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Pipeline Integrity Management for Ground Movement Hazards

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Project Background

Land use policies increasingly prevent pipelines from obtaining right-of-way for pipeline corridors that avoid ground movement hazards. Where ground displacement hazards cannot be avoided, the potential risks must be managed by suitable combination of design and operational strategies.

Objectives: Develop a comprehensive set of guidelines and recommended practices, in a format that can be implemented within the industry, for evaluating pipelines in areas subjected to large-scale ground movements.

Technical Approach: The Pipeline Research Council International, Inc. (PRCI), in concert with a research team drawn from C-CORE, D. G. Honegger Consulting (DGHC), SSD, Inc. (SSD), the USGS, PRCI industry sponsors that includes the Southern California Gas Company, TransCanada, El Paso, Marathon Pipelines, Williams Gas Pipeline, and Gaz de France, and the California Energy Commission are assessing and recommending current landslide risk management methods and practices for use within the pipeline industry. In addition, research activities are being carried out to address known deficiencies in current techniques for assessing pipeline response to large ground displacements. These guidelines will be made available from the PRCI publications web site at no charge. PRCI is supporting regular updates to the guidance document as necessary to incorporate future technological developments.

The broad technical tasks involved in the study include:

- definition of large ground displacement hazards,
- development of pipeline/soil interaction models,
- improved pipeline response modeling,
- utilization of pipeline geometry monitoring to assess pipeline condition and,
- options to mitigate risks of large ground displacement.

The result of this work will be a concise set of unified guidelines that can be readily implemented within the pipeline industry and serve as a basis for demonstrating that reasonable measures have been taken to address potential risks from large ground displacements.

Technical Status

Activities undertaken through the third quarter focused on the following tasks:

Task 1: Definition of Large Ground Displacement Hazards

Task 2: Improved Pipeline-Soil Interaction Models

Task 4: Us of Pipeline Geometry Monitoring to Assess Pipeline Condition

A summary of the technical status and results or conclusions to date are presented below for each of these tasks. Other project tasks are not scheduled to have significant activity until the fourth or fifth quarter of the project.

Task 1: Definition of Large Ground Displacement Hazards

Technical Status

The U.S. Geological Survey (USGS) is preparing a summary of the state-of-practice for defining ground displacement hazards related to slope movement and subsidence under the terms of a Cooperative Research and Development Agreement (CRADA) with D.G. Honegger Consulting. Topic areas related to slope stability that are being addressed by USGS include the following:

- GIS-based deterministic and probabilistic methods for estimating deep-seated landslide risk
- Field investigation methods
- Limit-equilibrium stability methods
- Numerical methods (e.g., finite element) for analyzing slope stability and ground displacement patterns
- Monitoring and instrumentation
- Testing methods for physical properties

At this point, background research is approximately 45% complete and a report summarizing the results of this research is about 20% complete. Other activities related to slope stability hazard definition are awaiting completion of an initial draft by USGS.

Potential contributors to a similar effort for ground subsidence hazards were identified by USGS this quarter. At this time, a portion of the CRADA funds are expected to be made available to USGS researchers at field offices in Tuscon, AZ and Sacramento, CA to prepare a summary of the state-of-practice with respect to the definition of ground subsidence from underground fluid withdrawal. The general topic areas to be addressed in the subsidence summary will be similar to those for landslide hazards.

Results and Conclusions

At this stage of the project, there are no results or conclusions to report.

Task 2: Improved Pipeline-Soil Interaction Models

Technical Status

Efforts on Task 2 were initiated at the start of the third quarter (current milestone period) and focused on the analytical development of a methodology to assess pipeline axial and bending strains from information available from an internal geometry pig. The development of the analytical methodology is described in Attachment A.

Results and Conclusions

Task 2.1: Engineering Practice for Pipeline/Soil Interaction Analysis

This subtask is complete. The review of engineering practice presented in PRCI report PR-271-0184 "Extended model for pipe soil interaction" EPSI (Catalog Number L51990) has been brought up to date. The associated report sections are now being finalised. The review has included the recent PRCI (2004) Seismic Design Guidelines and those of the American Lifeline Association (2001). Recommendations for improvements to these guidelines include the conclusions of the PRCI EPSI study, the findings of PRCI study PR268 "Pipe-soil friction reduction methods using geotextile fabrics" and recent publications in the last 5 years in the PSI area. Issues raised by the review include the effect of soil and pipe weight in assessing the soil resistance to pipe movement, the selection of appropriate system stiffness during the pipe soil interaction, the interaction rate, and the possible reduction in resistance after failure. Particular emphasis is placed on reviewing combined load effects such as that of Dr Hsu, Figure 1. These combined effects will be compared to the findings of the other Task 2 activities.

