Appendix H

Analysis of the Cost of Bed Degradation of the Bed of the Missouri River to the Missouri River Bank Stabilization and Navigation Project (BSNP)

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CENWK-ED-H 4 May 2017

MEMORANDUM FOR RECORD

SUBJECT: Analysis of the Cost of Degradation of the Bed of the Missouri River to the Missouri River Bank Stabilization and Navigation Project (BSNP)

1. Purpose. The Missouri River has experienced degradation of its bed over certain reaches of the river. The degradation has been most acute in the Kansas City reach (river miles 320 to 410) of the river but other reaches of the river, including reaches near Jefferson City and St. Charles, have also experienced bed degradation. River bed degradation adversely affects the BSNP in two ways: (1) outside bend revetments become undermined resulting in an over-steepened slope along the riverward face of the revetment and (2) the crown elevation of rock structures that are comprised of longitudinal stone fill along a azimuth line projecting out into the river, such as dikes and L-heads, become perched above their design elevation. The costs of rectifying these adverse impacts is the subject of this memo

2. Background. The BSNP is comprised of a system of rock filled dikes and revetments which stabilize the river in one location and constrict flow so that the river has a reliable navigation channel during an 8 month navigation season. Although the river is stabilized by the BSNP, the river flows through a sand filled alluvial valley with a depth to bedrock along the thalweg generally in excess of 50 feet. Thus, although the river has been stabilized in place by the structures of the BSNP, the alluvial nature of the river bed means that river bed degradation can adversely affect the BSNP in the following ways:

a. The bed elevation along the toe of the outside bend revetments drops and undermines the revetments (Figure 1). The stone fill in the revetment then self-launches, resulting in an over-steepened riverward slope. The over-steepened slope is less stable, more likely to fail, and requires reinforcement with additional stone fill. This is a direct consequence of bed degradation as the toe of a revetment is supported by the bed.

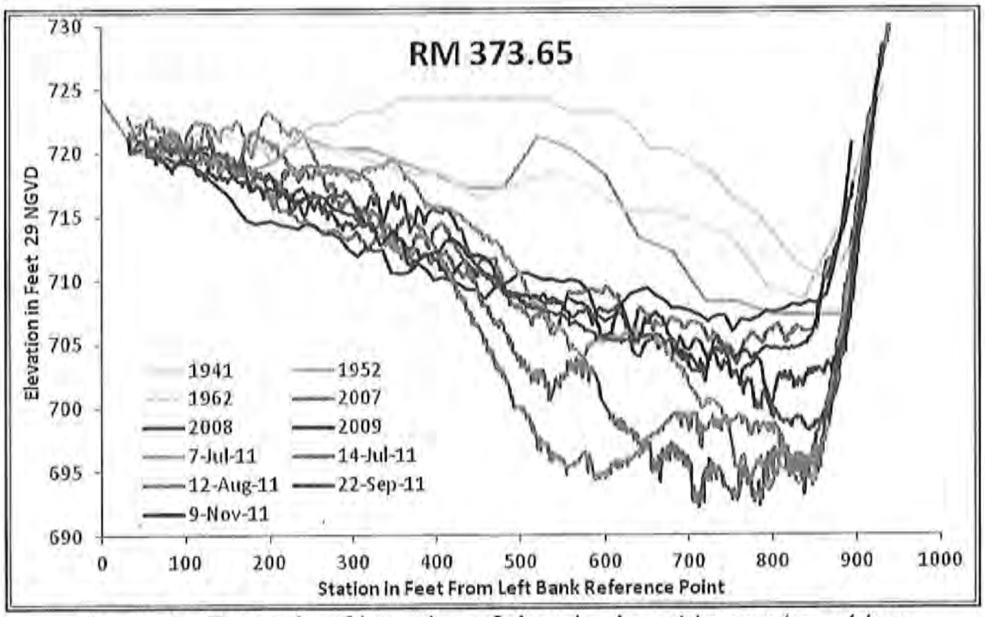

Figure 1: Example of lowering of river bed next to revetment toe.

b. The crown elevation of the dikes and L-heads become perched above their design elevation. This is a secondary impact of bed degradation as bed degradation affects the water surface of the Construction Reference Plane (CRP), which is the plane by which structure heights (elevation) are referenced. The perched condition of the structures reduces the over-topping frequency of the structures which leads to a build-up of sediment between the structures. The sediment vegetates, which slows the water flowing over the vegetation which then leads to more deposition during flood events. The result is a loss of aquatic habitat and reduced flow conveyance (Figure 2). The perched structures must be lowered by mechanical removal of the stone fill.

