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21.0 GEOTECHNICAL/GEOTHERMAL ANALYSES

21.1 INTRODUCTION

Presented in this section are design criteria for geotechnical/geothermal evaluation of pipeline route conditions. Criteria for the geotechnical/geothermal topics of frost heave, thaw settlement, pipe/soil interaction at bends, slope stability, foundation design, and prediction of thaw beneath the pipeline and other structures are included in this section. Criteria for other geotechnical topic areas, which warrant treatment on their own (e.g. workpad design and ditch moding), are addressed elsewhere in this document.

21.2 CODES AND CRITERIA

21.2.1 Codes

- Code of Federal Regulations, Title 18 – Conservation of Power and Water Resources
- Code of Federal Regulations, Title 49 – Transportation, Part 192, Transportation of Natural and Other Gas by Pipeline: Minimum Federal Safety Standards.
- Alaska Administrative Code, Title 5 - Fish and Game, Chapter 95 - Fish and Game Habitat
- Code of Federal Regulations, Title 23 - Highways, Part 645 - Utilities Section 111 Right-of-Way.
- United States Code, Title 30 - Mineral Lands and Mining.
- Code of Federal Regulations, Title 33 - Navigation and Navigable Waters, Chapter -II Corps of Engineers, Part 236 - Water Resource Policies and Authorities. Corps of Engineers Participation in Improvements for Environmental Quality AND Part 322 - Permits for Structures or Work in Or Affecting Navigable Waters
- Code of Federal Regulation, Title 36 - Parks, Forests and Public Property.
- Code of Federal Regulations, Title 40 - Protection of the Environment.
- Code of Federal Regulations, Title 43 - Public Lands: Interior, Subtitle B - Regulations Pertaining to Public Lands.
- Federal Right-of-Way Grant for the Alaska Natural Gas Transportation System Alaska Segment Serial No. F-24538 (December 1, 1980).
- Federal Energy Regulatory Commission conditional certificate of public convenience and necessity, issued on December 16, 1977, as such is finalized
- Alaska Statutes, Title 27 - Mining.
- Alaska Statutes, Title 38 - Public Land.

- Alaska Statutes, Title 46 - Alaska Coastal Management Program.

21.2.2 Criteria

21.2.2.1 Pipeline Frost Heave Criteria

The ANGTS pipeline will generally be operated in chilled mode. In areas where the pipeline is operated at freezing temperatures in unfrozen ground, a frost bulb may form. If soil and groundwater conditions in these areas are conducive to frost heaving, the pipeline may experience frost heaving forces.

Analysis for frost heave will include prediction of the operating pipeline hydraulic/thermal conditions along the route. This analysis, along with mapped soil thermal state data will show where the pipeline will be operated cold in unfrozen soils. In these areas, frost heave predictions will be made based on mapped soil conditions and results of frost heave testing and analysis. Where the pipeline is expected to heave, pipe stress and strain will be analyzed to evaluate risk. This process will be linked and automated to optimize this portion of the design.

The pipeline will be designed, constructed and operated to maintain risk of damage from frost heave at acceptable levels. Risk will be mitigated by optimizing operating temperatures, use of heavy wall pipe, or other measures, where required. Monitoring during operations may include use of in-line inspection devices (pigs), visual surveillance for surfical expressions of frost heave, or other suitable methods. Monitoring will identify pipeline segments that are frost heaving. Maintenance and repairs will be conducted as necessary on frost heaving pipeline segments to maintain pipeline integrity and safety.

Frost heave assessments will be performed for all pipeline segments wherein unfrozen and mixed frozen/unfrozen (or uncertain thermal state) soils are expected beneath the pipeline and within the design frost bulb. A “pipeline segment” is a portion of the alignment that has similar soil properties and stratigraphy. In mixed zones (zones containing both frozen and unfrozen soils) both frost heave mitigation and thaw settlement mitigation may be required in a single pipeline segment. In these areas, the pipeline will be designed and operated to maintain the risk of damage from either phenomena at acceptable levels, and mitigative measures will be designed to be compatible with one another.

Frost heave assessments will be designed based on office, laboratory and field work performed to date for the ANGTS project, plus advances that have been made in the field of pipeline frost heave assessment in recent years. Pipe strain criteria for frost heave are presented in Section 20.

21.2.2.2 Pipeline Thaw Settlement Criteria

The ANGTS pipeline will generally be operated in chilled mode. However, in some areas the pipeline will be warm. In areas where the pipeline is operated at above-freezing temperatures as it passes through frozen soils, a thaw bulb may form. A thaw bulb may also form due to surface disturbance or poor drainage. If soil conditions in these areas are conducive to thaw settlement, the pipeline may experience thaw settlement forces.

Analysis for thaw settlement heave will include prediction of the operating pipeline hydraulic/thermal conditions along the route. This analysis, along with mapped soil thermal state data will show where the pipeline will be operated warm in frozen soils. In these areas, thaw settlement predictions will be made based on mapped soil conditions and results of thaw settlement testing and analysis. Where the pipeline is expected to settle, pipe stress and strain will be analyzed to evaluate risk. This process will be linked and automated to optimize this portion of the design.

The pipeline will be designed, constructed, and operated to maintain risk of damage from thaw settlement at acceptable levels. Risk will be mitigated by optimizing operating temperatures, use of heavy wall pipe, or other measures, where required. Monitoring during operations may include use of in-line inspection devices (pigs), visual surveillance for surfical expressions of thaw settlement, or other suitable methods. Monitoring will identify pipeline segments that are settling. Maintenance and repairs will be conducted as necessary on settling pipeline segments to maintain pipeline integrity and safety.

