CEMVP-EC-D September 20, 2012

MEMORANDUM FOR RECORD

SUBJECT: Fargo-Moorhead Metropolitan Area Flood Risk Management Project (FMMFRM) - Diversion Channel and Low-Flow Design

1. PURPOSE

The purpose of this document is to outline the diversion channel and low-flow channel design, including changes since the feasibility study phase. This includes documenting the requirements of these features from the standpoint of hydraulics, geotechnical, and environmental concerns. The geotechnical methodology used when analyzing the diversion channel is also described and is needed in order to maintain consistency throughout the project.

2. REFERENCES

References and supporting documentation are listed below.

1) Red River Diversion, Fargo-Moorhead Metro Flood Risk Management Project, Feasibility Study – Phase 4 Volume 1 General Report. Prepared by Moore Engineering, Inc.; Houston Engineering, Inc.; Barr Engineering Company; and HDR, Inc. February 28 2011
2) Technical Report EL-9709 - Hydraulic Impacts of Riparian Vegetation; Summary of the Literature (Fischenich 1997)
3) U.S. Army Corps of Engineers. 2012, “Memorandum for Record – Vegetation within the Fargo-Moorhead Metro Diversion Channel,” U.S. Army Corps of Engineers – St. Paul District, St. Paul, MN
4) U.S. Army Corps of Engineers. EM 1110-2-1902. 2003. “Slope Stability,” U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.
5) U.S. Army Corps of Engineers. EM 1110-2-1913. 2000. “Design and Construction of Levees,” U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.
6) U.S. Army Corps of Engineers. 2012. “Fargo-Moorhead Metropolitan Area Flood Risk Management Project, General Report: Geotechnical Engineering and Geology,” U.S. Army Corps of Engineers – St. Paul District, St. Paul, MN
7) U.S. Army Corps of Engineers. 2012, “MFR-001, Levees and Excavated Material Berms Along the Diversion Channel,” U.S. Army Corps of Engineers – St. Paul District, St. Paul, MN
8) U.S. Army Corps of Engineers. 2011. “Fargo-Moorhead Metropolitan Area Flood Risk Management, Value Engineering Study Report, Report Number CEMVP-VE-FY12-01,” U.S. Army Corps of Engineers – St. Paul District, St. Paul, MN

3. PROJECT CONSIDERATIONS AND REQUIREMENTS

3.1. Environmental Considerations

A wide variety of mitigation features are required to offset the impacts associated with construction and operation of the project. Measures required for aquatic habitat and connectivity mitigation include stream restoration, riparian corridor restoration, a meandering low-flow channel in the diversion and providing fish passage. The fish passage will be provided at the diversion outlet, Rush River inlet, Lower Rush River inlet, Maple River aqueduct, Sheyenne River aqueduct, Wild Rice River control structure, Red River of the North control structure and several existing dams. Floodplain forest mitigation will be provided by re-establishing floodplain forest on 239 acres of floodplain agricultural land or pastured land. Wetland mitigation will be provided in the diversion channel by planting the bottom and fringe of the side slopes with native wetland species (MFR Vegetation in Diversion). The meandering low-flow channel and attendant grade control structures at bridge locations will facilitate the development of wetland habitat in the diversion channel.

3.2. Hydraulic Requirements

The hydraulic requirements associated with the main diversion and low-flow channel are:

- Ability to convey dominant discharge from local drains within a meandering low-flow channel,
- Ability to convey the 1% event discharge so that the water surface profile is generally below existing ground elevation,
- Ability to safely convey flows for events up to the inflow design flood, and
- Minimize erosion and sedimentation issues for Operations and Maintenance (O&M).

3.3. Geotechnical Requirements

The geotechnical requirements associated with the diversion channel and low-flow are:

- Ability to excavate the diversion channel and low-flow channel to required grades,
- Stability of the diversion channel during and after construction,
- Stability of the diversion channel slopes over the the long-term considering the potential for sediment deposition in the channel and vertical scour of the low flow channel., and
- Adequate protection of the diversion channel from erosive action through vegetative cover.

4. HYDRAULIC DESIGN

4.1. Diversion and Low-Flow Channel Features

The feasibility level design of the diversion channel generally consisted of a 250 ft wide channel bottom with 1V:7H side slopes that daylight at existing ground. The depth of the main channel ranged from 15 to 30 ft deep and the channel was set at a longitudinal slope of 0.8 ft/mile. The side slopes included geotechnical “benches” of 15 to 40 ft wide, as needed, to provide additional stability to meet the required factors of safety. At the center of the flat 250 ft wide channel bottom, was a small low-flow channel that was included to convey the runoff from small drains and streams, such as the Rush and Lower Rush Rivers. This low-flow channel for the entire diversion was sized to be 3 ft deep with a 10 ft bottom width and 1V:4H side slopes giving a low-flow cross-sectional area of 66 sq ft.

Even in early phases of feasibility, it was recognized that further analysis would need to be completed to fully design the low-flow channel. Other factors, such as the sinuosity of the low-flow channel across the main channel bottom width and the need for slope across the main channel bottom to allow for drainage, would also need to be considered.

The hydraulic modeling effort has proceeded in numbered phases since the beginning of the study effort. Since the feasibility study, ending in Phase 4, there have been two additional phases. While Phase 5 dealt mostly with improving the detail of the hydraulic model, Phase 6 began concurrently with the Value Engineering study of the FEIS (reference 8) and currently deals with optimizing and re-evaluating the design of the project features. During Phase 6, which is ongoing, more consideration is being given to the design of the low-flow channel, overall diversion invert slope, and final alignment of the diversion.

4.2. Bottom Width Sloping for Drainage

Surfaces such as the bottom width, the geotechnical stability benches, and the excavated material berm offset now include a 1V:50H, or 2%, cross-slope towards the center of the channel to provide adequate drainage within the project. As a result of the addition of the cross-slope to the bottom of the diversion, the overall bottom width is increased to 300 ft to retain approximately the same diversion top width and conveyance as the feasibility study. The following table (Table 1) details the changes to the main channel between Phase 4 and Phase 6.

Table 1: Main Channel Geometries during Phases 4 and 6

Table 1 - Main Channel	*Phase 4*	*Phase 6*
Bottom width	250 ft	300 ft
Cross-slope	0%	2%
Top width	450-750 ft	450-700 ft
Side slopes	1V:7H	1V:7H
Geotech stability benches	0-40 ft	0-30 ft
Excavation Material Berm Height	8-15 ft	15 ft max
Excavation Material Berm Slope	1V:7H	1V:7H
Excavation Material Berm Offset	50 ft	50 ft

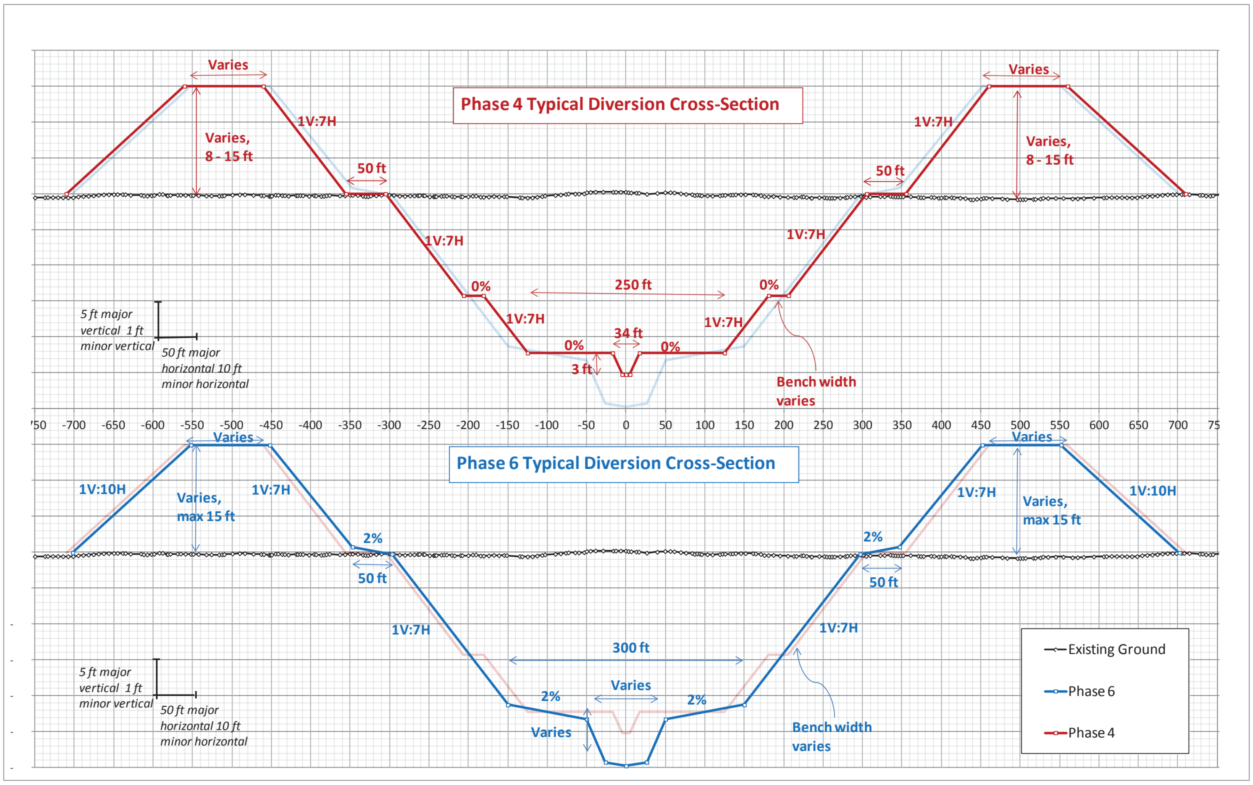

Figure 1: Graphical comparison of typical channel geometries in Phases 4 and 6.

