Kitimat LNG Facility, Deep Soil Mixing Design Build – Bish Cove, British Columbia

Executive Summary

The Kitimat Liquefied Natural Gas (LNG) project at Bish Cove involved design and construction of Canada's largest deep ground improvement works to date. Golder Associates Ltd. (Golder) and our team successfully delivered on the design-build of a Deep Soil Mixing (DSM) foundation for reinforced earth retaining walls of up to 20 meters in height that would later retain a proposed LNG facility.

The DSM construction works were undertaken using the Cutter Soil Mixing (CSM) technique, whereby the CSM cutter wheels cut vertically into the ground, thoroughly mixing the soil, while injecting cement slurry to create the desired stabilized column of soil. This CSM technique is ideal for the remote (marine access only) location of this site, where minimizing the amount of materials delivered to and removed from site is necessary.

The site's constrained geography and undulating topography presented a number of engineering and logistical challenges to the construction works. Through innovative construction methods and careful quality control procedures, 1,645 CSM panels were installed and 32,500 tonnes of cement transported by barge to the site, 27,500,000 litres of cement slurry batched for a total of approximately 73,900 cubic metres of soil treated (30 km in length when placed end to end).

Golder's construction division acted as prime contractor, managing the overall engineering and design, supply, transportation of equipment and material, construction and quality testing from project design through to successful completion. The scope of work included a site investigation, mixing trial, field trials and production works over a period of 18 months.

Project Objectives and Constraints

The Kitimat Liquefied Natural Gas (LNG) project involved design and construction of Canada's largest and most extensive, deep soil mixing ground improvement works to date. The client objectives for development of the proposed Kitimat LNG facility at Bish Cove, British Columbia, required extensive ground improvement work to accommodate a facility for the processing of gas on site. The site is approximately 17 km south of the town of Kitimat, in a deep-water fjord called Kitimat Arm, approximately 65 km from the Pacific Ocean.

As part of these ground improvement works, two Mechanically Stabilized Earth (MSE) walls, approximately 165 m and 300 m long forming an "L" shape were proposed at a location immediately north of the Bish Cove beach area (*Image 1)*. The design heights of the MSE walls ranged from about 20 m to about 18.5 m parallel to the shoreline, and from about 18.5 m to about 5.5 m for the section perpendicular to the shoreline.

Golder was awarded a $55 million dollar Design-Build contract for the design and construction of this extensive and deep ground improvement scheme to support these MSE walls.

The remote (marine access only) location of the site made it necessary to minimize the amount of materials delivered to and removed from site. The deep mixing technique, which uses the existing soil on site as a construction material, proved an ideal method to suit these constraints. In the Cutter Soil Mixing (CSM) process a mixing head comprised of two cutter wheels that rotate about a horizontal axis is lowered into the earth, loosening the existing soil and cutting it into small particles. A nozzle located between the mixing wheels injects cement slurry transforming the in-situ soil into a panel of homogeneous soil/slurry mass. (*Image 2)*

Technical Excellence and Innovation

Engineering Excellence

Golder conducted a phased geotechnical investigation to assess the shear strengths, compressibility and susceptibility to liquefaction of the weaker soils, and the depths to a suitable embedment layer. In addition, soil samples were obtained from the field for geotechnical laboratory testing as well as developing mix design trials for the proposed ground improvement. The data collected during the investigation, along with data from previous site investigations, was used to characterize the site and assess ground and groundwater conditions for the design of deep mixing ground improvements. (*Image 3)*

The site investigation showed extreme variability of geology and ground conditions. The site deposits typically included high-plasticity clays, organic marine silts, loose to dense sands, gravels, and boulders. Most CSM panels would end up being constructed within the above mentioned soil types.

The final layout consisted of two separate formations of barrettes designed to support MSE retaining walls. The CSM barrettes, R1 and R2, were set out perpendicular to each other. The proposed soil cement panels were to be constructed through weak and compressible soils and embedded into a dense sand and gravel. The performance requirements of the designed ground improvement scheme required minimum target panel strength of 2.5 MPa Unconfined Compressive Strength (UCS) for all soil cement panels. (*Image 4 and 5)*

The design-build team collaborated throughout the phased site investigation, geotechnical analyses, deep mixing design, field trials and construction stages, so as to optimize the design and construction of the deep mixing ground improvement scheme.