Figure 2: Example of accretion and vegetation (river mile 364) caused by perched structures.

Figure 3 indicates the typical layout of the structures of the BSNP. The analysis in this memo uses pre-existing data from the reach between river miles 340 and 420, where degradation has been most severe and actions have been taken to rectify the adverse impacts of degradation to the BSNP structures.

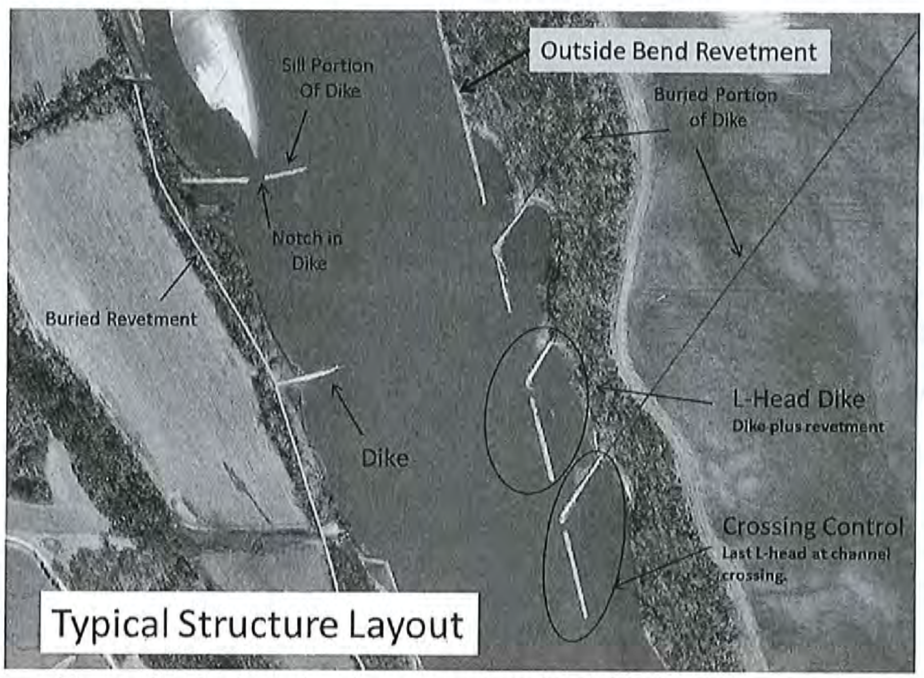

Figure 3: Typical structure layout and outside bend revetment.

3. Analysis.

a. As mentioned above, bed degradation requires reinforcement of the toe of the revetments and the removal of stone fill from river training structures such as dikes and L-heads. Toe reinforcement of dikes and L-heads, etc. is not required since their cross sectional area per linear foot of structure contains significantly more rock than outside bend revetments (Figure 4). The additional rock per linear foot provides a higher factor of safety for each structure and failure of the structure will generally not result in damage to adjacent private property. These structures are subject to periodic lowering of the crown as discussed below. The rock removed from the crown during lowering is wasted down the side of the structure and acts to reinforce the toe.