4.3. Low-Flow Channel Design Comparison

The original design of the low-flow channel assumed one size would accommodate all reaches of the diversion. It has been determined that the 3 ft deep low-flow channel was grossly undersized for the majority of the project reaches to handle the existing drainage. During Phase 6, the low-flow was redesigned to accommodate drainage inflows all the way along the diversion. As a result, the low-flow channel increases in size and capacity as the diversion moves downstream. For constructability and design purposes, this gradually increasing low-flow channel was designated into four separate reaches. Detail of the geometric configuration of these four low-flow channel sizes can be seen in the following table (Table 2).

Table 2: A comparison of low-flow channel geometries during Phases 4 and 6

Table 2 – Low-Flow	*Phase 4*	*Phase 6*			
LFC Reach	**Inlet to Outlet**	**Inlet to Drain 21c**	**Drain 21c to Drain 14**	**Drain 14 to Rush River**	**Rush River to Outlet**
Centerline Depth	3 ft	2.5 ft	4 ft	6 ft	6.5 ft
Side Depth	3 ft	2.4 ft	3.7 ft	5.6 ft	6.0 ft
Bottom Width	10 ft	10 ft	30 ft	45 ft	52 ft
Cross-slope	0%	2%	2%	2%	2%
Top Width	34 ft	30 ft	60 ft	90 ft	100 ft
Side Slopes	1V:4H	1V:4H	1V:4H	1V:4H	1V:4H
Area	66 sq ft	48 sq ft	170 sq ft	386 sq ft	469 sq ft
***Required Capacity**	Variable	3 cfs	133 cfs	470 cfs	710 cfs
****Design Capacity**	61 cfs	32 cfs	184 cfs	546 cfs	710 cfs

***Required capacity is the cumulative local drainage discharge entering the diversion up to a given reach; design capacity is the bankfull discharge of the low-flow configuration. The cumulative bankfull discharge was taken as 80% of the combined 1.5 year peak flows for local drains.**

****Design Capacity assumes side slopes "silt-in" from 1V:4H to 1V:2H side slopes.**

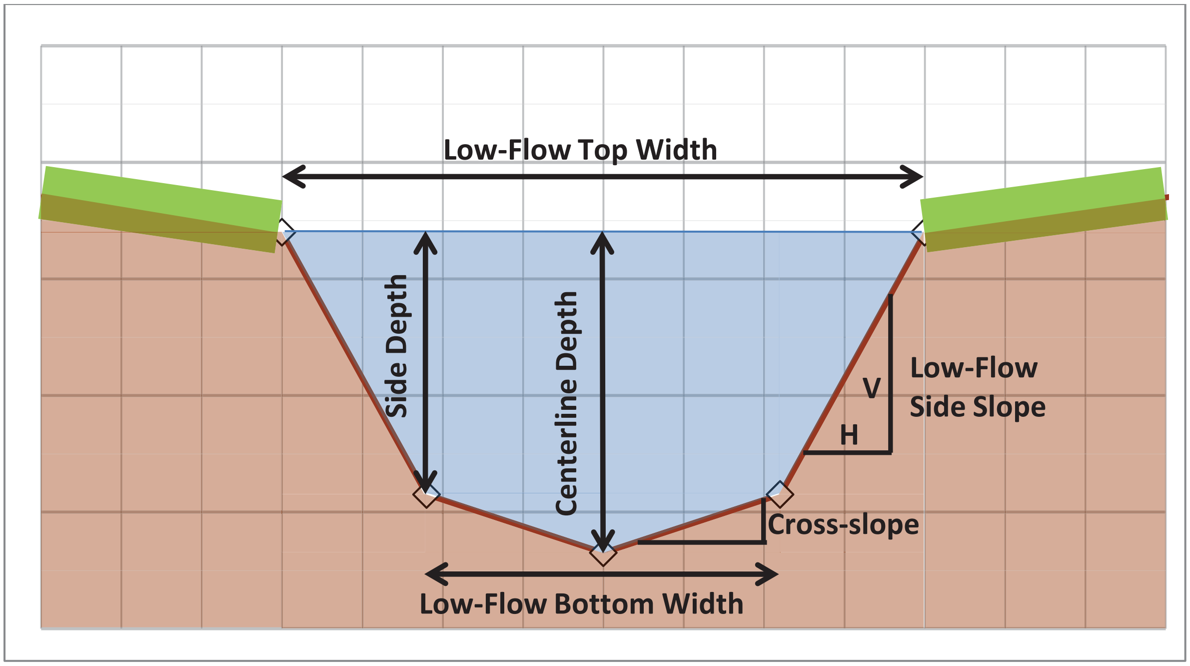

Figure 2: Schematic illustrating low-flow channel terminology

4.4. Slope and Sinuosity Design Comparison

The overall slope of both the diversion channel and low-flow channel ultimately ended up being designed at 0.8 ft/mile (0.00015%) for the Phase 4 design and modeling. During Phase 4, some modeling and discussion occurred as to how to meander the low-flow channel, but ultimately, no meander belt or modified low-flow slope were finalized. During Phase 6, more thought and discussion has occurred as to how to meander the low-flow channel (now with a much larger low-flow size) and what impacts come as a result of the meandering. One initial impact was that by meandering the low-flow channel, sinuosity was added and the slope of the low-flow needed to be somewhat less than the main channel. The other major impact of meandering is that lateral movement can potentially threaten the integrity of the geotechnical stability of the diversion channel side slopes. The slope and sinuosity of each phase is shown in the following table, Table 3.

Table 3: Channel slopes and sinuosity of the low-flow channel

Table 3 – Slope and Sinuosity	*Phase 4*	*Phase 6*
Low-Flow Slope	0.8 ft/mile (0.00015)	0.8 ft/mile (0.00015)
Main channel Slope	0.8 ft/mile (0.00015)	0.9 ft/mile (0.00017)
Low-Flow Sinuosity	1.0	1.125

4.5. Vegetation Plan

The plan to establish vegetation within the diversion channel is presented in the FMMFRM Project Memorandum For Record, “Vegetation within the Fargo-Moorhead Metro Diversion Channel.

4.6. Summary of Design Changes for Diversion and Low-Flow Channels Post-Feasibility Study

Recommended design changes include:

- **Add cross-slopes to the diversion channel to improve drainage within the diversion channel.**
- **Incorporate four different, larger sized low-flow channel reaches to incorporate local drainage from upstream to downstream along the diversion.**
- **Bottom width of diversion channel set at 300 ft below the Maple River which generally maintains the Phase 4 top width and provides room for some meandering of the low-flow channel.**
- **Steepen the main channel slope from 0.015% to 0.017% to allow meandering/sinuosity of the low-flow channel.**

Advantages

A. Improved drainage.

B. Reasonable chance for meandering (environmental mitigation) to occur throughout the entire diversion.
C. Low-flow channel will better contain channel-forming flows. If the low-flow channel were to remain undersized, water would fill the main channel too frequently, which would likely cause maintenance issues due to loss of vegetation and sediment deposition.

Disadvantages

A. Excavation quantities may increase slightly.

Outstanding Issues

A. Perform additional stability analyses to evaluate the effects of different low-flow channel erosion scenarios on the stability of the diversion channel side slopes.
B. Design of the diversion top elevation and excavated material berm top elevation.
C. Complete Drain 14 to Maple River Diversion Analysis.
D. Develop repair guidance.
E. Validate decisions when these further analyses are complete.
F. Determine how to merge the concept of meandering low-flow channel with the requirements of the Inspection of Completed Works.
G. Develop Project/Reach ‘Notice of Construction Completion’ strategy

5. GEOTECHNICAL DESIGN

5.1. General

The geotechnical performance of the diversion channel and low-flow is related to the stability of the excavated slope during and after construction, and long-term. Performance of the excavated slope can be related to the factor of safety for the critical slip surfaces obtained through a slope stability analysis. In general, as the factor of safety for the critical slip surface becomes smaller, approaching 1.0, the more likely a failure will occur.

In addition, the size of the failure surface plays an important role in evaluating the performance of the excavated slope. In general, small failure surfaces occurring at the toe of the main channel or slightly above could be a maintenance issue. Such failures would cause the side slope of the diversion channel and the channel bottom to become hummocky or uneven, making mowing and other maintenance operations difficult. The consequence of these small failure surfaces would reduce the efficiency of maintenance and may require the diversion slope and channel bottom to be regraded and reseeded, increasing costs for O&M.

Whereas small failure surfaces may be a maintenance concern, large failure surfaces that encompass the entire excavated slope could be a major issue. These large failure surfaces could potentially affect the excavated material berms/levees running parallel with the diversion, local drainage inlet structures, and recreational features located beyond the top of the slope. If a large failure surface would occur, it could potentially reduce the hydraulic capacity of the diversion channel in a localized area. In addition, the cost to repair a large failure surface would be expensive when compared to the small failure surfaces. One likely repair alternative would be flatten the excavated slope and unload material from the top of the slope.