Thaw settlement assessments will investigate conditions of total settlement, differential settlement, settlement span, and critical strain. The pipeline will be designed to satisfy pipe strain criteria presented in Section 20.

Site specific thaw settlement assessments may be performed for pipeline segments wherein thermal state, high soil thaw strain potentials, ground temperatures, gas temperatures or other conditions indicate significant risk of thaw settlement that could threaten pipeline integrity. If and when necessary, site specific mitigation measures will be designed and implemented. A “pipeline segment” is a portion of the alignment that has similar soil properties, thermal state, and stratigraphy.

Segments where estimated differential thaw settlements indicate that the allowable pipe strain limits will be exceeded will be designated for thaw strain mitigation. Thaw settlement assessments will be performed for all pipeline segments wherein frozen and mixed frozen/unfrozen (or uncertain thermal state) soils are expected beneath the pipeline and within the design thaw bulb. In mixed zones (zones containing both frozen and unfrozen soils) both thaw settlement mitigation and frost heave mitigation may be required in a single pipeline segment. In these areas, the pipeline will be designed and operated to maintain the risk of damage from either phenomena at acceptable levels, and mitigative measures will be designed to be compatible with one another.

Thaw settlement and thaw strain assessments will be designed based on office, laboratory and field work performed to date for the ANGTS project, plus advances that have been made in the field of pipeline thaw settlement assessment in recent years. Pipe strain criteria for thaw settlement are presented in Section 20.

21.2.2.3 Criteria for Pipe-Soil Interaction at Bends

Adequate support will be provided behind bends, based on results of analysis of pipe and soil stress, strain, and displacement under design loading conditions. Pipeline displacement and strain will comply with allowable strain limits presented in Section 20.

Evaluation of pipe-soil interaction at bends will include consideration of soil strength and deformation characteristics; present and predicted thermal state; position of the groundwater table relative to the pipeline; and other conditions that may affect the support provided by soils on the outside of sidebends, beneath sagbends, and above overbends. Mitigative actions may be necessary to provide support in some circumstances.

21.2.2.4 Slope Stability Criteria

The gas pipeline system will be designed and constructed using established industry practices to reduce risk from potential slope instabilities that could threaten the integrity of the gas pipeline or adjacent facilities such as TAPS or the Dalton Highway. Slopes may become unstable under static or dynamic conditions where forces tending toward failure exceed forces resisting failure. Forces resisting failure may decrease when originally frozen soils on a marginally stable slope thaw under static conditions. Forces tending toward failure may increase when seismic ground motion increases forces tending toward failure, or when soils liquefy under earthquake loading.

Risk assessment will be used to set allowable factors of safety for slope stability under various classes of exposure conditions and loading conditions. Exposure conditions include short term (e.g., construction), and long term (e.g., operations). Loading conditions include static conditions (including conventional slope stability and long term deformation of creep-susceptible slopes), and dynamic (seismic) conditions. Consequences considered in the risk assessment will include life/safety, environmental risk, pipeline integrity (operating and contingency), adjacent facilities, and property damage. Stability assessments under dynamic loading, including liquefaction analysis, will include consideration of the design contingency earthquake (DCE) and the design operating earthquake (DOE).

Care will be taken in design and construction to avoid disturbing slopes adjacent to existing facilities such as TAPS or the Dalton Highway. If ANGTS construction activities destabilize a slope that affects an adjacent facility, mitigation may be required. Stability analysis and mitigative design (if necessary) will be performed on a site-specific basis.

Site specific assessment of earthquake-induced liquefaction of soils may be performed for structures that cannot be permitted to settle during earthquakes. This investigation will consider, soil particle size distribution, relative density, location of the water table, surface configuration, failure mode, design ground motion, and other factors if relevant.

21.2.2.5 Foundation Criteria

Foundations for ancillary pipeline components will be designed using industry standard methods, and will comply with state and local codes as appropriate. Shallow and deep foundations will be considered, and the most appropriate foundation type will be selected. Foundations will generally be designed to maintain the thermal state of the soils in their initial state, either frozen or thawed. If the structure is expected to change the thermal state, mitigative measures will be taken.

21.2.2.6 Thaw Penetration Analysis Criteria

Thaw penetration for design problems other than those specifically addressed elsewhere will be estimated using technical procedures appropriate to the size, complexity and significance of the problem. Examples of where additional thaw penetration analysis may be necessary include foundations, and areas of surface disturbance.

Industry standard techniques will be used as appropriate. Procedures for predicting thaw penetration will include published, theoretical techniques such as the "trumpet curve" calculations, as well as numerical methods such as finite element models. The size and configuration of calculation sheets or numerical models will be appropriate for the specific design problem being addressed, and may vary on a case-by-case basis.

21.2.2.7 Other Geotechnical Topics

A number of geotechnical topics are not discussed in this section, because they are better addressed elsewhere in this document. These topics and the sections where they are discussed are listed in Table 21-1.