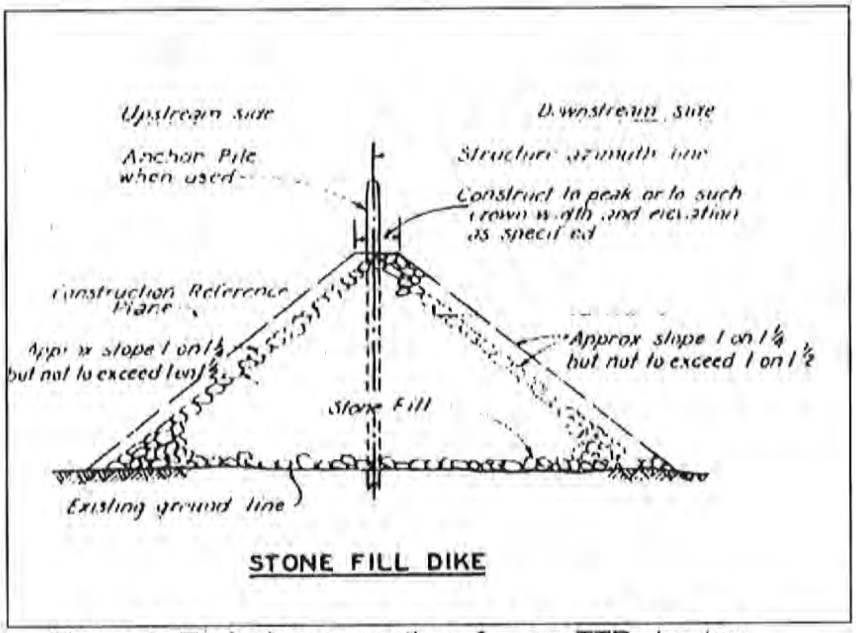

Figure 4: Typical cross section of a non-TTR structure.

b. Revetment Reinforcement. For this analysis, only revetments along the outside bends of the river were evaluated. The type of revetment generally encountered along the outside bend is known as a toe trench revetment (TTR). TTR is composed of rock placed along a graded bank to the dimensions shown in Figure 5. TTR has a rock layer 2-3 feet thick on the upper slope and a thickened trench fill along the toe. The other type of revetment encountered is a standard revetment which is composed of a woven wooden mattress weighted with a 2' thick rock layer along the entire slope. However, most standard revetment has been overlaid with additional rock so that it essentially has the same cross section as a TTR.

(1) At any point along the river, there is an outside bend revetment on one bank or the other as revetments start in the channel crossing, extend along one bank, and then terminate at the downstream crossing where the next revetment begins on the opposite bank.

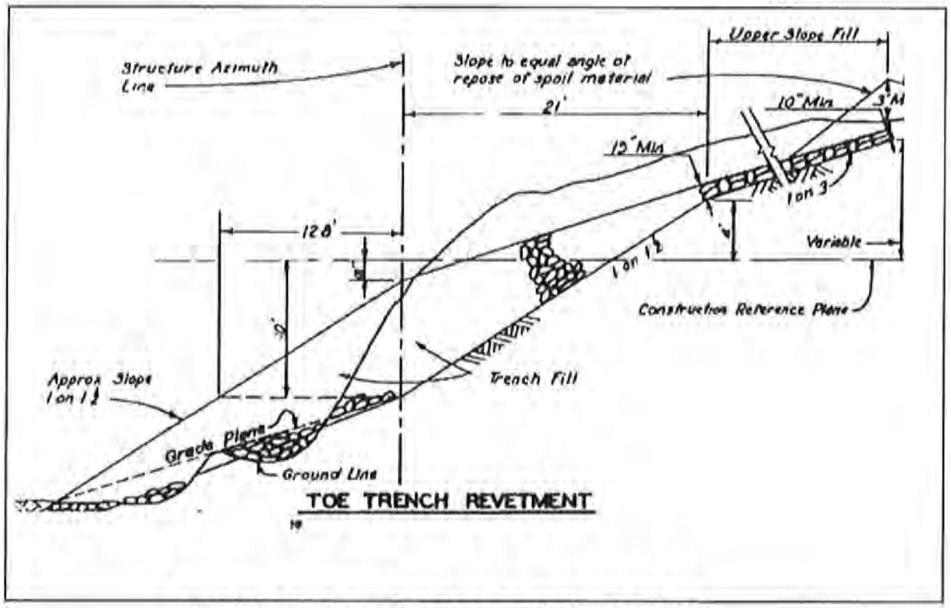

Figure 5: Typical cross section of a TTR.

(2) The lower riverward slope of a TTR is constructed at a grade of 1:1.5 (V:H) which extends from the toe up to the structure azimuth line. This analysis assumes that as the bed degrades, the riverward slope of the TTR steepens until the slope reaches a 1:1 slope. The 1:1 slope is assumed to extend vertically up to the CRP elevation at which point the 1:1 slope would be visible during low water inspections. The 1:1 slope is steeper (over-steepened) than the constructed minimal slope of 1:1.25 and is assumed to be near the slope angle at which the structure is no longer stable. At this point, the revetment is assumed to be reinforced by adding stone fill until the slope is once again a 1:1.5 slope. The calculated amount of rock needed for this repair is reduced by 37% to account for the quantity of pre-existing rock that slumped to the toe of the degraded revetment. See Figure 6 for a schematic of a typical failed and repaired TTR. The quantity of stone fill needed is calculated for one foot of degradation per mile of river.

