# D. Lee Petersen

ITASCA Consulting Group, Inc.
An Itasca International Company

## Senior Principal Engineer

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| ***Expertise*** | Soil-Structure Interaction, Numerical Modeling, In-situ Soil Modulus Measurement, Vibration Assessment and Monitoring, Coupled Mechanical-Thermal-Fluid Flow Numerical Modeling, Design of Deep Hard-rock Caverns, Design of Occupied Underground Space, Structural and Geotechnical Instrumentation |
| ***Education*** | Ph.D. (GeoEngineering), 1991<br>M.S. (GeoEngineering), 1978<br>University of Minnesota<br><br>B.S. (Mining Engineering), 1976<br>University of Wisconsin |
| ***Registration*** | Registered Professional Engineer: Minnesota, Missouri, Illinois, Colorado, Virginia |
| ***Professional Affiliations*** | Member: Society of Mining, Metallurgy and Exploration; SME Twin Cities Board of Directors; American Society of Civil Engineers. Member (Past President): Minnesota Geotechnical Society. International Society for Rock Mechanics; Board of Visitors, University of Wisconsin Geological Engineering Program; TRB Committee AFS40 Subsurface Soil-Structure Interaction; TRB committee AFS20 Geotechnical Instrumentation and Modeling |

***Professional Experience***

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| *2011 – Present* | *Itasca Consulting Group, Inc., Minneapolis, Minnesota*<br>*Principal Engineer* |
| *1982 – 2011* | *CNA Consulting Engineers, Minneapolis, Minnesota*<br>*Senior Consultant and Project Manager* |
| *1979 – 1982* | *J.F.T. Agapito & Associates, Inc., Grand Junction, Colorado*<br>*Project Engineer* |
| *1978 – 1979* | *University of Minnesota, Minneapolis, Minnesota*<br>*Staff Scientist* |

***Project Experience***

*Pompey's Pillar National Monument* — Project Manager and technical lead for assessment of rock conditions and rock slope stability for preservation of this noteworthy historic monument, where William Clark of the Lewis and Clark Expedition inscribed his name in 1806. Many others before and since have left pictographs and inscriptions on this small sandstone and shale mesa sticking up from the shores of the Yellowstone River near Billings, MT. The Bureau of Land Management identified three areas of rock slope stability and rockfall concern: the Clark signature area, Turtle Rock, and the lower rock area. Phase 1 work included high-resolution scan and photogrammetry of the pillar; a site visit and non-invasive site investigation; installation of preliminary instrumentation; a preliminary 3D geometry model of the critical areas, considering visible and hidden features; a rigid block *3DEC* model to estimate block stability; development of a rock block monitoring program concept; and development of the Phase 2 site investigation. Phase 2, which is underway, includes definition of the project, risk tolerance, and design criteria; on-site geotechnical investigation and associated laboratory testing; additional rock block monitoring; developing preliminary re-opening recommendations; evaluation of rock properties, joint characteristics (location, continuity, roughness, infilling, etc.), and bedding characteristics; enhanced *3DEC* models of the Signature Block and Turtle Rock locations with deformable blocks, incorporating the information from the site investigation and rock properties evaluation; developing a modeling plan (identify uncertainties in the subsurface information and develop a modeling matrix addressing the uncertainties, or what-if analyses); conduct *3DEC* modeling, including parametric study of what-ifs about rock properties, joints, bedding planes, etc.; conducting rockfall analyses; identification and modeling of remedial measures; preparing remedial measures details and cost estimate; and updated re-opening recommendations.

*Underground LRT Station Parking Ramp Feasibility Study* — Project Manager and technical lead for the feasibility study of expanding a parking ramp above an underground LRT station. Minneapolis-St. Paul International Airport (MSP is served by the Metro Transit light-rail (LRT) Blue Line). At Terminal 1-Lindbergh, where parking facilities are frequently near or at capacity, a proposed parking ramp expansion will overlie the existing underground LRT station. The LRT station is constructed in an excavation in the St. Peter sandstone and Glenwood shale, with a flat roof of the Platteville limestone. Excavation dimensions are about 55 feet wide by 40 feet high by 540 feet long, with the roof less than 30 ft below a parking exit plaza. The station is shallow, with the bottom of the Platteville limestone approximately 30 feet below the existing revenue control plaza for on-airport parking, which is located above the station. Construction of the parking ramp expansion involves two principal impacts on the LRT station: a) column loads on the Platteville limestone above or nearby the station; and b) excavation of the soil cover and some of the Platteville limestone above the station. As part of the feasibility study described below, the magnitude of these impacts was assessed by conducting 3D geostructural analysis of the station using Itasca's distinct element modeling software called *3DEC*.

