NorthMet Geotechnical Modeling Work Plan
Version 2 03/08/12

This document is the Work Plan for geotechnical modeling of the NorthMet Project as requested by the Geotechnical Stability Impact Assessment Planning Summary Memo, NorthMet Project EIS, dated May 18, 2011. The findings from the geotechnical modeling will be incorporated into a 3-Volume Geotechnical Data Package – and summarized and referenced as needed. NorthMet Project Geotechnical Data Package Volumes 1 through 3 will consist of:

- Volume 1 – Flotation Tailings Basin
- Volume 2 – Hydrometallurgical Residue Facility
- Volume 3 – Stockpiles

Project:

The project that will be evaluated is the project described in the Lead Agency Draft Alternative Summary as amended 03/04/11. This Work Plan will be reviewed and amended as necessary in response to project changes in the event such changes require substantive changes to previously analyzed facility designs.

Background:

The NorthMet Project includes two material disposal facilities that include dams, consisting of the Flotation Tailings Basin for final deposition of flotation tailings, and the Hydrometallurgical Residue Facility for final deposition of the hydrometallurgical residue. The Flotation Tailings Basin and Hydrometallurgical Residue Facility are designed using an iterative process whereby facility capacity requirements and geotechnical requirements are utilized to determine the facility geometry and overall sizing requirements to contain the tailings and residue expected to be generated through the life of the project. A third type of material disposal facility, which does not require dams but does entail foundation and slope construction, is the waste rock stockpiles at the Mine Site (a.k.a. Stockpiles).

An important input parameter to the facility designs are the slope stability safety factors. Acceptable slope stability safety factors are selected and then the facilities (Flotation Tailings Basin and Hydrometallurgical Residue Facility) are configured to achieve these safety factors as computed by modeling performed during facility design. In the case of Stockpiles, MDNR-mandated design requirements have been developed that result in acceptable safety factors.

The slope stability analysis methods that are used to compute slope stability safety factors are not required universally. In other words, some types of analysis are appropriate to some facility configurations while not applicable to other configurations. For example, undrained strength stability analysis (USSA) for slope stability is appropriate for the upstream construction approach planned for the Flotation Tailings Basin. It is not necessary for the Hydrometallurgical Residue Facility which will utilize downstream construction with a liner system. With this context the geotechnical work plans for the Flotation Tailings Basin, Hydrometallurgical Residue Facility, and Stockpiles are outlined below.

Flotation Tailings Basin Geotechnical Model for SDEIS, FEIS and Permitting:

The objective of the Tailings Basin Geotechnical Modeling for the SDEIS, FEIS and Permitting is to demonstrate the ability of the Critical Cross-Section (i.e., Cross-Section F; that cross-section anticipated to yield the lowest slope stability safety factor as indicated in the Preliminary Geotechnical Evaluation – March 2009) to comply with the required global slope stability safety factors. The information content of the March 2009 Preliminary Geotechnical Evaluation will be updated and formatted to accommodate the 3-Volume Geotechnical Data Package format, with content further amended as necessary to both reflect the Draft Alternative (March 4, 2009, and as amended) and to incorporate the specific guidance provided below. The following is a step-by-step summary of the planned Flotation Tailings Basin geotechnical modeling process.

1. Gather existing conditions data (i.e. basin topography, stratigraphy, soil and tailings strength and hydraulic characteristics, and other data as needed to support geotechnical modeling and Flotation Tailings Basin design). Note – this data has previously been compiled and presented in the Preliminary Geotechnical Evaluation – March 2009. This information will be incorporated into the Geotechnical Data Package – Volume 1, which will present the analyses outlined in this Work Plan. Results of in-laboratory testing of liquefied shear strength of NorthMet flotation tailings, completed subsequent the March 2009 evaluation, will be incorporated into the work prescribed in this Geotechnical Modeling Work Plan.

2. Develop tailings basin slope cross-sections (i.e., geometry and stratigraphy for existing and planned conditions) for the Flotation Tailings Basin for seepage and stability modeling. Models presented in the Preliminary Geotechnical Evaluation – March 2009 utilized surveyed cross-sections of the existing basin and proposed cross-sections of future dam raises; existing models will be reconfigured as needed to accommodate the modeling approach outlined in this Work Plan. This information will then be incorporated into the Geotechnical Data Package – Volume 1.