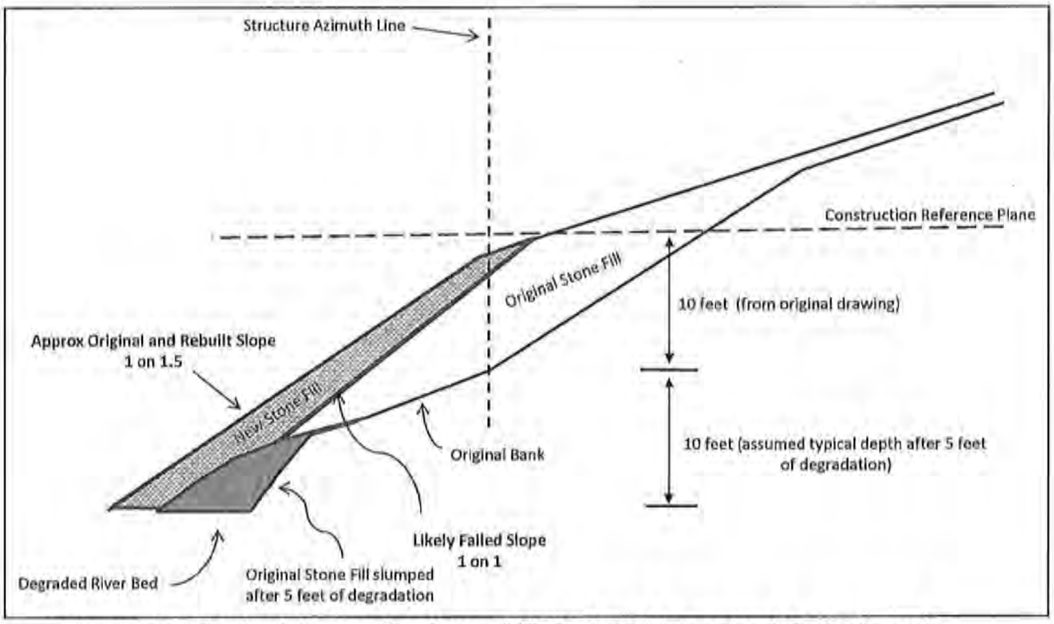

Figure 6: Typical Cross Section of Failed and Repaired Revetments

c. Structure Lowering. Structure lowering involves the mechanical removal of rock from the crown of the structures by means of floating plant. The floating plant usually consists of a trackhoe stationed on a spud barge and a tow boat to move the barge from location to location. The removed rock is wasted down the side of the structure. The total volume of rock needed to be removed, per river mile, per foot of degradation was determined by the following method.

Step 1. *Determine the volume of rock removed to date from structure crowns to bring structures to criteria height.* Beginning in 2002 there have been 5 iterations of structure lowering with the last iteration in fall 2015. The quantity removed from each structure, for each iteration, was recorded in the Structure History Database (SHD) after each lowering. The SHD was queried to sum the volume of rock removed, per river mile, for all lowering iterations, except for the fall 2015 lowering. The 2015 lowering was excluded because the structures lowered during this iteration were accounted for in the step below.

Step 2. *Determine the volume of rock remaining to be removed from structure crowns to bring all structures to criteria height.* In January 2015, every structure was visually inspected and the average height of each structure relative to the CRP recorded. The field data was post-processed to determine the number of feet each structure is above its criteria height and hence the number of feet each structure needs to be lowered. The length of each structure was determined by running queries in GIS using the structure layer, the rectified channel line, and the bankline. The volume per linear foot of structure, per foot of height that needs to be removed, was determined by field surveying typical representative structures and constructing a height verse volume table. Finally, the height each structure needs to be lowered was multiplied by the corresponding volume and the length of each structure. The resulting value was in cubic yards. The total number of cubic yards, per river mile, was summed.