*Minnesota Library Access Center (aka Elmer Andersen Library)* — Geomechanics Project Manager for site investigation and design of this underground library facility on the West Bank campus of the University of Minnesota. The project consists of two parallel caverns 65 feet wide by 600 feet long in dolomite, shale, and sandstone. The caverns are located under the Law School, Willey Hall, and the Studio Arts Building. Construction and permanent access is by a drive-in portal, and two shafts through glacial soils and limestone. CNA designed all underground structures, including roof and wall rock support, drainage and water control, shaft support, grouting for water control, and integration of existing facilities. Mr. Petersen conducted extensive *FLAC* modeling of this project as the basis for selection of rockbolt patterns, wall support, and construction sequence.

*Hiawatha Light Rail Transit* — Project Consultant for twin subway tunnels and a 66-ft wide station in the St. Peter sandstone under the Minneapolis-St. Paul International Airport, Minneapolis, MN. The unique geology of the Twin Cities, with a stiff, strong dolomite underlain by soft, friable sandstone is a desirable environment for constructing high quality and low cost underground space. For the twin tunnels, CNA produced one of two equivalent designs. CNA's option was developed for construction with conventional equipment (loaders, excavators, rockbolters, and roadheaders), and used a flat roof at the underside of the dolomite. The other equivalent design utilized a tunnel boring machine. One station design was produced with a wide-span flat roof and arched walls in the sandstone supported by curved concrete panels.

*Concrete Arch Dam Static and Dynamic Analysis* — Project Manager for the static and dynamic stability of a concrete arch dam. The nearly 60-year-old dam was designed for a very low peak ground acceleration of 0.05 g. Recent updates in regional seismicity and estimated levels of ground motion have necessitated an updated stability evaluation. The static and seismic stability of the dam was assessed using a 3D nonlinear finite difference model built using Itasca's 3D continuum software, *FLAC3D*. Using nonlinear constitutive models (including Mohr Coulomb and Ubiquitous Joint models), the joints in the dam concrete were explicitly modeled to have zero tensile capacity across both contraction and construction joints in the dam, while maintaining a nominal intact concrete tensile capacity. Thus, gaps, stress redistribution, and associated deformations are appropriately captured in the dam. The seismic stability analyses ultimately concluded that the dam remains stable with minimal deformations under the Safety Evaluation Earthquake due to the relatively low ground motions associated with the SEE (PGA of ~0.16g). However, the results of nonlinear modeling demonstrated that the concrete joints have an important role in the stress distribution.

*Minnesota Highway 53 Relocation ($2^{nd}$ Avenue Slope Stability)* — Project Manager for a slope stability assessment related to the relocation of Highway 53. The new project alignment is near the northwest edge of the Richelieu pit, where a slope failure occurred in a combination of glacial till and a slickensided clay. Itasca back-analyzed previous modeling, processed LIDAR data and developed cross-sections to replicate actual geometry, created a 3D subsurface model, determined drained and undrained material properties from CPT tests, calibrated an updated model with undrained slickenside clay properties, and analyzed stability of the post-failure geometry using calibrated slickenside clay properties.

*Minnesota Highway 53 Relocation (Rock Slopes)* — Project Manager and technical lead for assessment of rock conditions and rock slope stability for relocation of a major highway in Minnesota. Relocation of Highway 53 near Virginia, MN, plus subsequent mining by others, will create a so-called isthmus that carries the roadway from the current alignment to the east end of a planned bridge. The future mining will create about a mile of rock slopes up to 500 ft deep. Itasca characterized the jointing in the rock mass via coring, ATV/OTV logging, determined joint characteristics via drone-based photogrammetry, conducted kinematics assessments of slope failure mechanisms, and conducted discrete-element modeling using *UDEC* and *3DEC*.