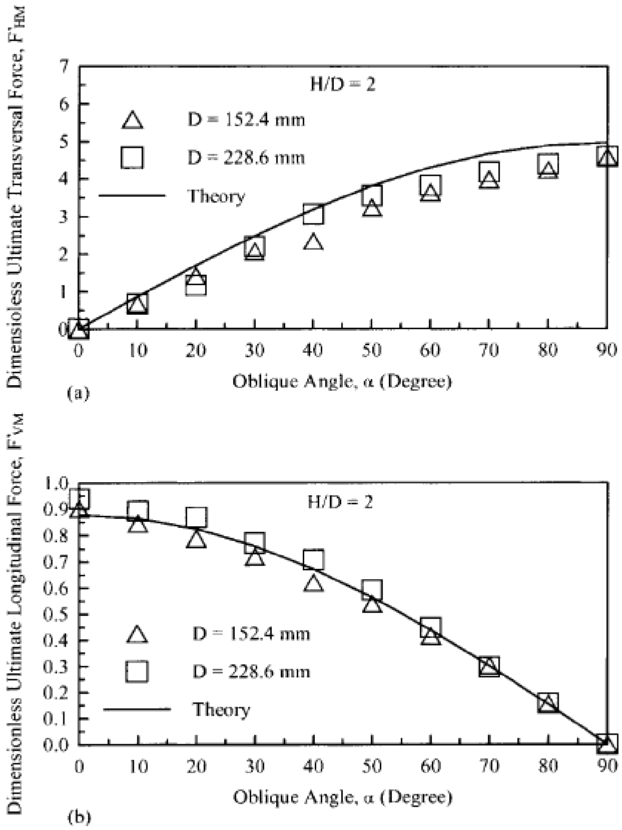

Figure 1 – Combined axial and lateral force interaction factors for loose sand, after Hsu et al (2001)

Task 2.2: Preliminary Analysis of Oblique Pipeline/Soil Interaction (Sand)

Current engineering guidelines for pipe soil interaction mostly estimate soil resistance due to simple load cases such as purely axial and purely lateral pipe movements. In this completed subtask, a numerical analysis on the effects of oblique pipe movement (Fig. 2, where α = oblique angle) in sand developed. The preliminary study considered a single rigid pipe buried in sand with a diameter of 0.328m and a burial depth of 0.936m as illustrated in Fig. 3a.

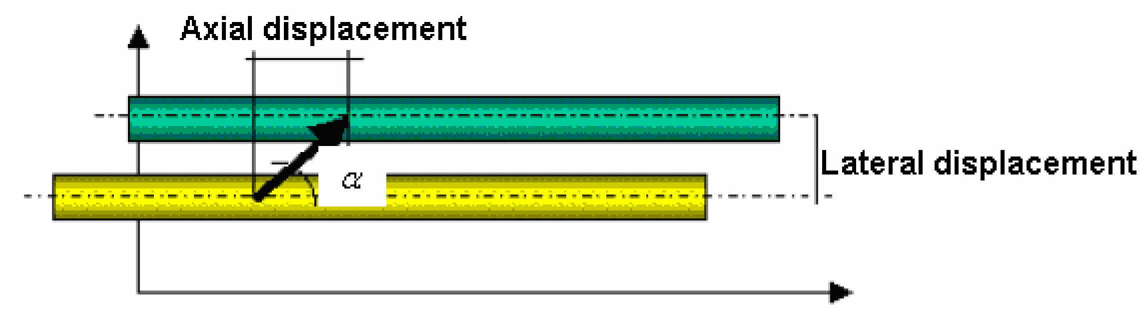

Figure. 2 Buried pipeline subjected to oblique movement.