The intent of the geotechnical analysis of the diversion channel and low-flow is to evaluate the stability of the excavated slopes using limit equilibrium slope stability analysis and deterministic factors of safety. The minimum required slope stability factors of safety are selected based on the following considerations:

- Minimize the probability that a large failure surface occurs, thus reducing the potential of having to complete difficult and expensive fixes (this requires a higher factor of safety)
- Allowing small slip surfaces to have lower factors of safety to help minimize the project's first costs (i.e. construction costs) while trying to minimize increases to O&M costs due to small failure surfaces.
- Recognize the fact that small failure surfaces can progress into large failure surfaces, therefore the lowest acceptable factor of safety for small critical surfaces must be above 1.0 to reduce the likelihood of such an occurrence.

5.2. Geotechnical Assumptions

There are a number of assumptions that are made when analyzing the diversion channel. These assumptions are listed below along with the reason(s) they were selected. For each assumption, there is indication on how conservative the assumption is and what effect the assumption has on the results of the stability analysis.

Table 5: Summary of Geotechnical Assumptions

Category	Assumption	Reason Selected	Conservative or Not	Effect Category has on Slope Stability Results (small, moderate, large)
Drained Shear Strength Parameters	Ultimate criteria (15% strain); 1/3:2/3 rule.	Progressive failures; Strain softening soil behavior; Potential for large strain.	Average conservatism	Large Effect on Results
Undrained Shear Strength Parameters	Ultimate criteria (15% strain); 1/3:2/3 rule.	Strain softening soil behavior; potential for large strain.	Average conservatism	Large Effect on Results
Pore Pressures	Pore pressures in stability calculations determined form seepage analysis.	A coupled seepage/stability analysis provides more realistic pore pressures than piezometric line.	Average conservatism	Moderate Effect on Results
Model extent	2000 feet from centerline of diversion.	Engineering judgment that groundwater table would not be affected 2,000 feet beyond project centerline which is verified by the results of seepage calibration modeling.	Average conservatism	Moderate Effect on Results
Groundwater Boundary Condition	Total head boundary condition set at 10 feet below ground surface along the vertical extent located 2000 feet from centerline.	Difficulty in determine water levels from borings; Evapotranspiration would effect upper 5 -10 feet; Results of the seepage calibration modeling that indicates 10 feet below ground surface provides reliable results.	Conservative	Moderate Effect on Results
Permeability values	Permeabilities selected using typical ranges of permeabilities based on soil types used; Upper foundation materials (Alluvium, Sherack, Oxidized Brenna) are one order of magnitude more permeable than lower foundation materials (Brenna, Argusville). Unit "A" till is 2 orders of magnitude more permeable than Brenna and Argusville.	Permeability tests difficult to run and only accounts for small sample size; Back calculations from consolidation tests indicate soils have similar permeabilities; Results of seepage calibration modeling; Setting the Unit "A" till permeability 2 orders of magnitude more permeable and using total head boundary conditions gives an upward flow gradient of groundwater from the Unit "A" till into the diversion channel.	Average conservatism	Small Effect on Results
Permeability ratio (k_x to k_y)	Alluvium, Sherack, and Unit "A" till formations have kx:ky ratios of 4 to 1. All other formations have k_x:k_y ratio of 1 to 1.	Engineering judgment; Sensitivity analysis indicated that using different k-ratios did not have major affect on the slope stability factor of safety; Results of seepage calibration modeling.	Average conservatism	Small Effect on Results
Water in Low-Flow	There is no water in the low-flow.	There could be times during the year in which no water is flowing in the diversion or low-flow channel.	Average conservatism	Small Effect on Results of Global stability; Small to moderate effects on localized stability including effects of erosion of the low-flow channel.

5.3. Geotechnical Modeling Requirements

In order to maintain consistency throughout the project for design of the diversion channel, each section analyzed must be modeled using the same criteria. The criteria to be used are described below.

5.3.1. Seepage Analysis

Steady-state seepage analysis is required in order to estimate pore pressures. The estimated pore pressures will then be used in the long-term (drained) slope stability analysis. There are many programs that are capable of analyzing steady-state seepage. The program used should also be able to export the results into a slope stability analysis efficiently. All seepage models should be setup with consistency no matter what program is used. Below is a summary of the model requirements for seepage analysis along with figures to depict the concept:

- "Half-space" models can be used due to the symmetry about the channel centerline. In instances where there is no symmetry, a "full cross-section" model must be used. Also, if the slope stability analyses indicate that the failure surfaces extend across the centerline, "full cross-sections" must be used.
- Model Size:
    - The model shall extend laterally, 2,000 feet offset from the centerline of the diversion channel.
    - Unit "A" till thickness: The thickness of the Unit "A" till at the base of the model shall be 50 feet.
- Meshing: The meshing for the seepage model shall be customized such that the pore pressures near the excavated slope are calculated with more frequency than at locations located a considerable distance from the slope. Three "meshing regions" can be used to facilitate this which are explained below and illustrated in the figures.
    - Meshing Region 1:
        - Associated Materials: All foundation materials above the till, at a distance extending 100 feet from top of excavated slope.
        - Mesh size: 2-foot
    - Meshing Region 2:
        - Associated Materials: All materials that are located in a region extending from 100 feet beyond top of excavated slope to 250 feet beyond top of excavated slope. This also includes the till material located beneath Meshing Region 1.
        - Mesh size: 4-foot
    - Meshing Region 3:
        - Associated Materials: All materials that are located in a region extending from 250 feet beyond the top of the excavated slope to the model extents.
        - Meshing size: 6-foot
- Permeability Parameters:
    - The permeability parameters used in the seepage analysis shall be those indicated in the *General Report: Geotechnical Engineering and Geology*.

  - "Saturated versus Unsaturated" Permeabilities: For materials which will likely be above the ground water table, the permeability of the material should account for the decrease in permeability due to soil suction.
  - Permeability Ratio: The permeability ratio, K, shall be the same as indicated in the *General Report: Geotechnical Engineering and Geology*.
- Boundary Conditions:
  - Total Head Boundary conditions shall be used along the vertical edge of the model that is 2,000 feet from the centerline. The value of the total head boundary condition shall be taken as 10 feet below ground surface.
  - Potential seepage boundary conditions shall be used along the face of the excavated slope for review of piezometric surface. This assumption considers that there is no water in the low-flow channel.