3. Develop seepage and stability models of the Flotation Tailings Basin using Geo-Slope International, Inc. modeling software (i.e., SLOPE/W, SEEP/W, SIGMA/W and QUAKE/W as necessary) for the following conditions:

    a. Normal operating condition at incremental lift heights for normal pool elevation with steady-state seepage conditions and including reduced infiltration rates for bentonite amended exterior face of new dams.
    b. Maximum dam height condition.
    c. Maximum dam height with increased pond elevation to account for pond bounce predicted to occur during a Probable Maximum Precipitation [PMP] event. Transient seepage analysis will be utilized as needed to account for the temporarily elevated pond condition produced by a PMP event. This model will also be used to evaluate a common potential static liquefaction trigger – pond bounce and will consider the impact of the rapid loading of the PMP on the shear strength of the tailings as an undrained load.

d. Maximum dam height and increased slope angle to account for conditions that could develop due to unmaintained slope erosion and/or due to over-steepening during slope construction. This model is to evaluate a common potential static liquefaction trigger – over-steepened slopes due to erosion at the toe of the current or new slope, similar to the occurrence already observed at the facility.
e. Maximum dam height and seismic loading to account for conditions that could develop due to local/or regional large-scale seismic activity. This model is to evaluate a common potential seismic liquefaction trigger scenario – earthquakes.
f. Post closure with cover effective (bentonite amended exterior face of new dams, beaches, and pond bottom) and with pond at design elevation (after closure, fail-safe water level controls will be implemented to limit pond bounce during a PMP event to at or near the pond design elevation).
g. Veneer stability to evaluate the stability of the bentonite amended exterior face of new dams. Veneer stability will be evaluated by computing the infinite slope Factor of Safety (using the no-seepage formulation where tailings seepage is not emerging on the slope and the parallel-seepage formulation where tailings seepage is emerging on the slope), with the soil friction angle chosen as a conservative value based on literature review. If the computed Factor of Safety is < 1.3, in-laboratory direct shear testing will be performed to confirm friction angle for site-specific bentonite amended tailings and Factor of Safety will then be recomputed. Adjust slope design as needed to achieve Factor of Safety ≥ 1.3 for veneer stability.

4. Using geotechnical data from Step 1, establish design data for use in Effective Stress Stability Analysis and Undrained Strength Stability Analysis. Review design data with MDNR. Also utilize established criteria to determine which materials behave in a contractive manner and could transition from non-liquefied strengths to liquefied (steady state) strengths (ref. Step 5.c). This is to accommodate triggering analysis by which materials will be modeled as non-liquefied if criteria are not exceeded, and modeled as liquefied if criteria are exceeded (Step 5.c.i.).

5. Utilize design data to design slopes to achieve the following:

   a. Effective Stress Stability Analysis (ESSA) – Factor of Safety ≥ 1.5 for effective shear strength conditions using drained parameters.
   b. Undrained Strength Stability Analysis (USSA) – Factor of Safety ≥ 1.3 for undrained shear strength conditions for non-statically liquefiable soils (i.e., end of construction case per dam raise).
   c. Liquefaction Analysis ($USSA_{liq}$)
      i. Contractive/Dilative Material Behavior Analysis – Identify materials having the potential to liquefy by classifying materials as contractive or dilative based on correlations published in Olson and Stark (2003) compared to site-specific field data (i.e., SPT blowcounts, CPT tip resistance, and shear wave velocities).
      ii. Static Liquefaction (i.e., induced by over steepening of slopes or pond bounce). Except for Factor of Safety values below in iii as modified by

the MDNR, follow the accepted methodology established by Olson and Stark (2003) in "Yield Strength Ratio and Liquefaction Analysis of Slopes and Embankments" to determine segments along the slip surface where liquefaction will be triggered.

iii. Perform slope stability analysis in SLOPE/W (using liquefied shear strengths applied to segments shown to liquefy).
    1. If the resulting Factory of Safety (FS_{Flow}) > 1.2, cross section is stable. Go to Step iii. 3..
    2. If the (FS_{Flow}) ≤ 1.2, modify or redesign the slope until the factor of safety criteria is met.
    3. Per the portion of the Olson and Stark methodology that assumes all contractive soils will liquefy, compute a "worst case" factor of safety for the section analyzed (FS_{Flow}) to aid judgments regarding the need for redesign or remediation.