The numerical model used is the finite element (FE) code ABAQUS/STANDARD. Fig. 3b shows the FE model used in this study.

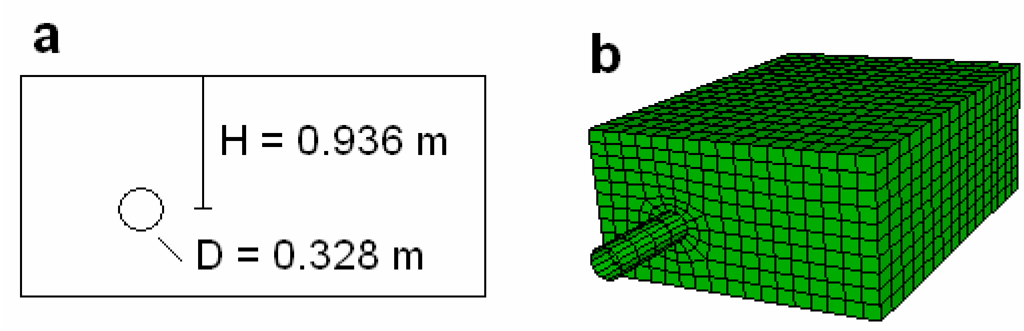

Fig. 3 a) Layout of the buried pipe, and b) FE model.

The numerical procedures were developed from those used for analysis of oblique interaction in clay for the PRCI EPSI study. The soils loads are evaluated from the uniform stress conditions acting around the pipe midsection.

Some results are presented below under Task 2.4.

Task 2.3: Centrifuge Modelling of Oblique Pipeline/Soil Interaction (Sand)

The results of the finite element analyses will be calibrated against data from reduced scale physical model tests conducted in a geotechnical centrifuge. The centrifuge environment subjects the physical model to the appropriate stress levels required to obtain similar behavior to that expected under full scale conditions.

A fine dry silica sand will be used in the model tests at 80% relative density. One testbed will be prepared containing 4 or more buried pipe sections, similar to that shown in Figure 4. A 20” diameter steel pipe will be modeled at 1/12.32 scale using a 1 5/8” C-1026 cold drawn seamless tube. A new servo controlled load actuator will be used to translate each buried pipe section through the sand bed. The interfaces between the actuator and the buried pipe and the strongbox, as depicted in Figure 5 are now being completed. The pipe loads and displacements will be measured. The pipes will be allowed to move vertically. There was a problem with the original load cells designed and built for this study. The load cells have been redesigned and machining will commence soon. The delay in signing contract also delayed material procurement, causing the initial 3 months slip in schedule.

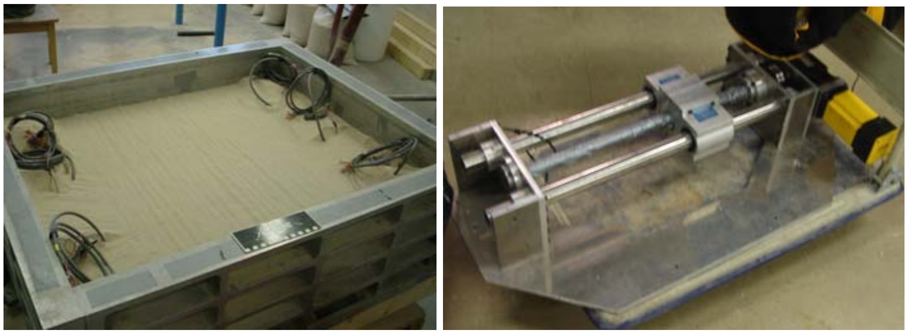

Fig. 4 a) Typical centrifuge model test bed with buried pipe sections and b) pipe load actuator (inverted)