Construction Methods and Materials

The use of the Cutter Soil Mixing (CSM) technique to construct barrettes consisting of overlapping rectangular panels of in-situ cement-treated soils, a deep mixing scheme, covering an area of approximately 12,900 m^2 and comprising some 1,645 CSM panels to depths of up to 30.7 m, was developed to provide the required static and seismic stability for the MSE walls, and meet the project-specific performance criteria. (*Image 6)*

CSM panels were constructed through varying thicknesses and discontinuous layers of fine-grained, very soft to soft marine deposits, and loose to compact sands, with occasional interbeds of dense sands and gravels. Panel completion criteria was based on soil response factors, as measured by the CSM equipment, with the design requiring a typical embedment of about 2 m into dense silty sand to sand and gravel to provide the required bearing. A total volume of approximately 73,900 m^3 of soil was treated with cement to consistently yield average unconfined compressive strengths exceeding 2.5 MPa.

To determine construction methods and mix designs that would meet design specifications, lab and field trials were undertaken by the construction engineering team.

Representative soil and groundwater samples were retrieved during the site investigation and used in a laboratory soil mixing test program. The chosen mix design had to be able to meet the technical specifications/requirements in all of the encountered soil types. Based on the results of the laboratory trial mix program, eight of the most promising mix designs were chosen for construction as field trial panels.

Golder began a phased mobilization of equipment and plant to site for the installation and testing of these panels. The trial CSM panels were wet grab sampled and cored, and UCS tests were conducted onsite. Panels with water to cement ratios of between 0.6 and 0.75 and cement contents of between 250 and 450 kg/m^3 were installed. Test results on wet grab and core samples collected from the eight field trial panels were used to set the binder content and construction method for the subsequent 1,645 production panels, which formed the main works of the project.

Rigorous Quality Management Program

The inherent challenge in using in-situ materials as part of a load bearing structure is that there is limited opportunity to test or confirm these materials prior to installing them, as would be available with conventional ground improvement methods. For example, concrete may be sampled and tested prior to placement in a bored caisson; I-beams or rebar may be tested at the mill prior to delivery and installation into the ground. With the deep mixing technique, the final combination and formation of the materials which comprise load-bearing elements occurs deep in the ground, far away from an inspector's eyes or the reach of conventional sampling equipment. This challenge necessitated a well-planned and robust Quality Management Program.

Construction Methods and Materials - To obtain the consistent quality of all 1,645 panels, a standard operating procedure for CSM operators was developed. Using the drill rig's digital instrumentation and B-Report software, quality control team members were able to observe installation parameters in real time and verify they were consistent with the binder dosages and mixing criteria outlined in the mix design. Calibration checks of the various inclinometers, flow-meters and sensors which fed the B-Report software were conducted at regularly scheduled intervals. Cement slurry to be injected into the ground was batched at an on-site batch plant, consisting of two cement mixing stations, three agitation tanks and two screw pumps. The cement batching process underwent rigorous testing including receipt of mill certificates, testing of mix-water, and specific gravity tests via mud balance on the cement slurry prior to injection into each panel. Load cells located in the cement mixing stations, used to proportion cement and water, underwent calibration checks on a regular basis. (*Image 7)*

Sampling – A purpose built wet grab sampler was manufactured to retrieve soil cement from the freshly constructed panels. The project performance requirements specified that a sample be retrieved for every 5 m of depth during wet grab sampling. These fresh soil cement samples were cast into 75 mm x 150 mm plastic cylinders and cured in a temperature controlled bath or curing room on site until testing was scheduled to occur. UCS tests were conducted at 7, 14, 28, and 56 days on the soil cement specimens. To conduct core sampling, a Fraste XL, a Fraste ML, and a HT 750 track mounted drill rig were mobilized to site. Core samples were retrieved in HQ diameter in 1.6 m runs using mud rotary drilling with linseed oil, polymer, or bentonite as drilling fluid additives. Prior to coring, each panel had to cure for a minimum of 21 days in order to avoid damage during drilling operations.

This sampling and testing program was instrumental in determining the in-situ properties of the CSM soil cement panels. A total of 615 HQ sized core specimens and 3,510 cylindrical wet grab specimens were tested for UCS, elastic modulus, strain, dry density, and water content. Each specimen was then classified into a soil category based on its position with relation to geology, specimen appearance, water content, and density.