*Stability Review of the Eastman Tunnel Beneath the Hennepin Island Dam* — Project Manager and technical lead for the stability and impact assessment of the Eastman Tunnel. Xcel Energy upgraded the Hennepin Island Dam at St. Anthony Falls near downtown Minneapolis, Minnesota. The Eastman tunnel underlies some or all of cells C1 through C4 of the Hennepin Island Dam. At issue during the FERC review was the stability of the foundation of cell C4, as it might be impacted by the presence of the Eastman tunnel. The Eastman Tunnel was constructed in 1869 to bring water power from the area near Nicollet Island above St. Anthony Falls to the industrial sites below Hennepin Island. However, the tunnel collapsed in 1869 during construction, and over the course of several years, the collapse widened and threatened to eliminate the Falls. Finally, the Army Corps of Engineers placed a tunnel plug and cut-off wall that prevented further collapse of the tunnel. The review findings included: the Eastman Tunnel rock conditions are typical of other Twin Cities locations; voids are uncommon in the Platteville limestone; natural and constructed caves and caverns are stable with spans up to four times wider than the Eastman tunnel; linear arch and numerical analysis methods calibrated by local and national projects predict that the tunnel was stable by a wide margin; the principal limestone roof shows no signs of distress (joint separations, centerline cracks); the tunnel sidewalls show no signs of distress; the tunnel was stable at the time of the review and would be stable after construction of Cell 4.

*Spruce Tree House Arch Analysis at Mesa Verde National Park* — Project Manager and technical lead for the stability assessment and remedial measures recommendations for a rock arch above the Spruce Tree House alcove at Mesa Verde National Park, Colorado. The alcoves into the host sandstone formation at Mesa Verde National Park contain cliff dwellings occupied by Ancestral Pueblo people from about 1190 to 1300. Spruce Tree House alcove, located across the Visitor's Center, is overlain by a rock arch that has lost pieces since opening for visitation in 1908. Several phases of remedial actions have occurred, the most recent in the 1960s. Recent falls have required new stability assessment and development of remedial actions.

*Assessment of Roof Fall Cause in an Occupied Underground Facility* — Project Manager and technical lead for assessing the cause of a major roof fall in an occupied underground facility. The facility, converted from a room-and-pillar limestone mine, experienced a roof fall in an entire bay. The assessment was based on investigation of pre-existing ground conditions, prior roof falls, site geology, weather records, ground support, linear arch modeling, and numerical modeling using *3DEC*.

*Due Diligence Assessment of Open Pit Mine Expansion* — Project Manager for a due diligence assessment for financing the expansion of an open-pit mine. The study included an initial assessment of pit geometry, past slope failure experience, and previous design work, followed by a site visit. After obtaining additional information, both geomechanics and hydrogeology assessments were completed, including adequacy of existing subsurface information, mine slope monitoring practices, mine dewatering practices, characterization of major discontinuities, and a risk assessment.

*Shaft Investigation and Rehabilitation Plan Project* — Project Manager for investigation and rehabilitation plans for a 1970s power plant utility shaft. The 25 ft diameter, 1100 ft deep shaft, in a sedimentary sequence of shales, sandstones, limestones, and coal provides access, communications, and power cabling from the underground powerhouse to the surface. Distress in the shotcrete liner was observed during planning for an upgrade. Investigation showed that a 40 ft to 50 ft segment of the shaft had poor quality and drummy shotcrete with severely corroded welded wire fabric reinforcement. The investigation included conducting sounding, drilling, and borehole camera services to determine the full extent of the distress. The remediation concept, which was severely limited by lack of access around the power cables, was a series of structural steel rings 4.5 ft on center, bolted to the rock in eight locations, plus polymer mesh.

*Site Investigation and Instrumentation Plan for an Underground Coal Gasification Project* — Project Manager for this pre-feasibility project. The project intends to extract coal gas from one or more coal seams at depths up to 800 meters. Innovative instrumentation using TDR cables, extensometers and microseismic monitoring was selected.

*Site Investigation and Mine Design for a Large Underground Cu-Ni-PG Mine* — Project Manager for this conceptual and pre-feasibility design project. This multi-year project includes a regional fault study, core logging and geotechnical analysis, ATV logging, characterization of the crown pillar, borehole gas studies, lake bottom sediment studies, aquifer tests, straddle packer tests, hydrogeologic modeling, characterization of persistence of major features, development of calibrated stochastic fault networks, refining rock mass strength estimates, refining rock mass domains, refining rock mass variability, incorporating mine development sequencing, incorporating faults and rock mass domains into mine design models, refining predictions of subsidence, dilution and pillar stability, evaluation of rockburst potential, evaluation of fill stability, evaluation of ground support requirements as a function of standoff distance and depth, and obtaining predictions of fault slip and aperture change for input to mine inflow models.