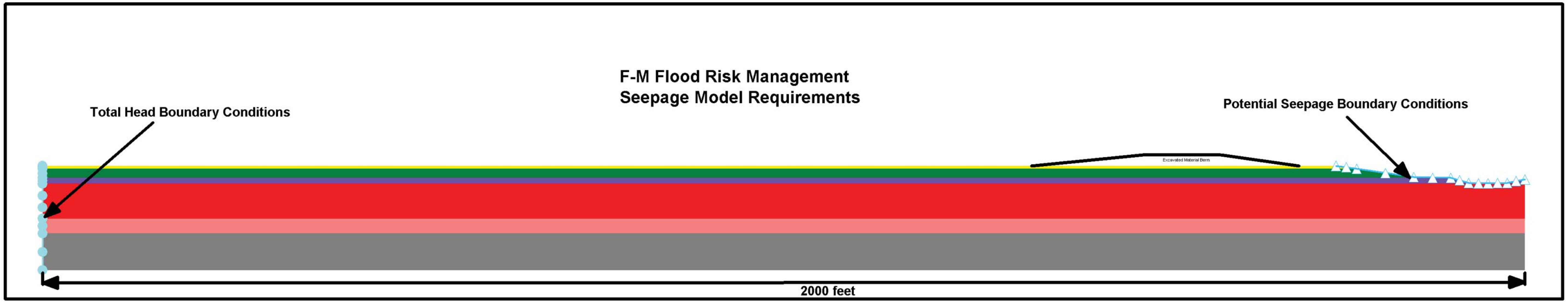

Figure 1: Seepage Model Boundary Conditions

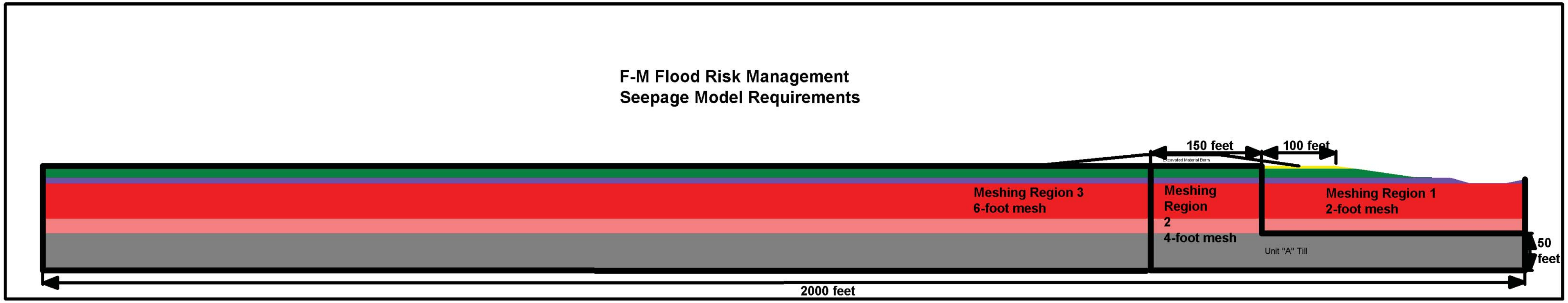

Figure 2: Seepage Model Meshing Regions

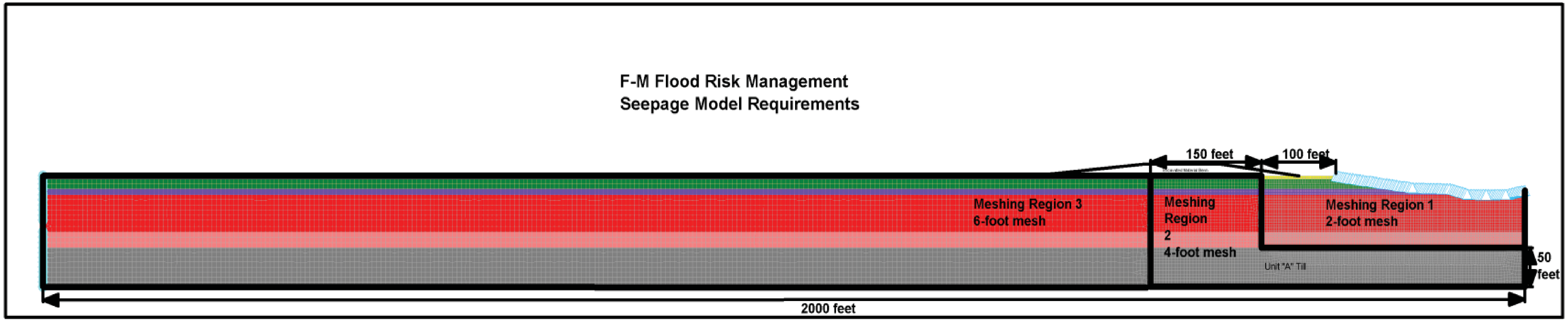

Figure 3: Seepage Model Meshing Requirements

5.3.2. Stability Analysis

There are many different slope stability programs available. A program should be selected that can couple the pore pressures computed by a steady-state seepage analysis into the stability analysis with ease. When running slope stability, the following requirements should be followed:

- Method: Spencer's Method for slope stability shall be used to determine the slope stability factor of safety.
- Number of Slices: A minimum of 30 slices shall be used.
- The minimum slip surface depth shall be 2 feet.
- Non-circular slip surfaces resulting from optimized circular surfaces shall be used. This is based on St. Paul's District's experience in analyzing slopes in the Red River Basin in which non-circular slip surfaces, containing a large neutral block, is most critical. Typically, the critical non-circular slip surface has been found to contain more than 3 segments.
- If using Slope/W from GeoSlope, the "optimization critical slip surface location" can be used to obtain a non-circular critical slip surface.

5.3.3. Modeling of Excavated Material Berm (EMB)

The construction of the diversion channel will require a large quantity of excavation. It is assumed that the excavated material will generally be distributed evenly between the two sides of the channel, creating EMBs that are hundreds of feet wide at the base. The EMB is required to be modeled in the stability analysis as this loading will affect the stability of the diversion channel. When modeling the EMB in the stability analyses, the EMB must be defined as a region and modeled as a material type. The EMB should be broken into two different regions, a semi-compacted excavated material region and an excavated material region to account for the likelihood that the material closest to the diversion channel excavation will be driven over and compacted more than material located further away from the excavation. For the semi-compacted material a unit weight of 123 pounds per cubic feet (PCF) should be assigned and the zone should extend 160 feet from the diversion side toe of the EMB. For the excavated material, a unit weight of 121 PCF should be used. The shear strength parameters for both the semi-compacted and excavated material should be the same, with an undrained shear strength of 600 pounds per square foot (PSF) and an effective friction angle of 14 degrees and cohesion intercept of 50 PSF. These selected shear strength parameters are similar to the in situ Brenna formation parameters as the excavated material will be placed randomly within the EMB and without very much compaction effort.

The use of the EMBs had not yet been finalized as the Local Sponsor is ultimately responsible for determining the end use of the EMBs which includes recreational features and grading. Below is the general layout of the EMB, but will need to be adjusted during design when the EMB end use and grading plan is finalized.

- 50-foot offset from top of diversion channel.

- Side slope on diversion side of EMB is 1V:7H.
- Side slope on landward side of EMB is 1V:6H.
- EMB top width varies to accommodate the quantity of excavated material, equally distributed on either side of channel.
- EMB may be stepped to increase the volume of excavated material that can be placed within a given footprint.
- Minimum of a 2% slope on any EMB “flat” surfaces.

5.3.4. Stability Cases

Over the course of the project, the diversion channel has been analyzed for five different geometric cases. Of these, only three are currently applicable to the design process. The cases represent the different locations and conditions of the low-flow channel. A summary of the different cases is as follows:

- Case 1: The low-flow channel is constructed in the middle of channel. This would be considered a normal loading condition. Case 1 is relevant to locations like bridges where the low-flow channel will be constructed in the center of the channel without a meander and will be armored to prevent natural meandering over time.
- Case 2: The low-flow channel is constructed offset from centerline to account for the maximum possible meandering of the low-flow channel within the meander belt. This would be considered a normal condition.
- Case 3 (obsolete): The low-flow channel begins to erode at the outside of the meander. The outside slope of the low-flow channel steepens up to 1V:2H and erodes 1 foot vertically . Case 3 and Case 4 are considered obsolete in light of the Meander Belt Width Analysis completed by Barr Engineering and the HEC-RAS Sediment Transport Analysis completed by USACE St. Paul District.
- Case 4 (obsolete): The low-flow channel continues to erode laterally and encroaches towards the toe of excavated slope. This would be considered an extreme occurrence. For this analysis, different amounts of erosion are analyzed (by reducing the offset between the toe of the main channel and the top of the low-flow channel) to determine when erosion becomes critical to the stability of the diversion channel slope. The maximum amount of erosion allowed is the condition in which all the required factors of safety are met. If repairs are not initiated and erosion of the low-flow channel continues, the global stability of the diversion channel slope could be reduced such that failure of the slope initiates. Case 3 and Case 4 are considered obsolete in light of the Meander Belt Width Analysis completed by Barr Engineering and the HEC-RAS Sediment Transport Analysis completed by USACE St. Paul District. Case 5 replaces Cases 3 and 4.
- Case 5: The bottom of the low-flow channel erodes 2 ft vertically and sedimentation occurs at the base of the diversion channel and along the diversion side slopes. Sediment deposition is modeled by creating a region consisting of “Alluvium” as

defined in the General Report: Geotechnical and Geology. Deposition is applied in a uniform thickness above the bottom of the diversion channel, tying into the top of the diversion and the low-flow channel side slope (see Figure 4). The x coordinates of the vertices representing the diversion toe, top of low-flow channel, and bottom of low-flow channel remain the same for Case 5 – there is no lateral component to erosion or sedimentation. Beginning with 1 ft, the depth of sedimentation is increased in 1 ft increments until one or more of the target factors of safety is not met. The acceptable amount of sedimentation is the maximum amount that meets the target factors of safety.

The intent of analyzing Case 5 is to estimate the stability of the diversion channel throughout the lifetime of the project, considering that erosion of the low-flow and sedimentation of the diversion will likely occur. The results of Case 5 can be used to determine when sedimentation has to be removed to prevent global instability of the diversion channel slope. Figures 4a and 4b below illustrate the different cases.