Site Laboratory - Due to the remote site location site, the relatively low strength of soil cement, and susceptibility to damage and/or disturbance of samples during transport, installation of a mobile site laboratory proved crucial to the success of the Quality Program. UCS testing with strain measurement was carried out using a Sigma-1 GeoTac load frame with 10,000 lb and 5,000 lb load cells. Three large temperature controlled curing baths, and a temperature and humidity controlled curing room were installed into the laboratory. At capacity, the mobile laboratory had room for temperature controlled storage of over 1,000 soil cement samples. The laboratory conducted UCS testing on over 3,000 soil cement specimens over the course of the project. In addition, over 700 soil cement specimens were transported to a CSA certified third party laboratory for UCS testing. In order to assess consistency of the results, UCS tests were generally conducted on a pair of specimens sampled at the same depth on the same panel and at the same age. Where testing was conducted by the third party laboratory, specimen pairs were separated, with one specimen being tested at the site laboratory and one specimen being tested at the third party laboratory. Forty percent of the specimen pairs were within 0.25 MPa of each other, and 63% of those tested were within 0.5 MPa of each other. A customized Graphic Information Systems (GIS) system was developed to handle the massive quantity of data collected.

Challenging Site Logistics

The mountainous terrain surrounding Bish Cove made for challenging road construction conditions: the majority of materials and equipment would have to travel via barge. The site is located along the Douglas Channel, a challenging marine environment characterized by wind gusts of up to 45 knots, 2 meter significant wave heights, and up to 6 meter variations in tide (ASL Environmental Sciences, 2010). An experienced marine construction team developed a barge-shore transfer procedure to safely transfer materials and equipment to site.

After completing the subsurface investigation, a BAUER BG36 (BG36) CSM Drill Rig was brought to site to install the initial field trial panels, transitioning into production panel installation directly afterwards. The BG36 was followed by a RG25S and a RG19T CSM rig; all three rigs were equipped with a BCM10 CSM attachment. (*Image 8,9 and 10)* The BCM10 CSM attachment consists of a 2.8 m by 1 m cutting cutter head containing two rotary CSM cutter wheels. Each wheel has the ability to hold up to 26 cutter teeth. (*Image 11)* To maintain production rates, two rigs operated simultaneously; each rig operated for 36 consecutive hours, followed by a 12 hour maintenance break. Wear and tear on rigs (particularly on the cutter head) was strongly influenced by geotechnical conditions across the site.

After the initial mobilization of equipment and facilities had been received onsite, the main logistical challenge consisted of providing sufficient cement to continue the construction process. The barge could carry approximately 160,000 kg of cement (in bulk bags) in good weather conditions; a crane transferred the cement to shore. (*Image 12)* At peak production rates, the construction process consumed over 150,000 kg of cement in a single 24-hour period. With limited storage capacity, onsite supervision had to carefully balance the site's equipment and material requirements with the weather, tide-schedule, freeboard of the barge, and the safety of the vessel and crew. The final 1,645 CSM panels were constructed over a period of 15 months, at times utilizing a 24 hour per day, 7 days per week schedule. During this period some 32,500 tonnes of cement were supplied and processed.

Environmental, Economic and Social Sustainability and Aesthetics

The Kitimat LNG Facility Deep Soil Mixing project was the first step in the much larger project of building a multi-billion dollar facility for natural gas export. A key component to the British Columbia Economic Action Plan, the development of LNG on the North Coast of BC has benefited both the local and provincial economies.

The project site is located in an area of environmental sensitivity, and construction works were conducted in close proximity to fragile marine areas. A comprehensive Environmental Protection Plan (EPP) was prepared by Golders' construction division to assist with meeting the environmental responsibilities during construction. The EPP identified activities and equipment-specific environmental impact avoidance or mitigation measures, and outlined applicable site planning, construction practices, and environmental management. Throughout the construction project, an Environmental Professional was on site during all construction works at times a 24/7 operation.

Whenever possible members from the local community were employed as construction operations support staff, offering marine transport, earthworks and storage facilities in addition to providing local accommodation for construction crews of up to 70 people during the 15 months of site works.