*Site Investigation and Mine Design for Expansion of a Multi-Orebody Cu-Zn Underground Mine* — Project Manager for this pre-feasibility project that involves three separate orebodies with different mining methods, geometries, and geology. Extensive drilling for ore reserve estimation has been conducted, but geotechnical logging is limited. Fracture frequency logging has been conducted for 17,200 meters of core in the immediate vicinity of the orebodies. Rock mass strength assessment was completed and modeling design work is underway.

*LUX & Majorana Experiment Designs for Sanford Laboratory at Homestake* — Project Manager for conceptual design and construction documents for these two experiments at Sanford Laboratory. The LUX experiment, a xenon-based detector sensitive to WIMPs (dark matter) will be sited on the 4850 Level in the Davis chamber. Majorana, a neutrinoless double beta decay experiment, will be located on the 800 Level (e-forming facility) and 4850 Level (assembly and detector spaces). Both experiments require rock excavation, clean spaces rated from Class 100 to Class 100,000, transition spaces, mechanical/electrical systems and fire and life safety provisions. All facilities are designed using the provisions of the prevailing building codes.

*Henderson DUSEL* — Project Manager of a multi-disciplinary team preparing the conceptual design for a deep underground science laboratory at the Henderson molybdenum mine in Colorado. The $300 million laboratory will provide caverns, research outposts and infrastructure for cutting-edge research in the physical sciences, biological sciences, geosciences, and engineering sciences. The design team is responsible for tunnel and cavern design, fire and life safety, egress and refuge, code assessment, electrical systems, mechanical systems, cooling systems, etc. Mr. Petersen was the principal liaison between the scientific community and the engineering team.

*Sudbury Neutrino Observatory (SNO) Expansion* — Project Consultant for design of the expansion of this internationally renowned and widely respected underground physics laboratory. Mr. Petersen's role was liaison with the laboratory scientists, space programming, conceptual design and layout, fire and life safety (including code applicability issues), and peer review of the site investigation and excavation design. The expanded laboratory will accommodate several large-scale experiments, several medium-scale experiments, and experiment support and prototyping facilities. The Observatory is located at the 6800 Level of the Creighton mine, near Sudbury, Ontario.

*MINOS Project* — Project Manager and lead civil engineer for design and construction services of the MINOS Far Detector Laboratory. This project produced the "target" cavern for the FermiLab–generated neutrino beam. The MINOS Far Detector is located 2341 feet underground at the Soudan Underground Mine State Park in northeastern Minnesota.

*Off-Axis NuMI Neutrino Detector Laboratory* — Project manager and lead civil engineer for conceptual design of this University of Minnesota project. The shallow neutrino detector laboratory is located approximately 10 km off-axis of the NuMi beam in northeastern Minnesota. The Off-Axis project conceptual design consisted of site evaluation, space programming, consideration of four construction alternatives, conceptual design of the preferred alternative, development of a work breakdown structure and cost estimate, and a construction schedule. Physicists from the University of Minnesota and elsewhere are actively pursuing funding for this project.

*Construction Impacts from Vibratory Compaction* — Prime Consultant for a Minnesota Department of Transportation research project to assess existing practices for precondition surveys and vibration monitoring for construction projects. The work includes researching MnDOT's practices and customs, the standards and policies of DOT, synthesis of literature and polling information, and development of a model policy.

*Mine Conversion and Rehabilitation* — Survey, evaluation, and rehabilitation recommendations for underground limestone mines before, during, and after conversion to inhabited space, including rock conditions, rock support, concrete linings, steel structures, water control, and drainage, recommendations for rock trimming and concrete placement to relocate an underground railroad line. Facilities include Geospace, Independence, Missouri; Rush Creek, Liberty, Missouri; Space Center Summit, Lee's Summit, Missouri; Gateway, Wampum, Pennsylvania; Oldham, Louisville, Kentucky; Cumberland Furnace, Tennessee; Redpath, Independence, Missouri; Interstate Underground Warehouse, Kansas City, Missouri; Stephenson Property, Kansas City, Missouri; CDC Property, Independence, Missouri.