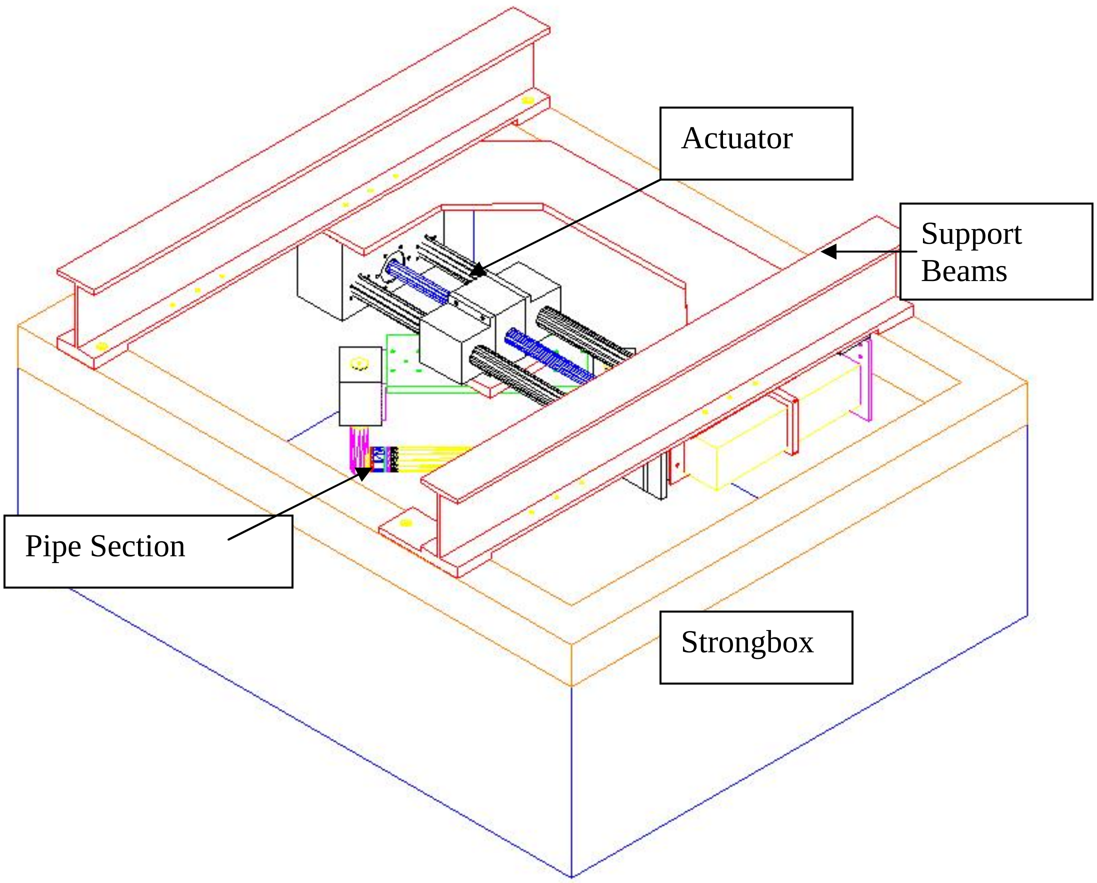

Fig. 5 Pipe loading actuator overview

Task 2.4: Parametric Analysis of Oblique Pipeline/Soil Interaction (Sand)

The analysis developed under Task 2.2 has been used to commence a parametric study. This study will be calibrated against the physical model test data as the results of Task 2.3 become available. The constitutive model used in this study so far is the Mohr-Coulomb model. The constitutive parameters considered include those listed in Table 1 for which associated results are presented below.

Table 1 Assumed constitutive parameters

Sand	E (MPa)	ν	ϕ	c (kPa)	ψ	f	γ (kN/m^3)
Dense	8	0.4	46^o	2	10^o	0.5	17.2
Loose	3	0.3	33^o	2	0	0.38	15.2

E = sand modulus of elasticity, ν = Poisson's ratio, ϕ = soil friction angle, c = soil cohesion, ψ = dilation angle, f = coefficient of the pipe-soil interface friction, and γ = specific weight.

The analyses first considered a monotonic displacement to 1 pipe diameter at the prescribed oblique load angle, Figure 2, of 0, 5, 15, 30, 45, 60, 75 or 90 degrees. The resulting dimensionless axial and lateral forces are shown in Figures 6a and 6b. The corresponding force interaction diagram, Figure 6c, shows two failure modes: For low oblique angles upto 15 degrees, failure is governed by slip along the pipe soil interface. For higher oblique angles up to purely lateral loading, failure occurs through the soil mass. A similar observation was made for oblique loading in clay in the PRCI EPSI study.