Image 1: **Birds Eye Satellite View**
Left Image: A distant view of the deep mixing zone, highlighted in blue, between Bish Cove and the Coastal Mountain Range. ***Right image***: Close up view of R1 and R2 layout adjacent to Bish Cove. (Google Earth, 2007)

Image 2: Cement slurry mixing with in-situ materials

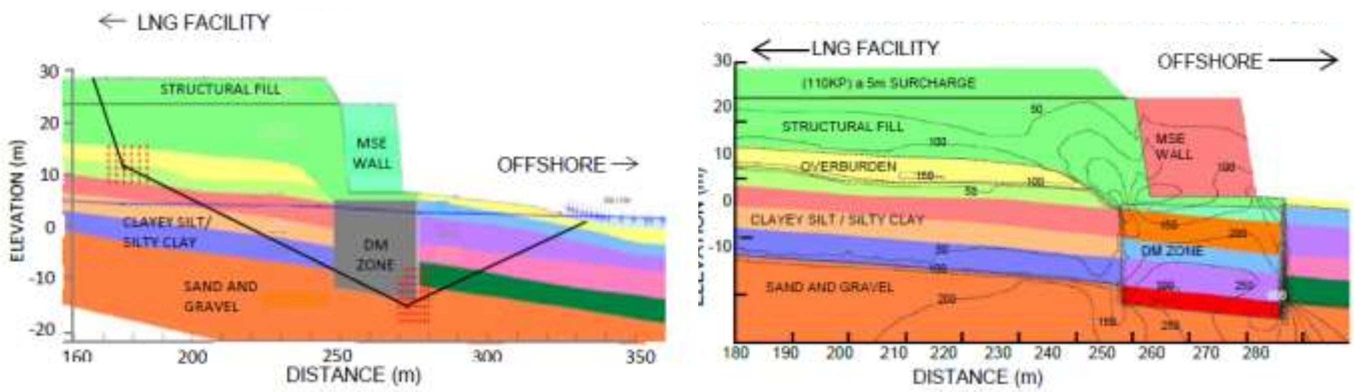


Image 3: Global Stability Analysis

Stability and Strengths Analysis for Deep Soil Mixing ground improvement zone. Showing foundation support for the planned 20 m high MSE Wall and structural fill placement for the LNG facility.

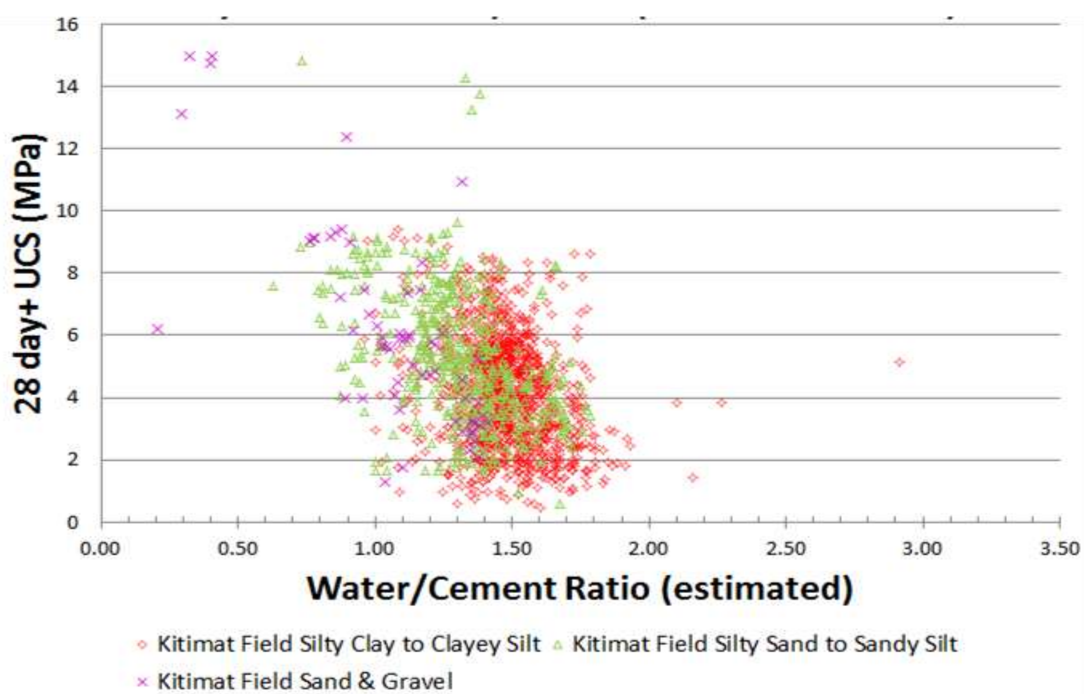


Image 4: 28 Day+ UCS versus estimated W/C Ratio for field sampled soil cement specimens