*San Jacinto National Underground Science Laboratory* — Project Manager for conceptual design of this proposed $200 million project near Palm Springs, California. CNA led a team of geologists, underground space planners, mechanical and electrical engineers in developing the technical design, which became the basis for the project proposal to the National Science Foundation and the Department of Energy. The project includes a 7,500 m tunnel into Mount San Jacinto and a cavern complex more than 2,000 m below the mountain peak.

*Technical Evaluation of U.S. National Underground Science Laboratory Sites* — Project Manager and principal engineer for this evaluation. CNA provided engineering assistance to a subcommittee of physicists charged with conducting a technical assessment of four proposed national underground science laboratory sites in the United States (Homestake, San Jacinto, WIPP, and Soudan). The work included visits to existing laboratories/experiments in the United States, Italy, and Japan. CNA prepared the capital and operating cost WBS used by the subcommittee to evaluate the site proposals and provided technical assessments of the site merits for conventional construction.

*Very Large Hadron Collider* — Project Manager and lead civil engineer for feasibility study of this next-generation particle accelerator located in northeastern Illinois. A CNA-led team provided a feasibility assessment and developed cost estimates for underground construction of a staged Very Large Hadron Collider (VLHC) at FermiLab. Conventional construction of the VLHC consists of a 233 km circumference tunnel ring, caverns, shafts, risers, and other tunnels and facilities. CNA's work addressed the anticipated construction costs for excavation, ground support, water control and lining of the underground, heavy civil portion of the conventional facilities. Preliminary designs and cost estimates were prepared for the approximately 60 mined and cut-cover caverns necessary for the project.

*NCHRP 15-29 Live Loads on Buried Structures* — Project Manager for this 30-month research project to assess the intensity of live loads on buried structures of varying depth and type. Included in the study are both rigid and flexible structures (concrete, metal, and plastic) with round, box, and long-span cross-sections. AASHTO Standard and LRFD Specifications differ in the manner that live loads are spread through fill onto culvert structures. Standard specifications apply surface point loads and spread loads at the rate of 1.75 times depths. The LRFD specifications apply live load through a tire footprint of 10 in by 20 in at the surface but attenuate with a lower coefficient (1.00 or 1.15 as a function of soil type) as the depth of fill increases. This research used 3D, numerical, model-based investigation of how live loads spread with depth as a function of soil and culvert type. The investigation included the following tasks: selection of appropriate software and soil models; 3D finite element analysis of about 830 buried culverts; development of simplified approximations that capture the behavior; and development of Simplified Design Equations for structural response, parametric analysis to determine the impact of the Simplified Design Equations on culvert design forces, recommendations for revised AASHTO specifications, and assessment of reliability. Modeling results show that live load spreading with depth depends upon depth, soil characteristics, and culvert characteristics. Pavements substantially reduce soil stress and structure forces, so the unpaved case controls. The distribution of vertical stresses on the plane at the crown of buried culverts varies substantially depending upon the soil properties, culvert characteristics, and depth.

*NCHRP 14-19 Culvert Rehabilitation to Maximize Service Life While Minimizing Direct Costs and Traffic Disruption* — Co-Principal Investigator. This project focuses on techniques for culvert assessment and repair that eliminate the need for road excavation and conventional culvert replacement. The primary goal of the project is to develop a Culvert Rehabilitation Handbook and recommended AASHTO specs, building on existing understanding of typical types of culvert deterioration requiring rehabilitation, methods for assessing culvert condition (both structure and soil), and performance of limit states and design procedures for culvert repairs. A secondary goal is to identify gaps in understanding and make advances to address those limitations.

*Intelligent Compaction Research and Demonstration Projects* — Project Manager for six sponsored and one unsponsored project to: determine the viability and competitive benefits of Intelligent Compaction (two projects); investigate continuous compaction control as a means for compaction of unbound materials in Minnesota roadway construction (one project); assess the use of the lightweight deflectometer for Intelligent Compaction QC testing and evaluate Intelligent Compaction field test results (one project); assist an Intelligent Compaction equipment manufacturer with demonstration project (one project); assist MnDOT with an Intelligent Compaction demonstration project; and develop software and processes for using Geographic Information Systems to process, store, and evaluate IC data.