Step 3. *Determine the number of feet of degradation at every river mile.* This step was accomplished by subtracting the elevation of the 1990 CRP from the elevation of the 2010 CRP. The CRP is periodically recalculated so that it tracks the actual 75% exceedance water surface. The 75% exceedance tracks the bed elevation and therefore changes in the bed are reflected in changes to the CRP. The exact relationship between changes in the bed elevation and change in the CRP is not relevant for this analysis since it is not the change in the bed elevation but the change in CRP that is used to determine if structures need to be lowered. Figure 7 shows the total cost (Step 1 and Step 2 added together) to lower structures per river mile compared to the feet of degradation per river mile. As can be seen in the figure, cost and degradation track each other closely. The exception is between river miles 365 and 380 where the cost is higher than the amount of degradation which is likely due to the high number of structures per river mile in this reach.

Step 4. *Determine the total volume of rock, per river mile, per foot of degradation.* This step was accomplished by summing the volumes per river mile obtained in Step 1 and Step 2 and dividing by the feet of CRP change, per river mile, derived in Step 3.

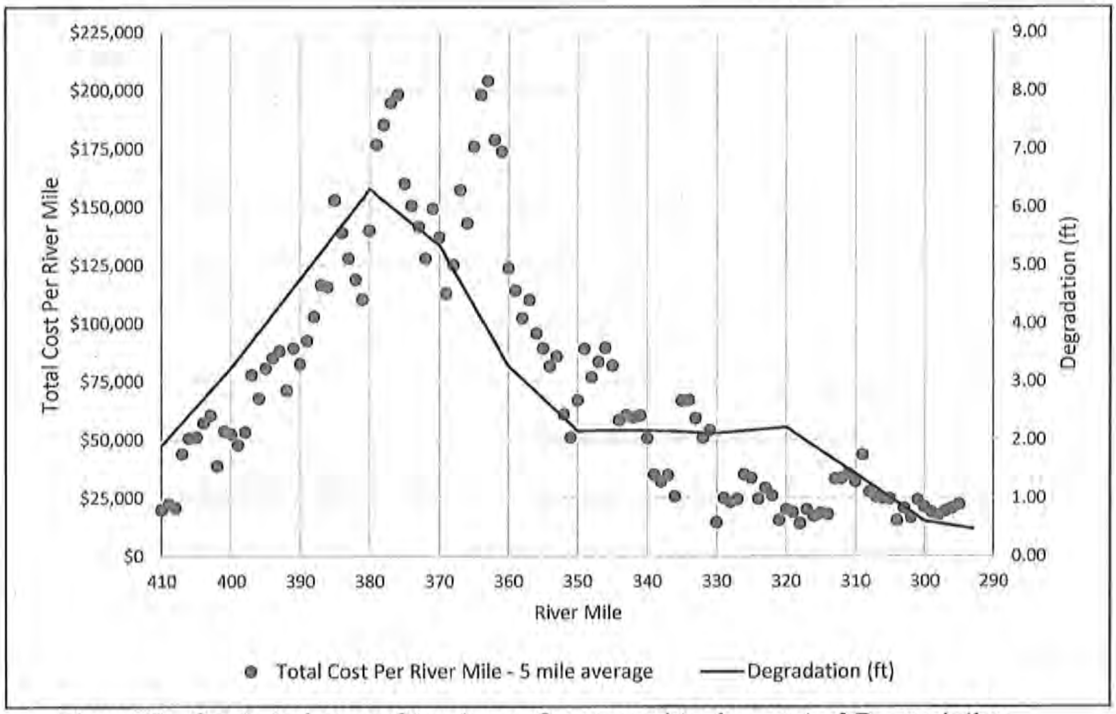

Figure 7: Costs to Lower Structures Compared to Amount of Degradation

4. Conclusions.

a. Revetment Reinforcement. The volume of rock needed for revetment reinforcement per river mile per foot of degradation, 9,678 tons, was multiplied by the 10 year average contract price for rock placement of $35 per ton. The result is $320,000 per river mile, per foot of degradation.

b. Structure Lowering. The total volume of rock removed to date and the total volume of rock calculated remaining to be removed is 141,000 cubic yards and 258,000 cubic yards respectively. The total volume per river mile was divided by the number of feet of degradation per river mile. This value was then averaged and multiplied by the contract price for rock removal obtained over the last 10 years, which is $22 per cubic yard. The result is $18,000 per river mile, per foot of degradation.

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