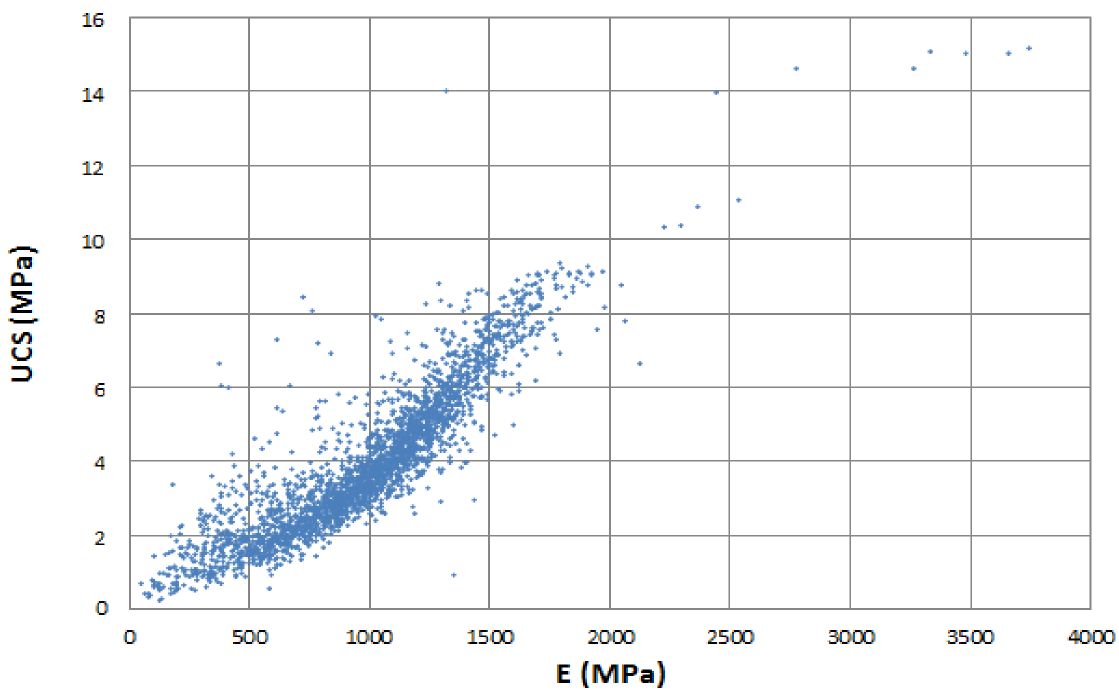


Image 5: Unconfined Compressive Strength versus Elastic Modulus

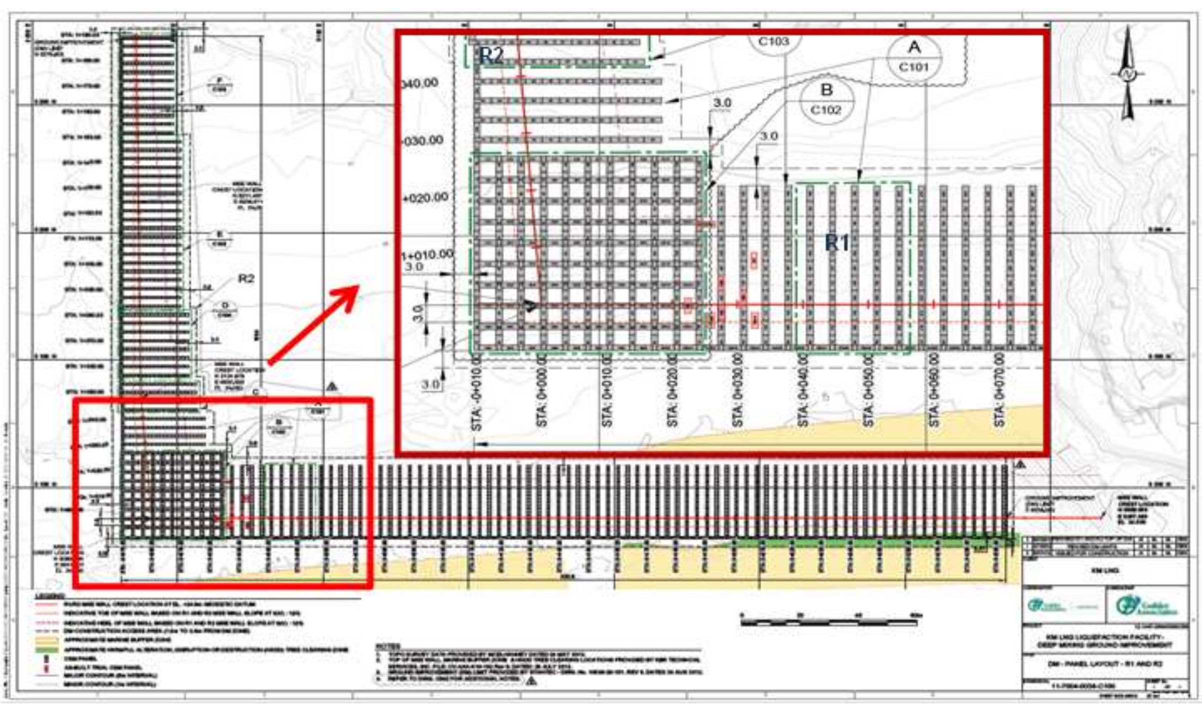
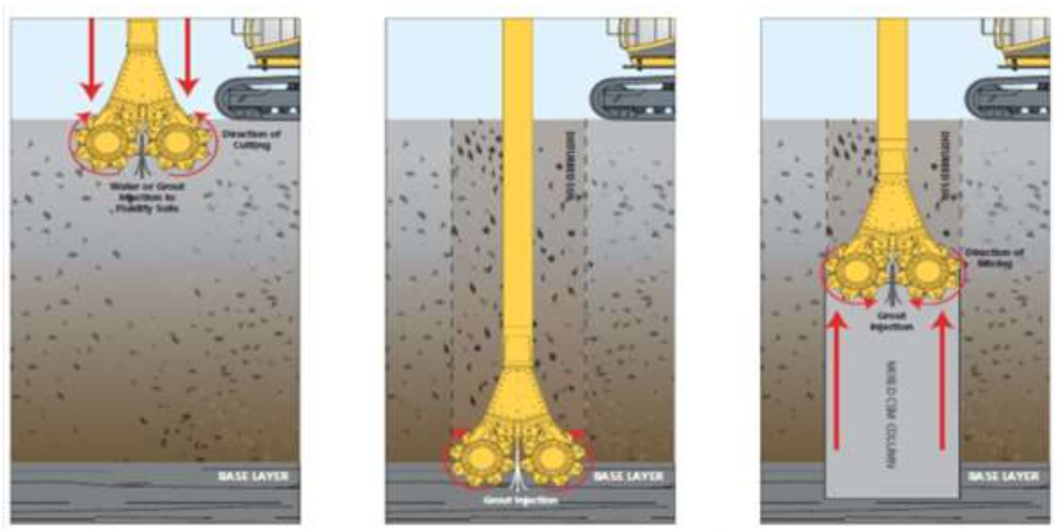


Image 6: Overview of the foundation design showing all 1645 panels in Barrettes



1. CUTTING PHASE 2. SOCKETING INTO BASE LAYER 3. WITHDRAWAL AND MIXING PHASE

Image 7: Schematic of the Cutting Wheels at work.

Image 8: BG36 and RG25 in operation, with Bish Cove in backdrop

Image 9: BG36 cutter head exiting completed panel

Image 10: Connecting BCM10 Cutter head to BG36 drill rig at start of project

Image 11: BCM10 cutter head mixing wheels fitted with TungStud cutting teeth

Image 12: Cement bulk bags off-loaded and awaiting transport to cement slurry mixing station