*GeoGauge Development* — Project Manager, Development of a Rapid Method for Measuring In-situ Soil Modulus. This project, an initiative under the Clinton administration's Technology Reinvestment Project, developed the Humboldt GeoGauge.

*T.H. 61 Glen Road* — Team Project Manager for this value-engineering project requiring retaining wall foundation improvement to control structural deflections. Foundation soils were soft and variable, including fine-grained layers—original treatment was extensive deep soil mixing. Under a value-engineering agreement, a portion of the foundations were improved by replacing loose granular soils with select granular borrow. The agreement made the contractor responsible for quality control during compaction and quality assurance afterwards. In the past, the soil compaction would have been specified and controlled using soil density. Development of practical methods for measuring or monitoring in-place soil modulus, including the Humboldt GeoGauge, small-scale plate load test, and the dynamic cone penetrometer, allowed an alternative approach. About 402 GeoGauge, 44 plate load, and 15 pressuremeter tests were conducted during the fall 2002 and fall 2003 foundation improvement.

*35W-T.H. 62 Crosstown Reconstruction* — CNA project manager for noise and vibration monitoring for this four-year highway reconstruction project. CNA conducted susceptibility analyses, preconstruction surveys on 500 structures, monitored vibrations with multiple seismographs at 50 sites, attended public meetings, and prepared annual summaries of the data.

*Saint Mary's Duluth Clinic expansion* — CNA project manager and lead geotechnical engineer for this assessment of potential blast-related damage and monitoring of blast-induced vibration. The clinic, located in downtown Duluth, expanded into an adjacent block, requiring rock excavation. Nearby structures potentially susceptible to blast-induced vibrations included: existing clinic facilities, nearby brick/masonry buildings; utilities in the alley; retaining walls associated with I-35, including tieback anchorage, overall stability, and connections between temporary and permanent parts of the wall; and tunnels structures on I-35, including tile, lights, and other interior fixtures. Our approach included review of as-built records, review of utility and structure condition, estimation of rock excavation parameters, estimation of likely ground and air blast magnitudes, judgment-based assessment of potential blast damage, and blasting specifications.

*Ironworld Discovery Center* — Project Manager for an independent assessment and evaluation of slope stability-related ground movements and building distress at Ironworld Discovery Center in Chisholm, Minnesota. Work included review of historic underground mining information; review of Interpretative Center, Observatory, and Ethnic Pod structure information; assessment of past, present, and future subsidence; assessment of structure damage potential; slope stability analysis; planning, installation, and monitoring of building and subsurface monitoring equipment; and development of plans and procedures for occupying the repaired structure.

*Ontario Power Generation, Deep Geologic Repository* — Consultant for pillar and roof design for a planned low and intermediate level waste repository in sedimentary rock 660 meters below surface. Two approaches were used, both relying on reliability methods: an empirical, design-based method, where the pillar strength is estimated from simple equations containing the pillar and room dimensions, the rock strength, and empirical parameters; and a numerical modeling-based method, where the modeling estimates the magnitude of plasticity zones. The empirical design-based method assumes statistical distributions for rock unconfined compressive strength (UCS), Geological Strength Index (GSI) and pillar width, and generates estimates of the probability of unsatisfactory performance. The numerical modeling-based method uses modeling results for deterministic rock mass parameters and generates reliability-based values for the expected cost of remedial measures. For each method, the result is the pillar width required for consistent values of expected incremental cost or probability of unsatisfactory performance. The reliability-based methods produce consistent measures of the likelihood of pillar distress. In comparison, factor of safety methods are inconsistent, in the sense that two pillar designs with the same factor of safety may have quite different probabilities of unsatisfactory performance.

*Underground Science City, Singapore* — CNA Project Manager for the feasibility assessment of a very large underground office park in Singapore. The assessment included site analysis, site geology appraisal, previous site investigation evaluation, space programming, preliminary planning and design for three underground space layouts, detailed layout development for the preferred layout, and a construction cost estimate. The preferred layout was a regular, room-and-pillar underground complex consisting of 36 caverns each 20 meters wide by 22 meters high by 75 meters long. All caverns branch off a main concourse that connects underground entry points. The gross underground floor area was approximately 290,000 square meters. The design featured a flexible layout and provided daylight and connection to the surface deep underground through a massive open atrium. The assessment concluded that the project was feasible and would cost approximately S$1.13 billion.