Additional analyses identified any further axial resistance that could be mobilized at the higher interaction angles. The load case included two steps: (1) an oblique pipe movement equal to 25% of the pipe diameter (0 to 100% of analysis) followed by (2) an axial pipe movement up to 100% of its diameter (100% to 200% of analysis), Figure 7..

Additional axial resistance was found for interaction angles greater than 45 degrees by comparing say resistances at 90 and 150% displacements. The mobilized lateral resistance decreases, as expected, between these 2 levels. The ratio of axial to lateral resistance around the 150% level is consistent with the coefficient of the pipe-soil interface friction. This indicates a change in failure mechanism to slip along the pipe soil interface. Similar observations were made for loose sand conditions. These observations of the normal soil forces on the pipe controlling its axial (shear) resistance are not however consistent with that observed by Dr Hsu in both dense and loose sands, eg Figure 1. This difference will be investigated as the study continues.

These observations will be considered in Task 3 to improve the structural "beam-spring" type modeling of pipeline soil systems. There is apparent merit in replacing the axial soil spring by a frictional slider controlled by the normal pressure imposed by the lateral and vertical soil springs.

The parametric study has also included the effects of cohesion and alternative mesh discretisations. Further parametric studies will consider the effects of initial pore suction and alternative geometries.

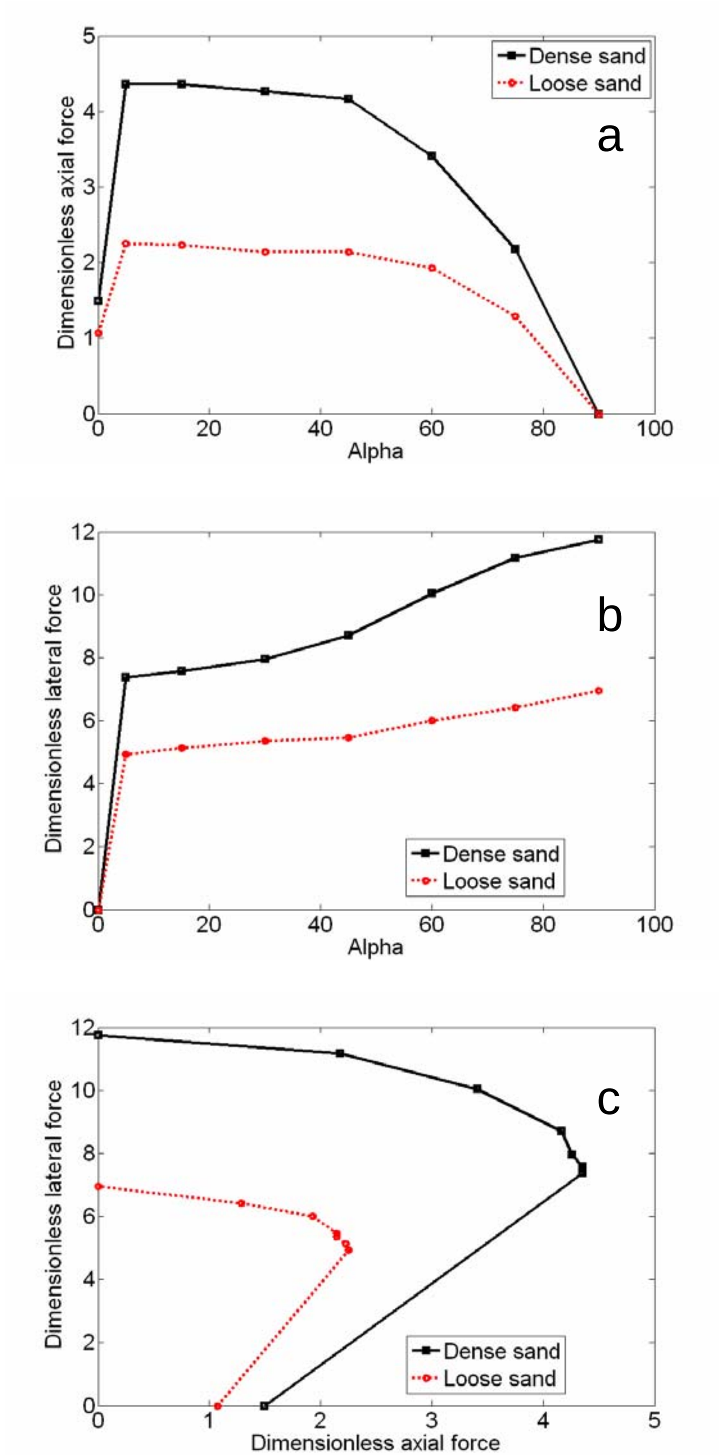

Fig. 6 The predicted (a) dimensionless axial soil resistance, (b) dimensionless lateral soil resistance in dense and loose sands for different oblique angles, and (c) interaction diagrams.