Table 21-1 Geotechnical Topics Discussed in Other Sections

Topic	Section Number and Title
Cut and Fill Sections in the Construction Zone	Section 9, Workpad Design
Embankment Design	Section 9, Workpad Design
Ditch Mode Selection	Section 13, Ditch Configuration
Ditch Backfill, Bedding and Padding	Section 13, Ditch Configuration
Ditch Plugs	Section 13, Ditch Configuration
Fault Crossings	Section 17, Fault Crossing
Bridge Foundations	Section 14, Bridges
Thaw Penetration Beneath Thermal Workpad	Section 9, Workpad Design
Ditch Wall Stability	Section 13, Ditch Configuration

21.3 <u>DESIGN PARAMETERS AND DESIGN APPROACH</u>

21.3.1 Geotechnical and Geothermal Data

Geotechnical/geothermal information describing the proposed route of the gas pipeline has been obtained from the literature, aerial photo interpretation, field investigations, borehole drilling programs, data from previously constructed adjacent projects, laboratory tests, and geotechnical analyses. Additional data may be gathered if gaps are identified in the existing data.

Because of the diverse conditions anticipated and length of the alignment, the project has adopted the use of Engineering Terrain Unit Analysis (ETUA) as a basis for design. ETUA is a system of mapping and terrain/landform analysis and data management. The premise is to use airphoto interpretation to identify three-dimensional bodies of terrain (termed landforms) based on mode of geologic origin and physical characteristics. Each landform has a characteristic and describable set of geotechnical properties or range of properties. Because of the characteristic and identifiable topographic and vegetative features and soil properties associated with them, landforms can be identified and mapped by air photo analysis combined with ground-truth data from field reconnaissance, boreholes, and other site investigation methods.

The characteristic ranges in properties of landforms have further been found to be dependent on the physiographic subprovince in which the landform is located, according to similar geomorphic setting. As an example, glacial till in the Delta-Gerstle Lowland Region would generally be expected to have a higher density than glacial till in the Central Brooks Range. This would be attributed to the Delta-Gerstle Region having in the past been overlain by thick ice sheets while only smaller mountain glaciers occupied the Central Brooks Range. This has been justified by a statistical analysis of measured borehole data from glacial till landforms of the two regions. Refinement of ranges in geotechnical properties with respect to physiographic subprovince provides an additional region-related database for estimating appropriate values.

The project ETUA including physiographic province and subprovince division boundaries will be reviewed and updated as necessary to reflect advancements in the field since the original ETUA was completed.

Use of the ETUA method does not reduce the importance of boreholes or other site-specific data but permits maximum use of data from individual locations and allows for interpretation or extrapolation of data into areas where site specific information is lacking. This concept has been used successfully on similar projects throughout the world, including the TAPS. A basic means of presenting the ETUA data is a geotechnical alignment sheet series. A geographic information system (GIS) will be used to manage the ETUA and other geotechnical data for this project.

21.3.2 Selection of Geotechnical/Geothermal Parameters for Design

Geotechnical and geothermal design parameters will be selected from the data sets described above. Additional guidelines and basic approach to geotechnical and geothermal analyses are given in the following subsections.

21.3.2.1 Frost Heave Analysis – Parameters and Approach

Geotechnical parameters necessary for frost heave analysis and design include soil data such as particle size distribution, unit weight, and moisture content; pressure on the freezing front; frost penetration rate and frost heaving rate; longitudinal, bearing and uplift resistance; load/deflection characteristics; and climatic data. Most soil data will come from existing ETUA and results of existing geotechnical investigations. If data gaps are identified, they will be filled as necessary. Climatic data will be updated to include most recent data from stations along the route. Limits of application of climatic data will be based on geographic similarities along the line.

The approach to frost heave analysis will be to couple route soils data with climatic data and pipeline thermal predictions and pipe stress analysis. The process is depicted on Figure 21-1, and is a parallel approach to that for thaw settlement described in the following subsection. Pipeline and ground thermal conditions will be predicted using a coupled hydraulics/geothermal model. This model will be comprised of a linear hydraulics model of the pipeline with two-dimensional "slices" of soil defined at intervals along the pipeline. The slices are defined principally by the ETUA, thus geotechnical information will accompany each slice that allows prediction of frost heave. The hydraulics model will predict temperatures along the pipeline for a given throughput and inlet temperature and pressure, initial soil temperatures, and gas properties. The pressure and temperature of the flowing gas depends upon the heat flux through the pipe wall which, in turn, depends on the pipe interaction with the subsurface thermal state. The geothermal model will use a two-dimensional finite element approach to find the subsurface thermal conditions at the slice location based on the combined effects of surface climatic variations and pipe wall temperature. The result will be a series of "snapshots" along the pipeline of the changing thermal condition of the subsurface over time, which is in turn used to estimate the heat flux along the alignment to the flowing gas. The result is an estimate of the magnitude and timing of freezing of initially thawed ground. The same process is used to predict thawing of initially frozen ground, as described in the following section.

The pipe/soil thermal regime and geotechnical properties that define the soil's frost susceptibility will then be input into a frost heave predictive equation. The frost heave equation will be verified from the results of extensive frost heave laboratory and field testing performed to date for this project, as well as other appropriate data that may be available. The equation will use such parameters as particle size distribution, unit weight, moisture content, pressure at the freezing front, rate of frost penetration, and rate of frost bulb growth to predict the size of the frost bulb, and the magnitude of frost heave. The magnitude of pipe strain resulting from the predicted frost heave will be analyzed as described in Section 20. Predicted pipe strain values will be compared to the allowable pipe strains for frost heave, which are also presented in Section 20.

Problematic areas identified in performing this route-wide analysis will be subject to site-specific analysis. The site-specific analysis will follow the same general approach, but will utilize more refined soil and thermal inputs.