iv. Seismic Liquefaction (i.e., induced by seismic event)
    1. Develop material damping coefficients for LTVSMC and NorthMet tailings.
    2. Use Geo-Slope software to compute initial stresses and steady-state pore-water pressure distribution.
    3. Apply earthquake loads via QUAKE/W (earthquake loads to be obtained from probabilistic seismic hazard analysis [PSHA]) and compare results to a SLOPE/W yield undrained model to identify the elements within the model that liquefy as a result of the seismic loading.
    4. Use published triggering relationships and model results to determine segments along the slip surface where liquefaction will be triggered (Olson & Stark, 2003, Yield Strength Ratios and Liquefaction Analysis of Slopes and Embankments).
    5. Perform slope stability analysis in SLOPE/W (using liquefied shear strengths applied to elements shown to liquefy) to compute FS_{Flow} for the entire cross section.
        a. If FS_{Flow} > 1.2 no further action is needed.
        b. If FS_{Flow} ≤ 1.0 modify or redesign cross section.
        c. If FS_{Flow} >1.0 and < 1.2, perform deformation modeling in SIGMA/W to predict the magnitude of deformation.
            i. If the level of deformation is acceptable to Dam Safety, no further action is needed.
            ii. If the level of deformation is unacceptable to Dam Safety, modify or redesign cross section.

6. Based on design data, report design and operating requirements necessary to maintain required slope stability safety factors and deformation requirements (if deformation analysis is triggered in Step 5) for the critical slope cross-section (assumed to be Cross-Section F for SDEIS modeling).

7. Perform a sensitivity analysis using the USSA slope stability model with yield undrained shear strength values. Evaluate shear strength data inputs that by mutual MDNR and PolyMet agreement have the greatest variability. Use engineering judgment to establish a range for these data inputs. Evaluate the impact of data variability on computed slope stability safety factors for the purpose of focusing operational-phase data gathering on the most critical stability model data inputs.

   Produce a graphical representation of the data spread of strength values used to help agency technical staff understand how design values (called “average” values in Version 1) were determined. Include information regarding how many data points were used to derive each plot of data.

8. Following MDNR Dam Safety review and approval of Critical Cross-Section modeling process/procedures and outcomes, proceed with modeling cross-sections G (north side of Cell 2E) and N (south side of Cell 1E) for final Flotation Tailings Basin design (for input to SDEIS, FEIS or Permitting as determined by MDNR).

Reporting – the Geotechnical Data Package Volume 1 will present the background/supporting information and results of the Flotation Tailings Basin geotechnical analyses described in this Work Plan. Geotechnical Data Package – Volume 1 will contain the pertinent content previously presented in the Preliminary Geotechnical Evaluation – March 2009; reconfigured in response to MDNR Dam Safety requests to group all geotechnical data by material type (i.e., LTVSMC coarse tailings, fine tailings and slimes, NorthMet bulk tailings, etc.) rather than by data type (i.e., hydraulic conductivity, liquefied shear strength, undrained shear strength, etc.). Furthermore, analysis methods required by this Work Plan and the associated results will be presented in Geotechnical Data Package – Volume 1 to the extent that analysis methods and results supersede contents of the Preliminary Geotechnical Evaluation – March 2009. Included will be descriptions and drawings depicting existing conditions and what will be built, results of geotechnical analyses for operating and post-closure conditions, and presentation of all model input parameters and model outputs. Where model input parameters are derived from multiple data points, the approach utilized for input parameter selection will be described. Included will be a description of how stability is anticipated to vary over time following tailings basin closure.

Hydrometallurgical Residue Facility Geotechnical Models for SDEIS, FEIS and Permitting:

The objective of the Hydrometallurgical Residue Facility Geotechnical Modeling for the SDEIS, FEIS and Permitting is to:

- demonstrate the ability of the most sensitive slope cross-section to comply with the required slope stability safety factors for global stability,
- demonstrate the ability of the composite liner system to comply with infinite slope stability safety factor requirements, and to
- demonstrate the capability of the composite liner system to withstand the strain anticipated due to differential settlement that may occur in the facility foundation materials.

The following is a step-by-step summary of the planned Hydrometallurgical Residue Facility geotechnical modeling process.

1. Gather existing conditions data (i.e. facility foundation material stratigraphy and strength data, hydrogeologic data and other data as needed to support geotechnical modeling of the Hydrometallurgical Residue Facility). Note – portions of this data have previously been compiled and presented in the Preliminary Geotechnical Evaluation – March 2009. This information will be incorporated into the Geotechnical Data Package Volume 2 and will be supplemented with additional facility location-specific data. Data on existing baseline water sources at the site, including surface discharges from the surrounding highlands, will be gathered for consideration during hydrometallurgical residue facility design. The facility will be designed to accommodate any such surface discharges and hence these discharges will not impact geotechnical modeling of the hydrometallurgical residue facility.