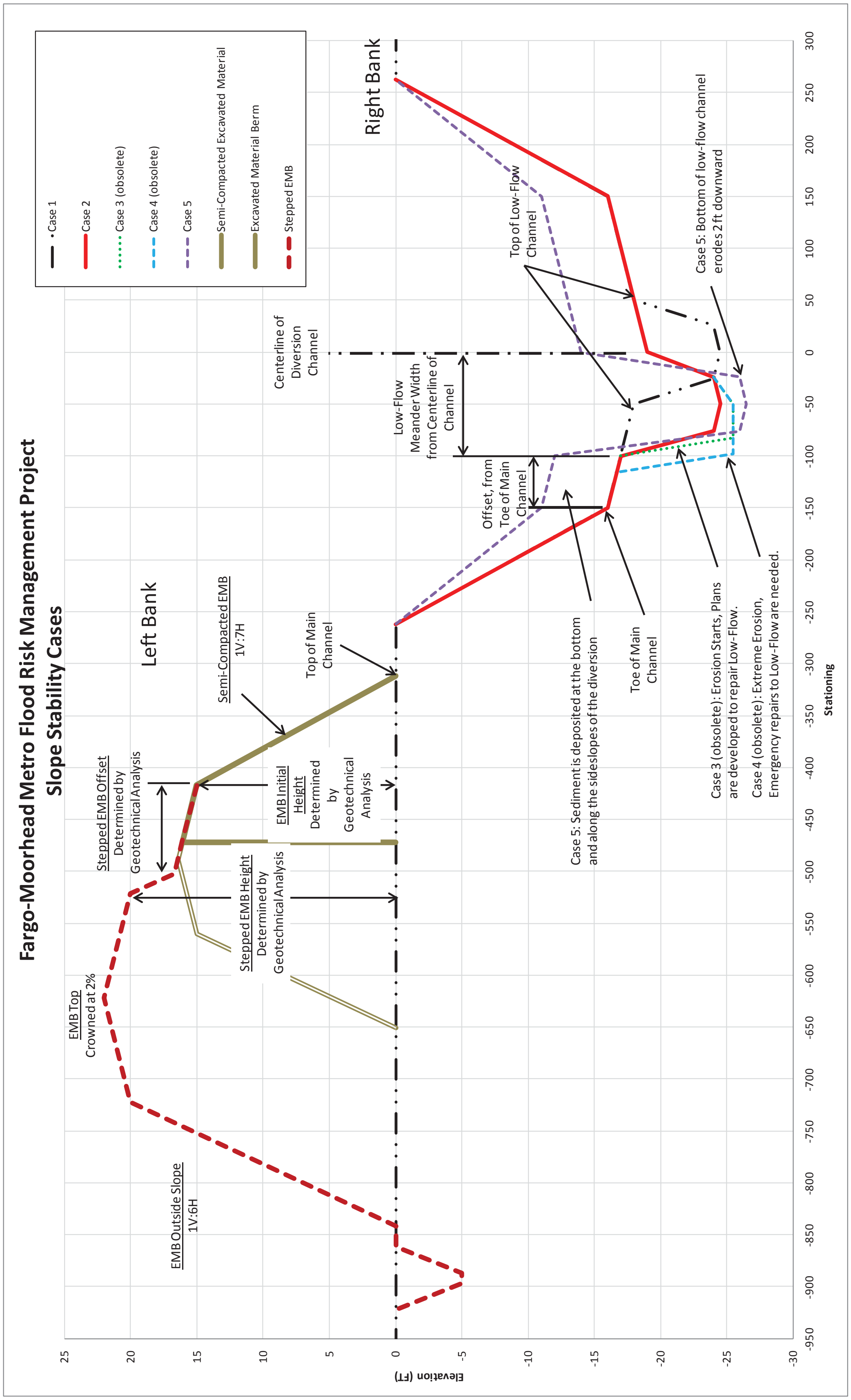

Figure 4a: Depiction of Slope Stability Cases

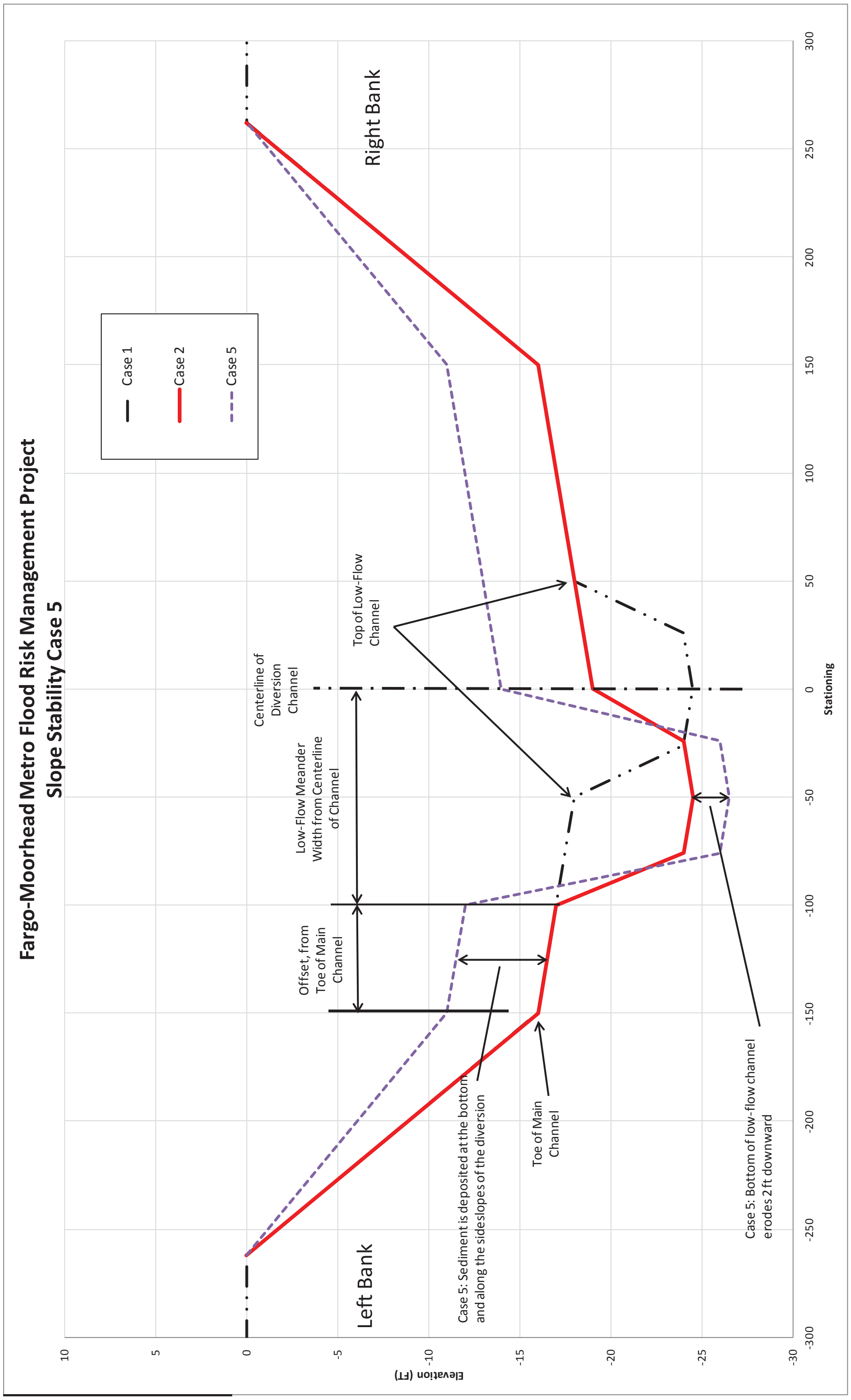

Figure 4b: Close-up Depiction of Slope Stability Case 5

5.3.5. Target Factors of Safety

The Corps Engineering Manual (EM) 1110-2-1902, Slope Stability identifies the minimum required factors of safety (FS) for dams while EM 1110-2-1913, Design and Construction of Levees identifies the minimum FS for levees. Neither of these manuals specifically identifies the minimum required FS for excavated slopes associated with a diversion channel. EM 1110-2-1902 recommends that for slopes other than that associated with dams, that the minimum FS be selected based on uncertainty of the shear strength parameters and the consequences of failure.

In general, the two major conditions to be analyzed for the diversion are the long-term (steady-state seepage) and the end-of-construction conditions. The long-term (steady-state seepage) conditions use effective stress shear strength parameters (drained) coupled with pore water pressures. The pore water pressures are estimated through the use of numerical analysis that is capable of running a steady-state seepage analysis. The end-of-construction condition neglects pore water pressures and the use of undrained (total stress) shear strength parameters is required.

The five cases represent different geometric configurations that have different likelihoods of developing over time. This was taken into consideration when selecting the target factors of safety. Case 1 and 2 represent the constructed project condition and require the highest factors of safety. Case 3 (obsolete) is considered to evaluate the stability of the channel if erosion of the low-flow were to start. Erosion of the low-flow may be small and occur over a long period of time, thus a lower FS is considered acceptable. Case 4 (obsolete) represents the scenario in which extreme erosion of the low-flow has occurred. It is expected that through normal O&M of the project and annual inspections, that erosion of the low-flow is fixed prior to it becoming extreme, so the likelihood of this case occurring is small. Based on this, a lower FS than Case 3 is acceptable. Case 5 assumes 2 ft of erosion in the low-flow channel and varying amounts of sediment deposition in the diversion. The amount of erosion is considered to be relatively conservative. Deposition can have both geotechnical and hydraulic impacts that will require setting triggers for the performing maintenance. Frequent channel surveys will be required to quantify deposition, and limits will be set for the amount of allowable deposition. In this sense, Case 5 is analogous to Case 4. In addition to considering the occurrence / likelihood of the different cases, the size of the critical slip surface and associated cost of repair were also taken into account. For critical slip surfaces that would encompass the entire excavated slope or a majority of the slope, referred to as "global" slip surfaces, a higher FS was required. The higher FS for this "global" slip surface would result in lower probability that any major slope stability failure would occur. A smaller critical slip surface was also considered that encompassed the majority of slope but not the entire slope. This is referred to as a "lower slope" slip surface. Because the "lower slope" slip surface encompasses a smaller portion of the slope and could be indicative of a "sloughing failure surface" which would require additional maintenance but would not affect the entire project, a lower FS was accepted. The final critical slip surface condition analyzed is referred to as the "localized" slip surface. This search looks at slip surfaces initiating in the lower portion of the slope and toe of the excavated slope. A minimum FS is required in order to provide for stability at the toe of the excavated slope so the unraveling does not occur, which could lead to "global" slope stability concerns.

“Localized” surfaces that initiate at the toe of the diversion represent the smallest possible slip surface that could impact the diversion side slope. It is anticipated that this type of failure would have a minimal impact on the project functions. Additionally, there is some conservatism built into the models, particularly with regards to the assumed seepage boundary conditions and the selected shear strengths. For these reasons the target factor of safety for “localized” slip surfaces for Case 5 is 1.0.

The target factors of safety to use for each case, condition, and slip surface size are summarized below.