21.3.2.2 Thaw Settlement Analysis – Parameters and Approach

Geotechnical parameters necessary for thaw settlement analysis and design include data such as soil type, unit weight, moisture content, degree of saturation, porosity and specific gravity; thaw penetration rate; longitudinal resistance; load/deflection characteristics; and climatic data. Most soil data will come from existing ETUA and results of existing geotechnical investigations. If data gaps are identified, they will be filled as necessary. Climatic data will be updated to include most recent data from stations along the route. Limits of application of climatic data will be based on geographic similarities along the line.

The approach to thaw settlement analysis will be to couple route soils data with climatic data and pipeline thermal predictions. The process is depicted on Figure 21-2, and is a parallel approach to that for frost heave described in the previous subsection. Pipeline and ground thermal conditions will be predicted using a coupled hydraulics/geothermal model. This model will be comprised of a linear hydraulics model of the pipeline with two-dimensional "slices" of soil defined at intervals along the pipeline. The slices are defined principally by the ETUA, thus geotechnical information will accompany each slice that allows prediction of thaw settlement. The hydraulics model predicts temperatures along the pipeline for a given throughput and inlet temperature and pressure, initial soil temperatures, and gas properties. The pressure and temperature of the flowing gas depends upon the heat flux through the pipe wall which, in turn, depends on the pipe interaction with the subsurface thermal state. The geothermal model uses a two-dimensional finite element approach to find the subsurface thermal conditions at the slice location based on the combined effects of surface climatic variations and pipe wall temperature. The result is a series of "snapshots" along the pipeline of the changing thermal condition of the subsurface over time, which is in turn used to estimate the heat flux along the alignment to the flowing gas. The result is an estimate of the magnitude and timing of thawing of initially frozen ground.

The thaw progression and geotechnical properties that define the soil's thaw settlement potential will then be input into one of a series of predictive equations. The thaw strain equations will be verified from the results of extensive thaw settlement laboratory testing performed to date, as well as from other data sources if appropriate. The equations will use such parameters as soil, unit weight, moisture content, degree of saturation, and porosity to predict the depth of thaw beneath the pipe, and the magnitude of thaw settlement. The magnitude of pipe strain resulting from the predicted thaw settlement will be analyzed as described in Section 20, and compared to the allowable pipe strains for thaw settlement also presented in Section 20.

Results of thaw strain tests performed on undisturbed, frozen samples will be analyzed by regression analyses, as a function of soil index properties such as particle size distribution, moisture content and frozen dry density. Soils will be grouped together according to broad soil type (e.g. "silt", "sand", "silty gravel") and regression equations will be developed to fit the test results, and allow prediction of thaw strain. Thaw strain potentials for soil layers along the alignment will be selected by reviewing index properties of soil samples from boreholes within the segment, and/or ETUA data. The index properties selected will then be used in regression equations that predict thaw strain.

Thaw settlement assessments will be performed for pipeline segments wherein frozen and mixed frozen/unfrozen (or uncertain thermal state) soils are expected beneath the pipeline and within the design thaw bulb. The thaw bulb could result from a surface disturbance, convective heat transfer from groundwater flow, or warm pipeline operations.

Thaw settlement magnitude will be the product of thaw penetration and thaw strains of the soils in the settling zone. The magnitude of potential differential thaw settlement for each segment will be computed by subtracting the magnitude of general thaw settlement in the zone from the maximum thaw settlement. If non-settling soils bound a settling segment, the differential settlement may equal total settlement. Additionally, a generic analysis of the effects of non-uniform support within a potential settling section of pipeline will be performed.

As the thaw front moves beyond the horizontal plane defined by the pipe bottom elevation, thaw consolidation of the soils below the pipe bottom promotes a loss of support for both the pipe and overlying soils. This produces a net downward load on the pipe due to the weight of the soil prism above the pipe spring line and to the downdrag force acting on each side of the soil prism above the pipe.

Problematic areas identified in performing this route-wide analysis will be subject to site-specific analysis. The site-specific analysis will follow the same general approach, but will utilize more refined soil and thermal inputs.

21.3.2.3 Pipe-Soil Interaction at Bends – Parameters and Approach

Pipe-soil interaction at bends will be analyzed to ensure that the pipe is adequately supported under the various loading and soil conditions expected during the life of the project. Design parameters used in the analysis of pipe-soil interaction at bends will include soil spring constant and resistance (or soil load-displacement characteristics) that are derived from more basic parameters, including moisture content, unit weight, particle size distribution, friction angle, cohesion, ice bond strength and creep characteristics of frozen soils, pore pressures, including seepage forces and excess pore pressures. These parameters will be considered for both the native soils and the backfill materials, as appropriate. Pipe design parameters will include allowable strain limits as presented in Section 20, and pipeline load/deflection characteristics.

Design conditions to be analyzed may include:

SOIL CONDITIONS

- Frozen and Thawed Thermal State
- Ice-Rich and Ice-Poor Frozen Soils
- Weak and Strong Unfrozen Soils
- Native Soils and Imported Backfill

GROUNDWATER CONDITIONS

- Moist Versus Saturated
- Hydrostatic Versus Excess Pore Pressures
- Bulk Unit Weight Versus Submerged Unit Weight
- Total Stress Versus Effective Stress

LOADING CONDITIONS

- Short Term Versus Long Term
- Elastic Versus Plastic
- Sagbends Versus Overbends Versus Sidebends

Bends will be provided with adequate soil support based on elastic-plastic analysis of pipe stress, strain, and displacement under design loading conditions and the allowable limits on stress and strain in the pipe given in Section 20.0.