2. Gather additional residue strength and hydraulic conductivity data and/or representative published data for use in facility design. This information will be incorporated into the Geotechnical Data Package Volume 2 to the extent needed to facilitate the modeling outlined herein.

3. Develop residue facility layout and slope cross-sections (i.e., geometry and stratigraphy for existing and planned conditions) for proposed residue facility stability and deformation modeling. Note – seepage through the residue facility embankments will be inhibited by the composite liner system and seepage modeling will be an unnecessary component of this analysis.

4. Develop global and infinite slope stability models and deformation models of the facility using Geo-Slope International, Inc. modeling software (i.e., SLOPE/W, SEEP/W and SIGMA/W as necessary). Model the following:

    a. Deformation of hydromet residue facility foundation and liner system.

b. Infinite slope stability of hydromet residue facility liner system (if necessary/applicable).
c. Global stability of hydromet residue facility embankments.

Model maximum residue facility dam height with minimum and maximum pond elevation, and post closure – cover effective with minimum pond elevation. Model for effective shear stress conditions. Modeling for undrained shear strength conditions will not be necessary due to lined facility design with imported and mechanically placed dam fill and lack of seepage through the dam.

5. Configure geotechnical data for model input. Model input parameters will be based on data collected for and presented in the Preliminary Geotechnical Evaluation – March 2009. For materials to be imported for construction, engineering judgment will be used to select conservative shear strength parameters for input to the slope stability analysis and liner deformation analysis.

6. Use SLOPE/W to calculate the Global Safety Factor for the following conditions:

   a. Effective Stress Stability Analysis (ESSA) – Safety Factor $\geq$ 1.5
   b. Slope failures on external face and internal face of residue facility embankments.

7. Perform infinite slope stability analysis to confirm that load from residue deposition will be transferred to facility foundation soils and will not induce excess strain in facility liner materials.

8. Perform deformation modeling to predict magnitude of deformation and resulting strain in the facility liner system for comparison to allowable strain in liner system. Allowable strains are material-specific and will be determined from manufacturers specifications for the materials selected for the facility liner.

9. Report final basin design and operating requirements necessary to maintain required slope stability safety factors and deformation requirements.

9. Reporting – the Geotechnical Data Package Volume 2 will present the background/supporting information and results of the Hydrometallurgical Residue Facility geotechnical analyses described in this Work Plan. Included will be descriptions and drawings depicting existing conditions and what will be built, results of geotechnical analyses for operating and post-closure conditions, and presentation of all model input parameters and model outputs. Where model input parameters are derived from multiple data points, the approach utilized for input parameter selection will be described. Included will be a description of how stability is anticipated to vary over time.

Stockpile Geotechnical Models for SDEIS, FEIS and Permitting:

The objective of the Stockpile Geotechnical Modeling for the SDEIS, FEIS and Permitting is to comply with Mn Rule 6132.2400 (stockpile slopes will be as required by 6132.2400 Subp. 2. B. and stockpile foundations will be as required by 6132.2400 Subp. 2. A. (1)). These are design requirements that have been established to insure acceptable slope stability safety factors for global stability and acceptable foundation stability, the latter of which relates to the capability of the geomembrane liner system to withstand the strain anticipated due to differential settlement that may occur in the stockpile foundation materials.

The following is a step-by-step summary of the planned Stockpile geotechnical modeling process.

1. Gather existing conditions data (i.e. facility foundation material stratigraphy and strength data and other data as needed to support foundation design). Existing site information will be utilized for analysis performed in support of the SDEIS and FEIS, with additional data gathered and designs updated as needed for final design in conjunction with permitting. Existing information will be incorporated into the Geotechnical Data Package Volume 3

2. Configure stockpile slopes to meet or exceed minimum dimensional requirements established by Mn Rule 6132.2400.

3. Perform stockpile subgrade settlement analysis to predict magnitude of deformation and resulting strain in the stockpile liners for comparison to allowable strain in the liner system. Allowable strains are material-specific and will be determined from manufacturers specifications for the materials selected for the stockpile liners.

4. Report final stockpile design and operating requirements necessary to maintain required slope stability safety factors and liner performance requirements.

5. Reporting – the Geotechnical Data Package Volume 3 will present the background/supporting information and results of the Stockpile geotechnical analyses described in this Work Plan. Included will be descriptions and drawings depicting existing conditions and what will be built, results of geotechnical analyses for operating and post-closure conditions, and presentation of all model input parameters and model outputs. Where model input parameters are derived from multiple data points, the approach utilized for input parameter selection will be described. Included will be a description of how stability is anticipated to vary over time.