*Silver Cliff Highway Tunnel* — Final Design and Construction Services Project Manager for conceptual design, site investigation, geotechnical report, preliminary and final design, cost estimating, special provisions and construction services for this 1300 feet long, 50 feet wide highway tunnel. Principal author of the geotechnical data report and geotechnical design summary report. Construction services included review of shop drawings & submittals, construction engineering, construction inspection, assessment of ground conditions, non-tunnel construction services (roadway, m/e, etc.), and alternative dispute resolution techniques including owner-engineer-contractor partnering. This project received the US DOT Federal Highway Administration 2002 Biennial Award for Excellence in Highway Design.

*Preliminary Rock Slope Assessment for an Industrial Facility* — Project Manager and lead geotechnical engineer for a preliminary stability assessment of several miles of mine pit rock slopes. The slopes are adjacent to the infrastructure corridor of a proposed industrial facility. Our work plan included review of historic pit photographs, topographic information, general site geology, rock outcrop and slope mapping to determine rock characteristics (including rock material, bedding and jointing), characterization of the rock slope failure mechanisms observed, and a preliminary stability assessment of the specific locations. Results included that the site rock slopes were cut by three joint sets, slope behavior depends upon slope orientation, the slopes are generally stable with ongoing raveling, large-scale failures have occurred in the past, groundwater not playing a significant role in slope stability, less jointing was observed on north facing slopes, and large-scale joints and the related block failures may be associated with faults.

*Assessment of Condominium Construction on Adjacent Rock Slopes* — Project Manager and lead geotechnical engineer for an assessment of a rock slope disturbed by condominium construction. This project entailed review of site information, including: readily available bedrock geology information; assessment of the site geometry; rock joint mapping; assessment of the condition of the bluff; and the effects of condominium construction. Findings included judgment that the rock slope adjacent to the condominiums was potentially unstable and that additional rockslides could occur at any time.

*Assessment of Rock Slopes Supporting a Hiking Trail and Bridge* — Project Manager and lead geotechnical engineer for an assessment of rock slopes supporting a proposed hiking/biking trail and bridge. A portion of the Gitchi Gami Trail near Split Rock State Park passes between the Lake Superior cliff and T.H. 61. In a critical section about 200 feet long, the cliff is between 8 ft and 50 ft from the crest of the 40-ft high cliff. The first phase assessment required site reconnaissance, including joint mapping, erosion rate and cliff geometry. After a bridge was chosen to span the critical section, the second phase addressed stability of the bridge foundation based on rock wedge stability analysis. Engineering issues were rock slope stability, rate of erosion and raveling and bridge abutment locations. We conducted site reconnaissance; site geologic and rock joint mapping in outcrops; rock joint mapping in trenches and stability assessments. Findings included: that the slope was experiencing ongoing, progressive sloughing, some rock block slides had occurred; but we did not observe joints at the critical locations that could influence trail or bridge stability.

*U.S. Silica South Ottawa Tunnel* — CNA Project Manager for design services for this materials handling tunnel under the Illinois River. Responsibilities included project conceptualization, site reconnaissance, boring program, evaluation of ground conditions, tunnel design and risk assessment. The tunnel presents an interesting case study of project changes driven by ground conditions uncovered by phased borings. The project was bid after several alignment and elevation changes.

*T.H. 169 Underground Mines Study* — Team Project Manager and lead geotechnical engineer for this MnDOT-sponsored assessment of historic underground mining on existing roadways. The work included information gathering about historic mining methods and locations, reconnaissance geophysics to evaluate methods and determine subsurface conditions under several miles of busy divided highway, test drilling, risk assessment and information synthesis.

*Silver Cliff Tunnel Project Long Term Instrumentation Monitoring and Interpretation* — Project Manager for the long term monitoring and interpretation of the permanent instrumentation at the Silver Cliff project. Project instrumentation includes inclinometers, single and multipoint borehole extensometers, temperature probes. The instrumentation is read every six weeks and a data and interpretation letter report prepared.

*Lafayette Bluff Highway Tunnel* — CNA Project Manager for conceptual design, site investigation, geotechnical report, preliminary and final design, cost estimating, special provisions, construction engineering and monitoring for a 650-foot long, 60-foot wide near-surface highway tunnel. Construction services included review of shop drawings & submittals, construction engineering, construction inspection, assessment of ground conditions, non-tunnel construction services (roadway, m/e, etc.), and alternative dispute resolution techniques including owner-engineer-contractor partnering.