The results of the bend design analyses will be applied to the route soil conditions. Allowable bend angles, bend restrictions or special design measures will be indicated on the construction drawings and/or in the specifications.

Bend design is based on the lowest soil resistance that can be reasonably expected for each of the loading conditions. For frozen soils subject to thaw, the lowest soil resistance occurs when the soils thaw while the bend load is being applied.

21.3.2.4 Slope Stability Analysis – Parameters and Approach

Parameters required to evaluate slope stability along the pipeline route include slope configuration; soil stratigraphy, utilizing both existing borehole data and ETUA, as appropriate; initial, post-construction and post-operations thermal state; soil unit weight and moisture content; particle size distribution; soil friction angle and cohesion; frozen soil strength; location of water table; and pore pressure distribution.

The approach to evaluating slope stability along the pipeline alignment is charted on Figures 21-3 and 21-4, and is described below. Existing geotechnical and survey data will be used to the greatest extent possible. The data will be analyzed to develop a list of potentially unstable slopes. The potentially unstable slopes will be tabulated and ranked based on the existing information. Field reconnaissance will be conducted to verify the list of potentially unstable slopes, and to search for potentially unstable slopes that were mistakenly omitted from the list.

Slope stability analysis will be performed for the potentially unstable slopes that remain on the list following the field reconnaissance. Existing data will be used in the analysis. Appropriate analytical techniques will be selected, depending on the slope configuration, stratigraphy, thermal conditions, design earthquake loads, and other pertinent factors.

For static stability analyses of both thaw plugs and unfrozen slopes, factors of safety against failure will be computed using limit equilibrium methods. Effective stress analysis will be used where appropriate. For unfrozen slopes, a water table depth will be assumed based on local data, and a simple technique such as infinite slope analysis will be performed.

Limit equilibrium analysis is performed by comparing the strength of a soil or rock mass along an assumed failure plane to the forces tending toward failure, then computing the factor of safety for the slope. Infinite slope analysis is appropriate for analysis of stability of slopes where the depth to the failure plane is small compared to the length of the slope, and the size of the failure block may be considered infinite. Limit equilibrium analysis assuming a curved or irregular surface may also be used where appropriate.

Earthquake stability for both thaw plugs and unfrozen slopes will be assessed using pseudo-static analyses for the preliminary analyses, and assuming infinite slope failures. In these analyses a lateral force will be applied to the slope. The magnitude of the lateral force will be a function of specified seismic coefficients that will vary along the route. Total stress or effective stress will be used in the analyses depending on whether the slope being analyzed is expected to be undrained or drained during an earthquake. This condition is largely a function of the soil type, with coarse soils possibly draining during the earthquake, and finer soils would likely be undrained. For soils that can be considered free draining, effective stress analyses will be used.

For pseudo-static factors of safety greater than one, earthquake induced slope displacements are likely to be negligible. For slopes where the pseudo-static factor of safety is less than 1.0, further analyses will be required. In these analyses, failure mechanisms other than infinite slope failure may be considered.

Liquefaction potential under earthquake loading will be screened using existing methods that take into consideration such parameters as standard penetration test blow counts, relative density, and particle size distribution. More refined liquefaction analysis may be performed on a site-specific basis.

If data gaps exist, they will be identified following the stability screening process described above. Plans will be made to collect any data that is required in order to complete stability analyses. The additional, necessary data will be collected to provide input to stability analyses. The data collection would likely include topographic surveys, and geotechnical investigation.

Stability analyses will then be completed, and the slopes will be graded based on the results. Mitigative measures or monitoring requirements will be identified for potentially unstable slopes that may impact the integrity of the ANGTS pipeline or adjacent facilities.

Cut and fill slopes that will result from ANGTS pipeline construction will be analyzed as necessary following the same procedure outlined above.

Stability of rock slopes will be analyzed using the appropriate techniques of rock mechanics and structural geology. These techniques will rely on parameters such as rock strength, slope configuration, and orientation of bedding, joints, and faults for evaluation of slope stability.

21.3.2.5 Ancillary Foundations – Parameters and Analysis

Many parameters will be used in analysis and design of foundations for pipeline ancillary structures. These parameters will include climatic conditions, thermal inputs from the structure being built, initial and future ground temperature profile, adjacent surface conditions, stratigraphy, soil moisture content (frozen and unfrozen), location of the groundwater table, depth of seasonal frost, soil unit weight, friction angle, cohesion, refrigeration system performance factors, adfreeze bond strength, latent heat of fusion, specific heat (frozen and thawed), thermal conductivity, creep characteristics, thaw settlement potential, frost heave potential, lateral load resistance, soil-steel friction angle, bearing capacity, and the tolerance of the structure to foundations movements.

Foundations for ancillary pipeline components will be designed using industry standard methods. Shallow and deep foundations will be considered, and the most economical, technically feasible foundation option will generally be selected. Generally speaking, the design philosophy will be to maintain the thermal state of the soils in their initial state.

Shallow foundations (e.g. spread footings) may be used for unfrozen soils. Shallow foundations may also be used on frozen soils where the structure will not thaw the frozen supporting soils, is tolerant of the predicted thaw settlement, or is to be located on thaw-stable soils.

Deep foundations (e.g. piles) may be used in frozen or unfrozen soils. Vertical load capacity will be provided via skin friction, adfreeze bond, or end bearing, as appropriate. Lateral load capacity will be provided by the near-surface soils.

Active or passive refrigeration systems may be used to improve foundation soil performance in conjunction with deep or shallow foundations.