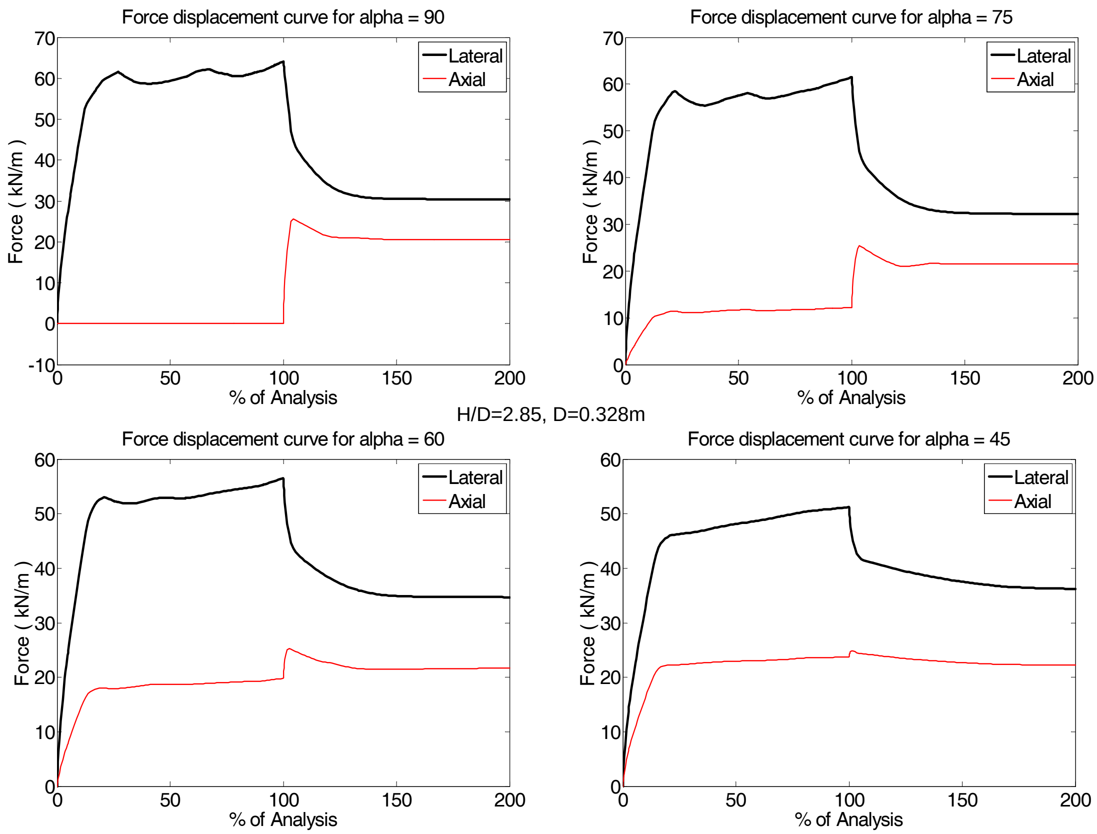

Fig. 7 Force-displacement curves at different oblique angles obtained for dense sand subjected to the two-step loading case.

Task 4: Us of Pipeline Geometry Monitoring to Assess Pipeline Condition

Technical Status

A method for deducing the strain induced in laterally displaced pipelines from geometry pig measurements has been developed.

Results and Conclusions

A detailed discussion of the method developed for deducing strain induced in laterally displaced pipelines from geometry pig measurements can be provided at the request of the project team.