Table 6: Summary of Required Factor Safety. Note that Cases 3 and 4 are obsolete

Case	GLOBAL Long-Term	Comment
1 & 2	1.4	Factor of safety is the same as required for levee design. This provides for stable slope under normal conditions.
~~3~~	~~1.3~~	Factor of safety is slightly reduced. The stability of slope is still maintained while allowing for adjustment of low-flow under unusual conditions.
~~4~~	~~1.2~~	Factor of safety is again reduced to account for extreme erosion, which is an extreme condition. Repairs to the low-flow would be initiated before
5	1.2	Factor of safety is reduced to account for extreme erosion and maximum allowable sedimentation.

Case	LOWER SLOPE and LOCALIZED Long-Term	Comment
1 & 2	1.2	The LOWER SLOPE and LOCALIZED searches represents smaller slip surfaces that encompasses lower portion of slope. If failure were to occur along these smaller failure surfaces (sloughing), there is minimal effect to excavated diversion slope, therefore lower factor of safety is warranted.
~~3~~	~~1.15~~	Factor of safety is reduced because condition is unusual.
~~4~~	~~1.15~~	Factor of safety is reduced because condition is extreme.
5	Lower- 1.15 Localized- 1.00	

Case	End-of-Construction	Comment
1 & 2	1.3	Factor of safety is the same as required for levee design. This provides for stable slope under normal conditions.
~~3~~	~~1.2~~	Erosion will occur over time, and the pore pressures around the excavated slope will be trying to reach steady state seepage conditions, but will not be fully established. So the pore pressures in the excavated slope is between the undrained and drained conditions.
~~4~~	~~N/A~~	Major erosion and sedimentation likely to occur over long period and pore pressures in excavated slope are likely to be at or near steady state seepage conditions, therefore undrained analysis is not appropriate as there is no excess pore pressures.
5	N/A	

5.3.6. Slip Surface Search

In order to evaluate the different sized critical slip surfaces, different slip surface searches are required. Each slope stability program has its own slip surface search routines. An appropriate search routine must be selected and used with consistency throughout design. To illustrate this, a search routine using the “Entry and Exit” slip surface option in GeoStudio is described below. This routine was selected as it is easy to use and replicate between sections to keep consistencies. The requirements of the “Entry and Exit” slip surface ranges are summarized below.

5.3.6.1. Global Long-Term Stability

- Entry Points: The range begins at the toe of the excavated material berm, extending past the top of excavation slope and ends at a depth equivalent to ¼ the total height of the excavation, measured from the ground surface down to toe of excavated slope.
- Exit Points: The range begins 5 feet above the toe of the excavated slope and extends 10 feet beyond the edge of the pilot channel. For Case 5, the range begins 5 ft above the “new” toe created by the sediment deposition.

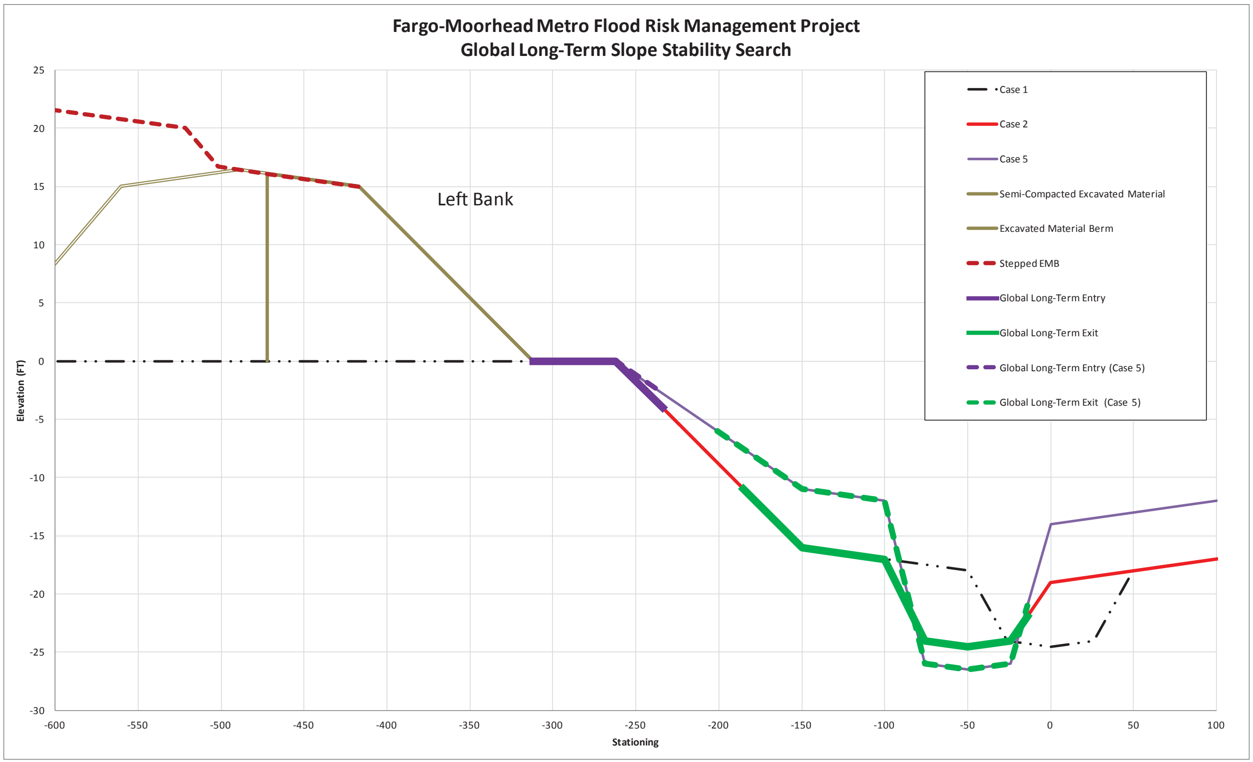

Figure 5: Global Long-Term Slope Stability Search

5.3.6.2. Check of EMB on Global Stability

A check of the global stability shall be done in which the entry points of the slip surface extend above the EMB.

- Entry Points: The range begins at the outside edge of the EMB and ends at the diversion side toe of the EMB. When a stepped EMB is present, the range should be adjusted to cover the entire top of the stepped EMB.
- Exit Points: The range begins 5 feet above the toe of the excavated slope and extends 10 feet beyond the edge of the pilot channel. For Case 5, the range begins 5 ft above the "new" toe created by the sediment deposition.

