tests**

20. **Lack of repeatibilty of Kate Aubrey traditional micromodel tests**

23. **Unknown flow characteristics through notches/dikes**