*Soudan 2 Detector Laboratory* — CNA Project Manager for site investigation, design studies, construction documents, construction monitoring for a 2340-ft deep cavern for a physics laboratory. Mr. Petersen was the principal author of the geotechnical data report and geotechnical design summary report for the Soudan 2 project.

*Compressed Air Energy Storage Project* — Project Manager for this utility-sponsored project, providing technology assessment and development, planning, conceptual design and cost estimates for a compressed air energy storage project. This technology allows a utility to reduce peak daytime generation needs by storing energy in high pressure air at depths of 1500 to 2500 feet. Water is used to compensate the air storage caverns, producing nearly constant pressures, and requiring pressure tunnels and shafts. A large facility might require 1,000,000 cubic yards of caverns, plus deep shafts to provide for air and water transport.

*Minneapolis East Interceptor* — Project Engineer for geotechnical analysis, geotechnical report, and design studies. Mr. Petersen was the principal author of the geotechnical data report and geotechnical design summary report for the Minneapolis East Interceptor.

*Development of a hybrid numerical model for seam or vein mining* — The model was based on the displacement discontinuity method for representing the offseam portion of the problem, and the finite difference method for representing the seam materials. Initial development of the hybrid model, using simple implementations of the displacement discontinuity and finite difference methods demonstrated feasibility. The method was found to yield good results for a simple two room, one pillar problem, compared to other numerical analysis methods. However, using the finite difference method to represent the seam material (rather than the simple spring representations used previously) had a significant influence on the numerical behavior of the displacement discontinuity method. Execution times were increased due to the actual calculations done in the finite difference model, and because the finite difference model slowed the rate of convergence of the iterative method used for solving the displacement discontinuity equations. The basic displacement discontinuity implementation was enhanced by providing for unconstrained seam geometry, semi-infinite (half plane) problems, simultaneous use of fictitious stress elements to represent nonseam excavations and out of core solution for large problems. The basic finite difference implementation was enhanced by providing for nonlinear seam behavior (tension cutoff or no tension material, Mohr Coulomb plasticity and ubiquitous joint material). The enhanced hybrid model was applied to a series of yielding pillar problems, including a single yielding pillar; multiple yielding pillars; and barrier pillar selection where both panel and barrier pillars are yielding. A back analysis was conducted of the Soudan iron mine to demonstrate application of the hybrid model to vein problems. Finally, a coal mining problem having a clay seam in the floor was analyzed. Overall, the hybrid model developed herein was found to be sufficiently accurate and economical to make it a valuable tool for the analysis of seam and vein mining problems.

*Nuclear Waste Disposal* — Conducted numerical analysis of conceptual designs of nuclear waste repository in basalt, salt and crystalline rock, including short- and long-term thermal analysis of the emplaced waste and surrounding rock, and stress and displacement analysis of the excavations.

*In-situ Retorting of Oil Shale in Western Colorado* — Project engineer for a four-year mine design and technology development program for underground oil shale retorting. Mine layouts were from 1000 ft to 2000 ft deep, and included excavating and blasting 165 ft wide by 165 ft long by 281 ft high retorts, or excavating 60 ft wide by 60 ft long by 60 ft high rooms. Specific work included structural review of the designs, regional structural analysis, a ground control program and development of underground test plans. Regular underground inspections and evaluations were conducted at both the Cathedral Bluffs and Logan Wash sites to evaluate ground conditions and determine rock support requirements.

*Nuclear Waste Disposal* — Conducted numerical analysis of conceptual designs of a nuclear waste repository in basalt, including short- and long-term thermal analysis of the emplaced waste and surrounding rock, and stress and displacement analysis of the excavations.

*Development of design methods for Saint Peter sandstone pillars* — Twin Cities geology is conducive to development of underground space, because stiff, strong limestone suitable for large roof spans is underlain by the soft Saint Peter sandstone, suitable for room excavation. Design methods were needed to size Saint Peter sandstone pillars for underground developments at varying depths and room spans. The design methods were based on a literature review of existing methods for all types of pillars, back analysis of pillars in local non-engineered sand mines, laboratory testing, and numerical modeling.