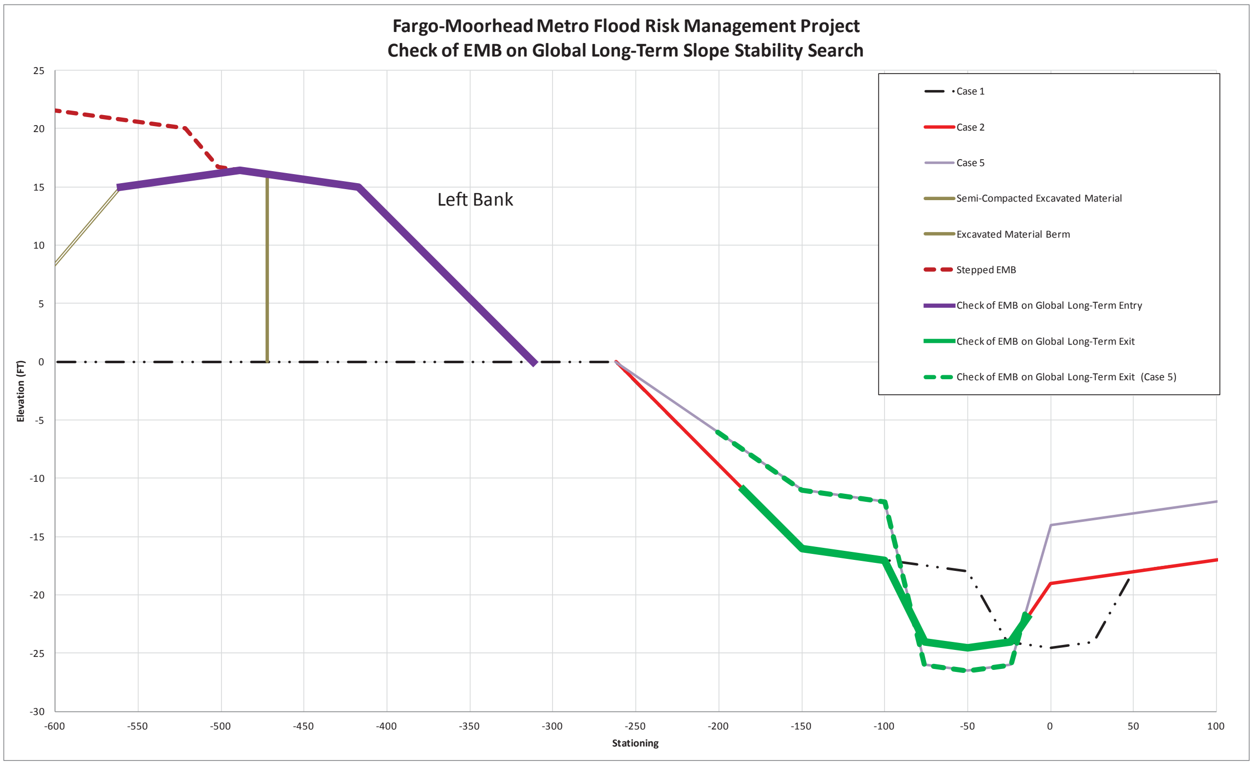

Figure 6: Check of EMB on Global Long-Term Slope Stability Search

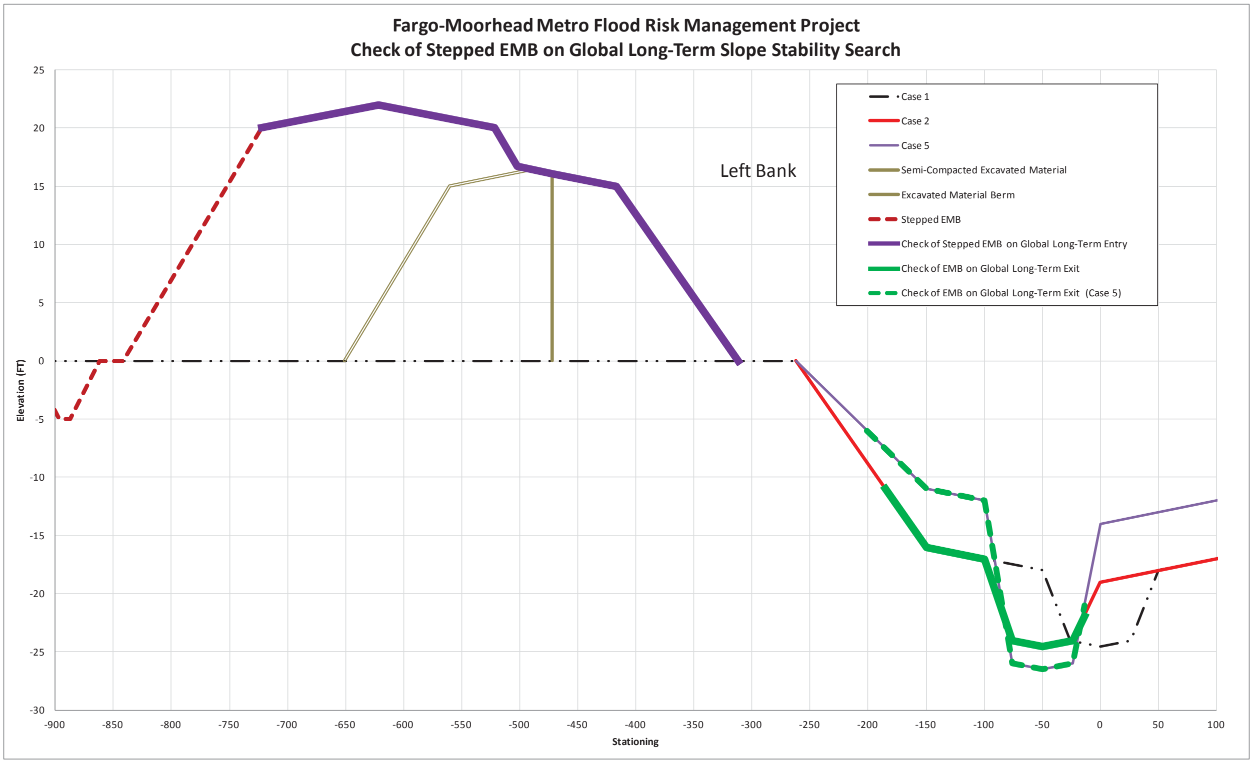

Figure 7: Check of Stepped EMB on Global Long-Term Slope Stability Search

5.3.6.3. Lower Slope Long-Term Stability

- Entry Points: The range begins at a depth equivalent to ¼ the height of the excavation, measured from the ground surface to toe of excavated slope and ends 5 feet above the toe of the excavated slope. For Case 5 the range ends 5 ft above the "new" toe created by the sediment deposition.
- Exit Points: The range begins 5 feet above the toe of the excavated slope and extends 10 feet beyond the edge of the pilot channel. For Case 5 the range begins 5 ft above the "new" toe created by the sediment deposition.

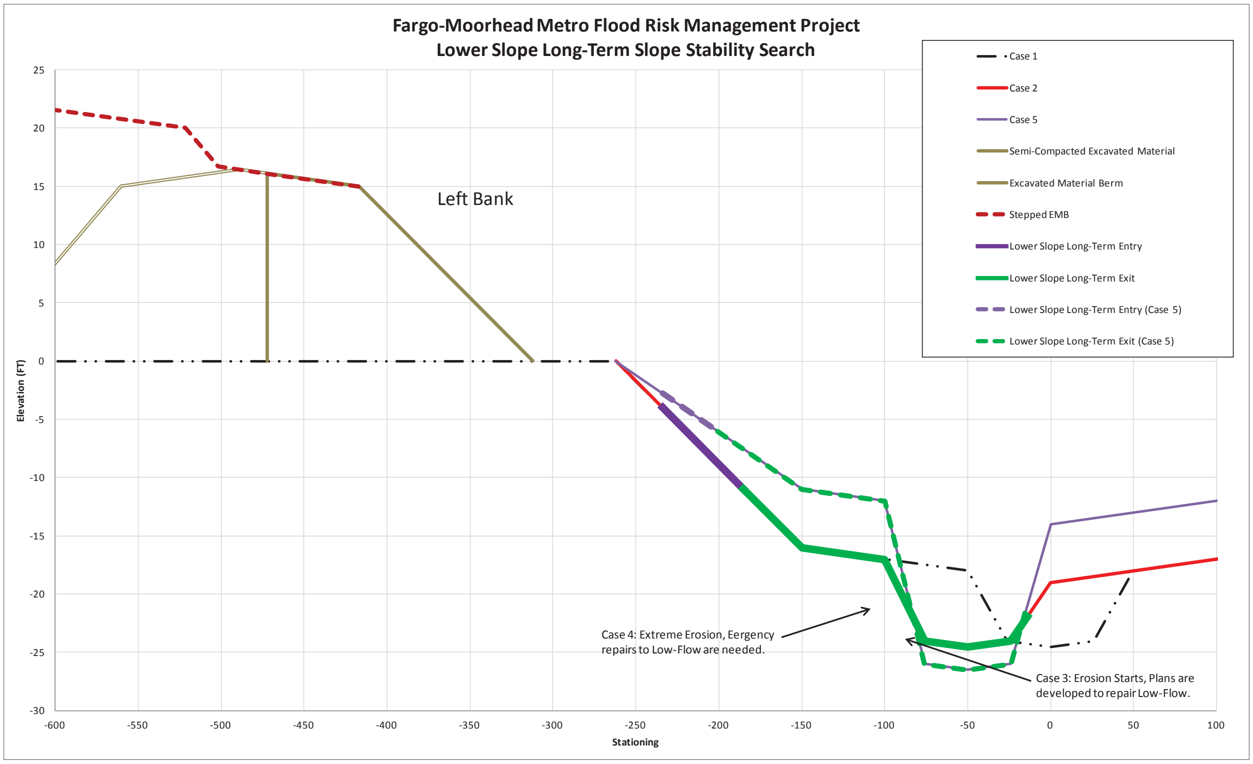

Figure 8: Lower Long-Term Slope Stability Search

5.3.6.4. Localized Slope Long-Term Stability

- Entry Points: The range begins at a depth equivalent to ¼ the height of the excavation, measured from the ground surface to toe of excavated slope and ends at the toe of the excavated slope. For Case 5 the range ends at the “new” toe created by the sediment deposition.
- Exit Points: The range begins at the toe of the excavated slope and extends 10 feet beyond the edge of the pilot channel. For Case 5 the range begins at the “new” toe created by the sediment deposition.