21.3.2.6 Thaw Penetration – Parameters and Analysis

Parameters to be used in the thaw penetration analysis will include climatic conditions, thermal inputs from the pipeline or other structure being built, surface conditions, stratigraphy, soil moisture content (frozen and unfrozen), soil unit weight, soil make-up (organic versus mineral), latent heat of fusion, specific heat (frozen and thawed), and thermal conductivity.

Thaw penetration for design problems other than those specifically addressed above will be estimated using technical procedures appropriate to the size, complexity, and significance of the problem. These procedures will include simple techniques such as hand calculations and the Modified Berggren Method, as well as finite element thermal models. The size and configuration of numerical models, including such considerations as 2- versus 3-dimensional, conduction-only versus conduction-plus-convection, will be appropriate for the specific design problem being addressed, and may vary on a case-by-case basis.

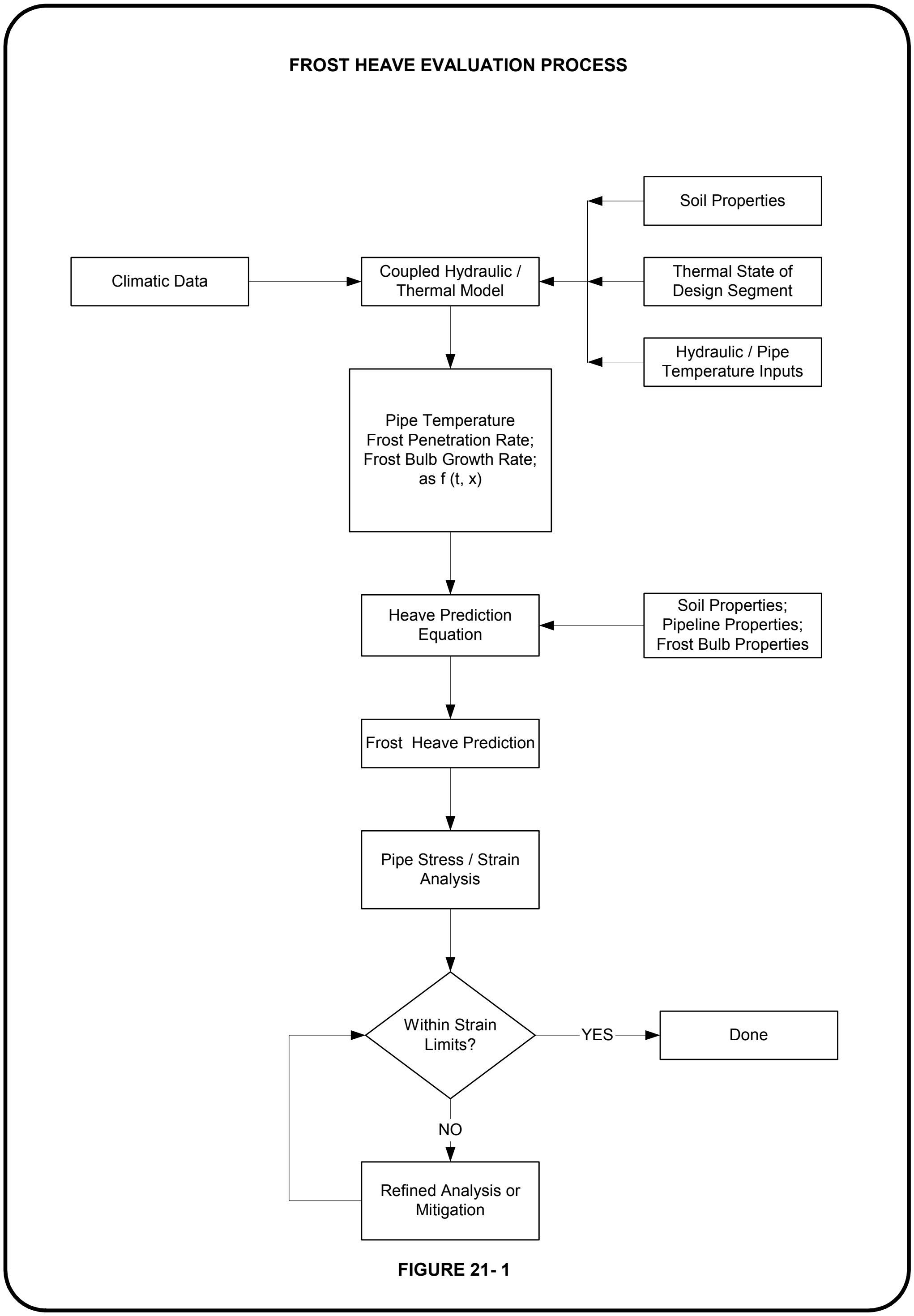

Figure 21-1 Frost Heave Evaluation Process

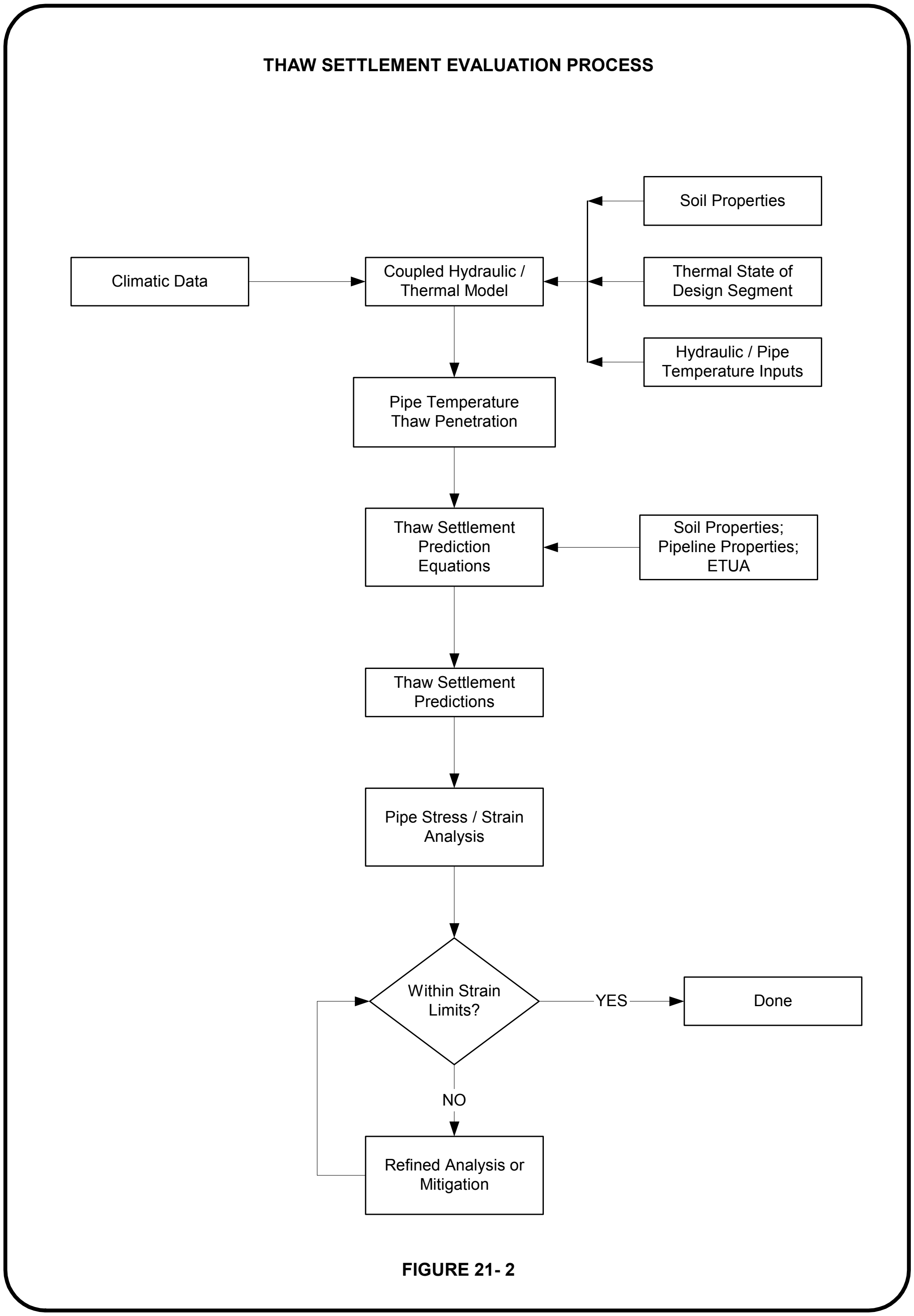

Figure 21-2 Thaw Settlement Evaluation Process

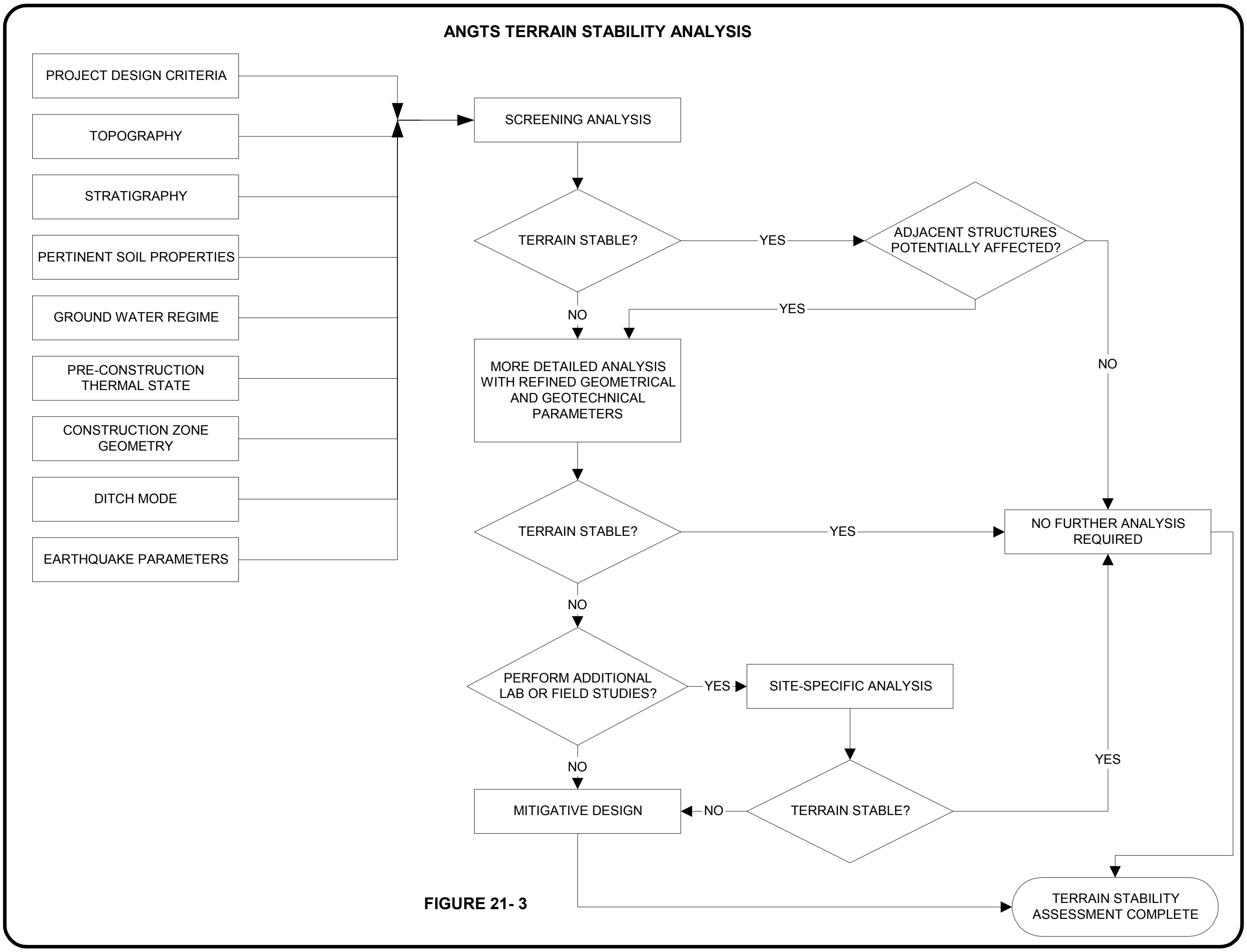

Figure 21-3 ANGST Terrain Stability Analysis

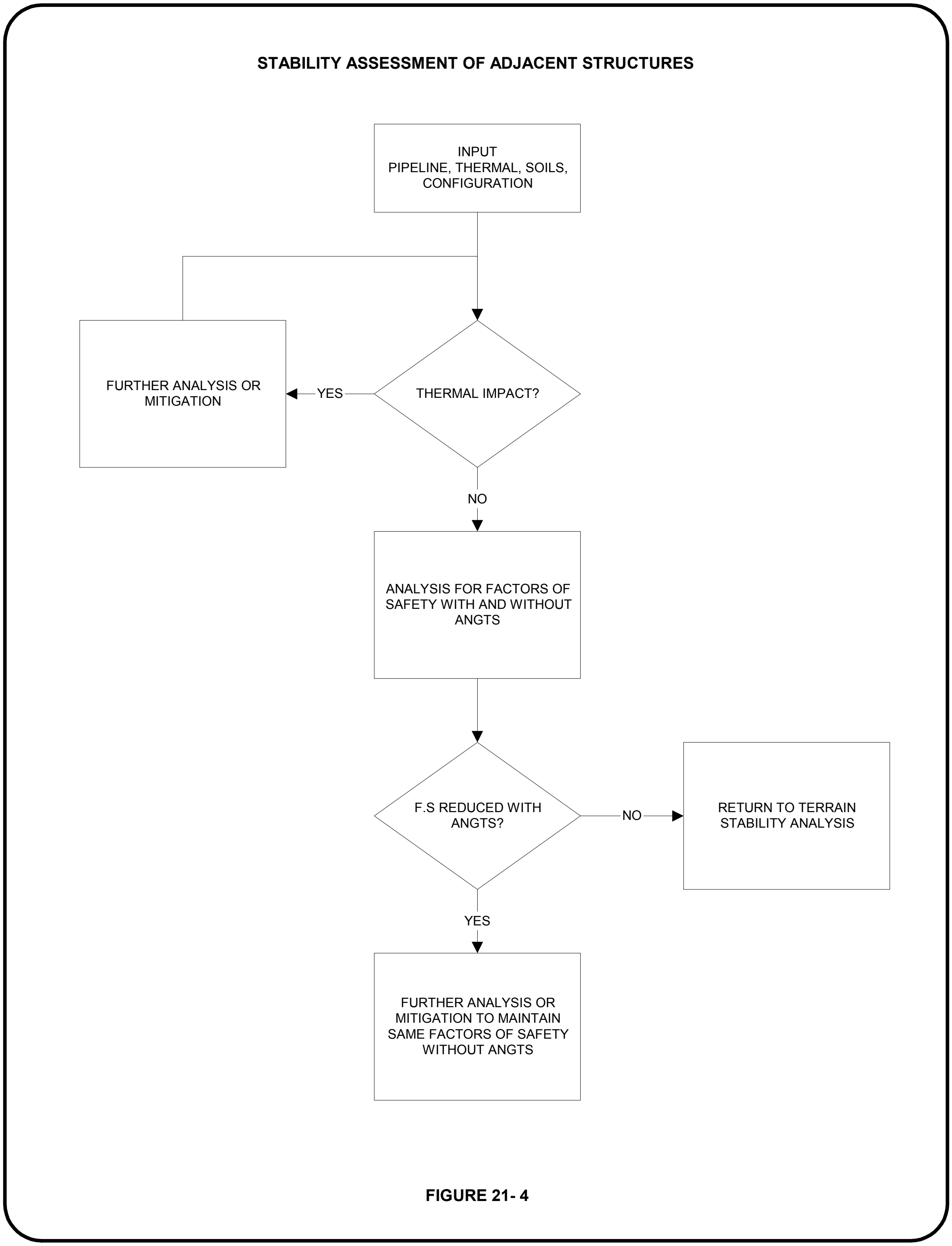

Figure 21-4 Stability Assessment of Adjacent Structures