Business Status

Tasks 2 and 3 are mainly funded (58%) by the Canadian federal governments Atlantic Canada Opportunities Agency (ACOA) through C-CORE: The "Risk Mitigation Strategies for Subsea Infrastructure" program will assist in protecting subsea infrastructure through better management of ice hazards. Through this program, C-CORE will work with several partners to build on the Atlantic Canada region's existing expertise in ice hazards management. It will develop world-class capability for the provision of commercial engineering services. It will also facilitate design recommendations to address the protection of, and risk mitigation strategies for, subsea infrastructure in ice environments. With a total cost of more than $7.6 million, this program will receive up to $3 million from the Atlantic Innovation Fund over three years.

The program is divided into two Joint Industry Projects: PIRAM & SIRAM led by C-CORE. The kick off meeting for both projects, especially the Pipeline Ice Risk Assessment & Mitigation project, was held on March 5 and 6 in St John's Newfoundland. Some of the initial findings of this DOT sponsored study were presented to the potential industry participants in the PIRAM JIP, including Chevron, ConocoPhillips, ExxonMobil, Husky Oil, Norsk Hydro, PetroCanada and Statoil. The DOT study will feed into the appropriate analysis of submarine pipelines subjected to large ground movement caused by gouging ice keels, such as icebergs and pressure ridges.

Plans for Future Activity

Activities for Tasks 1, 2, and 4 will continue in the next quarter (milestone period). In addition, work will initiate on Task 3, Improved Pipeline Response Modeling. Planned activities for these four tasks are presented below.

Task 1: Definition of Large Ground Displacement Hazards

Technical Progress

A 75% to 85% complete draft on the state-of-practice for defining slope movement hazards is expected from USGS by the end of March. This preliminary draft will be reviewed with the intent of identifying areas requiring additional clarification and "gaps" in the topic area coverage. The final draft report from USGS is expected to be completed by the end of April.

It is expected that the scope and budget for USGS researchers identified to support the summary of the state-of-practice for defining subsidence hazards will be finalized by the end of March. The target date for completing the subsidence report is the middle to end of May. This will allow time for the USGS to respond to review comments.

Information in the reports provided by USGS will be used as resource material to develop a draft guideline document on defining slope stability and subsidence hazards suitable for end-user application. This draft guideline is scheduled to be completed by the end of the next quarter and distributed, along with the USGS reports, to three project team reviewers.

Meeting and Presentations

The project team will participate and present as part of the DOT PHMSA 2007 Peer Review.

Task 2: Improved Pipeline-Soil Interaction Models

Technical Progress

A method for deducing the strain induced in laterally displaced pipelines from geometry pig measurements has been developed. In the next quarter the viability and the efficacy of this method will be evaluated.

The planned activities for next two months include:

- Task 2.3: Centrifuge Modelling of Oblique Pipeline/Soil Interaction (Sand)
  - Conduct centrifuge experiments in sand (frictional) test bed. This activity was delayed due to load cell issues previously described, but should be completed on schedule.
- Task 2.4: Parametric Analysis of Oblique Pipeline/Soil Interaction (Sand)

- These analyses will be calibrated and completed as the results of Task 2,3 are available.

- Task 2.5: Centrifuge Modelling of Oblique Pipeline/Soil Interaction (Clay)
  - These tests will commence on the completion of Task 2.3.
- Task 2.6: Calibrate numerical models (clay) and conduct parametric study
  - Preliminary analyses have commenced. Parametric analyses will be undertaken.

Meeting and Presentations

The project team will participate and present as part of the DOT PHMSA 2007 Peer Review.

Tests and Demonstrations

Tests are planned as outlined under Tasks 2.3 and 2.5 above.

Task 3: Improved Pipeline Response Modeling

Technical Progress

- Task 3.1:Evaluate alternative soil formulations and Task 3.2:Evaluate alternative pipeline formulations
  - These are most likely to commence in the month 3 of the new quarter.

Meeting and Presentations

The project team will participate and present as part of the DOT PHMSA 2007 Peer Review.

Task 4: Us of Pipeline Geometry Monitoring to Assess Pipeline Condition

Technical Progress

The viability and the efficacy of the method for deducing the strain induced in laterally displaced pipelines from geometry pig measurements will be evaluated.

Meeting and Presentations

The project team will participate and present as part of the DOT PHMSA 2007 Peer Review.