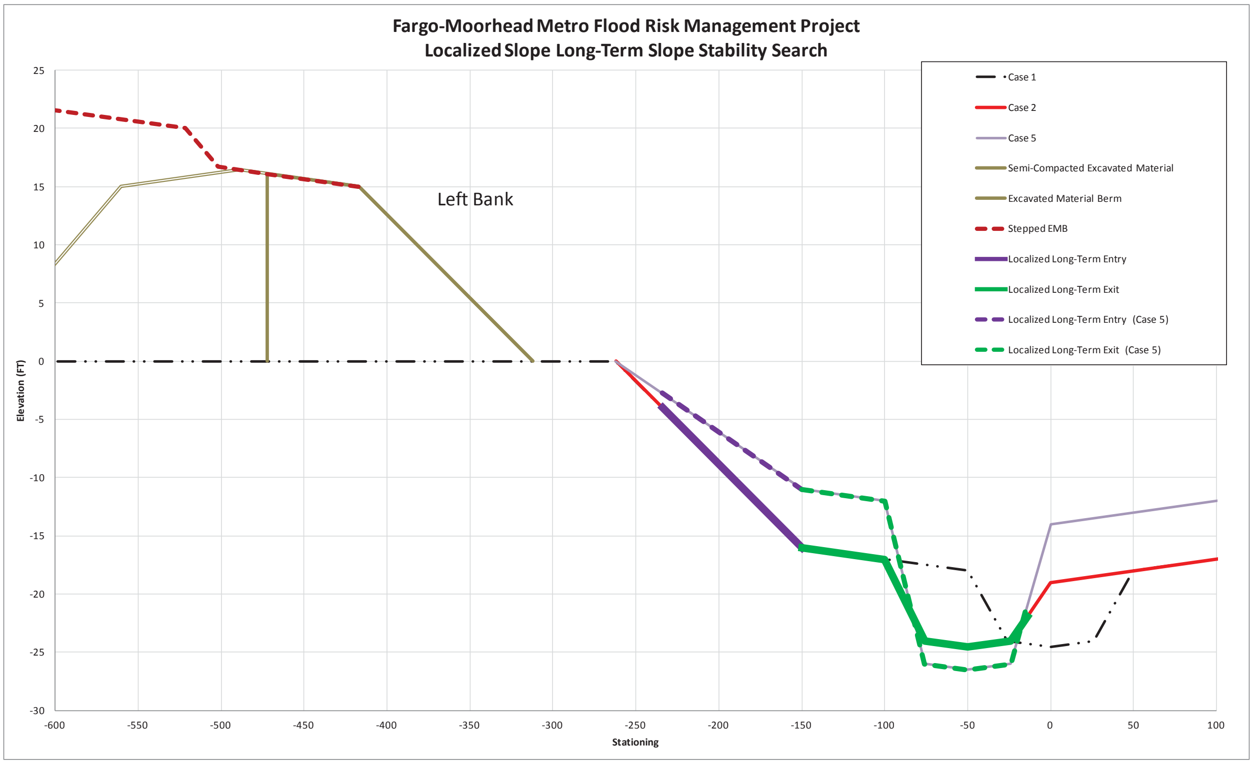

Figure 9: Localized Long-Term Slope Stability Search

5.3.6.5. End-of-Construction Stability

- Entry Points: The range begins at the outside edge of the EMB and ends at the diversion side toe of the EMB. When a stepped EMB is present, the range should be adjusted to cover the entire top of the stepped EMB.
- Exit Points: The range begins 5 feet above the toe of the excavated slope and extends 10 feet beyond the edge of the pilot channel.

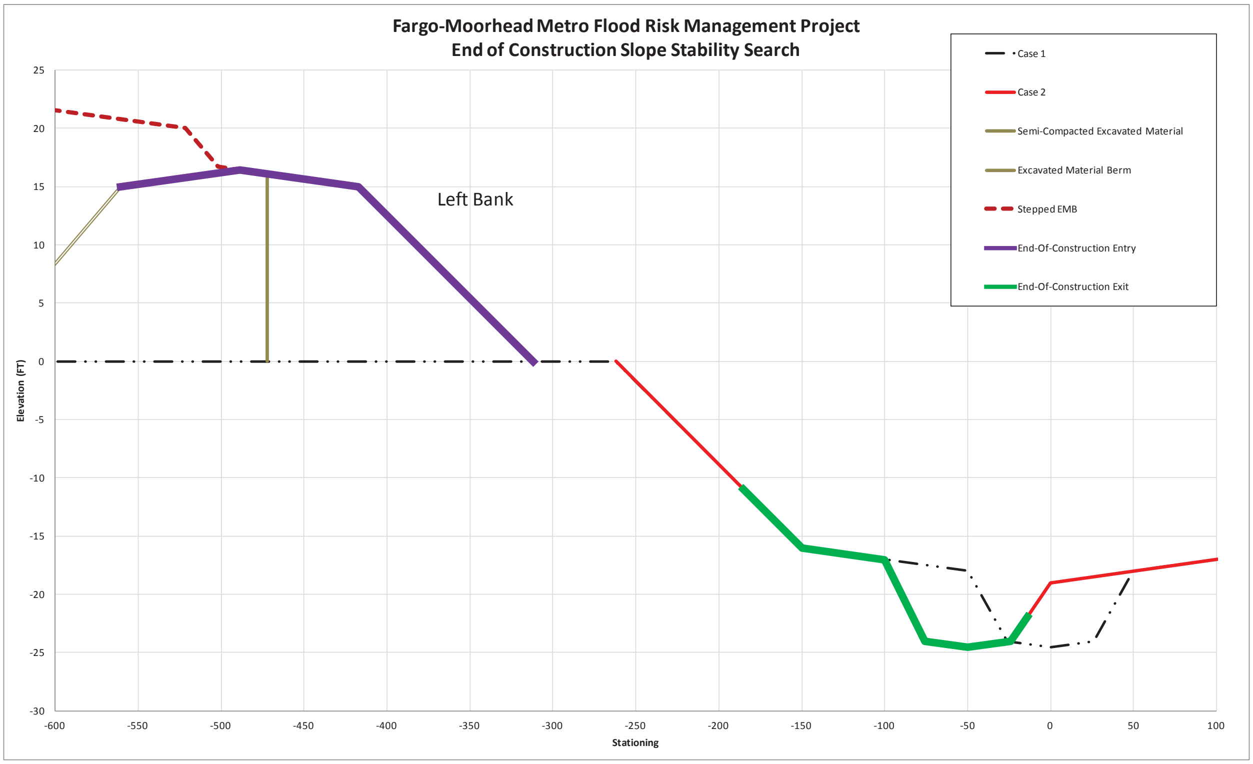

Figure 10: End-Of-Construction Slope Stability Search

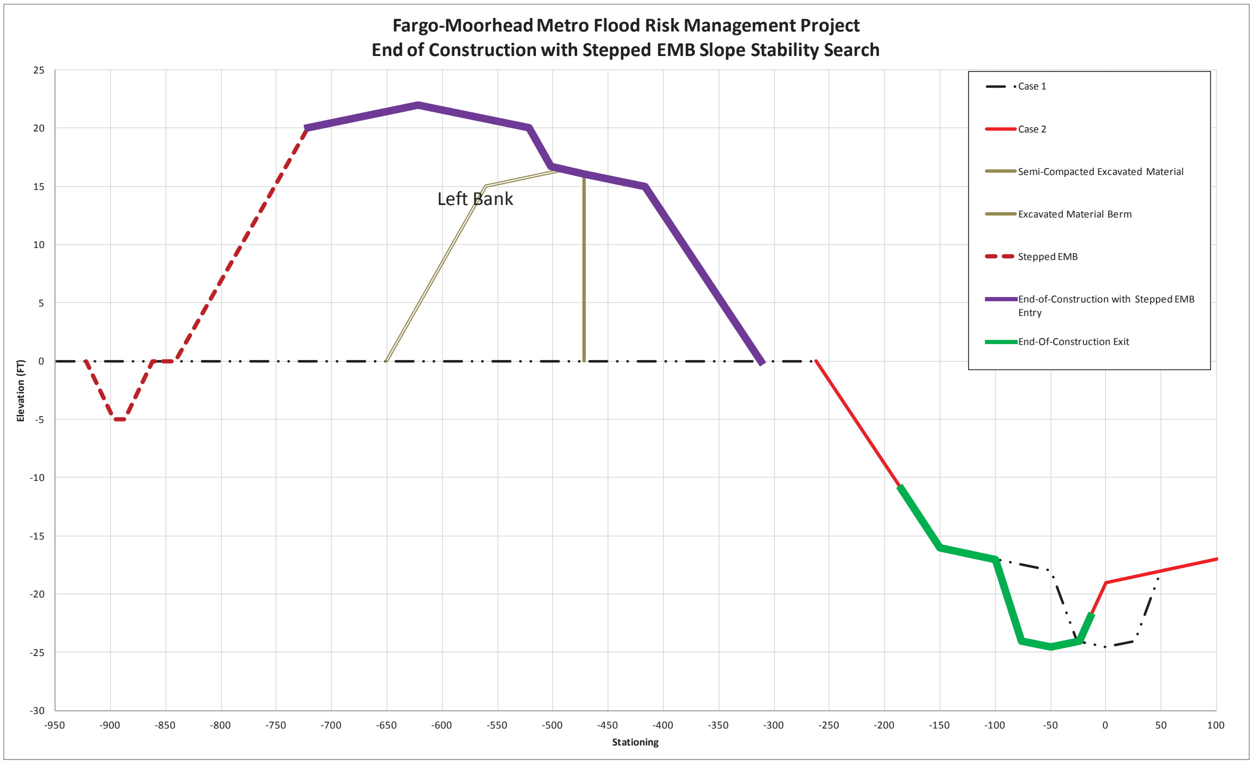

Figure 11: End-0f-Construction with Stepped EMB Slope Stability Search

5.3.6.6. "V" Shaped Surfaces

Sometimes when the optimization procedure used by Slope/W is implemented, the optimized surface appeared to be more representative of a "V" shape surface with no neutral block. Such surfaces sometimes do not represent realistic potential slip surfaces as documented in field studies. When this occurs, the critical optimized surface shall be validated using another program.

The St. Paul District has completed some analyses in regards to optimized failure surfaces that appear to be a "V" shape. To date, the St. Paul District has been able to validate that the factors of safety determined for these "V" shape failure surfaces are appropriate. Additional investigation is warranted though.

5.3.7. Levees Along the Diversion Channel

Levees are required only along the right bank of the diversion channel as they provide flood risk management benefits to the Fargo-Moorhead Metro area. On the left bank, there is no requirement to manage flood risk. The requirements for the right bank levee and the EMBs are outlined in FMMFRM Memorandum for Record, "MFR-001, Levees and Excavated Material Berms Along the Diversion Channel." This MFR also discusses the requirements for vegetation-free and vegetation-management zone requirements for the levees and EMBs.

6. REVIEW

The MFR underwent DQC review and ATR review prior to signoff.

7. CONTACT

Any questions concerning this MFR should be directed to Gary Wolf, Co-Technical Manager, MVP.

8. SIGNATURES

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