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PRCI Project Ref: ENV-1

QUARTERLY PUBLIC REPORT

Pipeline Integrity Management for Ground Movement Hazards

Date of Report:	June 15, 2007
Contract No:	DTPH56-06-000015
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For Period Ending:	June 15, 2007

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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 fourth quarter focused on the following tasks:

Task 1: Definition of Large Ground Displacement Hazards
Task 2: Improved Pipeline-Soil Interaction Models
Task 3: Improved Pipeline Response Modeling
Task 4: Use 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.

Task 1: Definition of Large Ground Displacement Hazards

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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 (DGHC). 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

USGS delivered summary reports on landslide hazard definition this quarter. These reports are being reviewed by topic area experts on the DGHC team in preparation for a review meeting with USGS on July 12 and 13, 2007 at the USGS offices in Golden, CO. This meeting was originally scheduled to occur this quarter but needed to be postponed to accommodate prior commitments by the various participants.

A similar USGS effort related to quantifying ground subsidence hazards was initiated this quarter and has been completed. The draft report on subsidence hazards will be distributed for review and review comments will be addressed at the July 12 and 13, 2007 meeting at the USGS offices. The USGS landslide hazard report has focused on characterizing the pros and cons of available methods of hazard identification and hazard modeling with particular attention to newer technologies. Some of these technologies appear quite promising. For example, Figure 1 illustrates the level of detail that can be obtained in identifying slide geometry with laser scanning techniques.

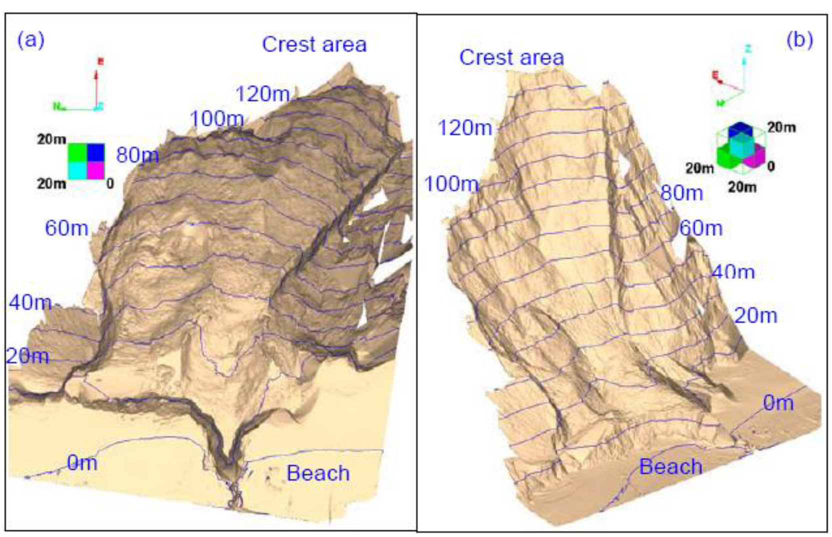

Figure 1: Example images of landslide area obtained by laser scanning (A), shaded relief and contour map, plan view, (B) oblique view

Results and Conclusions

The USGS summary notes that reliability in modeling landslides is challenging. Quantifying the likelihood and severity of a slide hazard is a key requirement of formal reliability based design approaches that some in the industry are actively promoting. Substantial uncertainty remains in any numerical model results and the input data are usually sources of much greater uncertainty than the method of computation. Most probabilistic analyses lack the necessary data to compute an actual annual probability of failure; rather they provide a measure of the uncertainty in the input data and the computed factor of safety or displacement.

Understanding the expected reliability associated with estimating the likelihood and severity of ground displacement hazard is critical to formulating recommendations on appropriate mitigation measures, particularly those measures that rely on incorporating design features to allow the pipe to accommodate a specific amount of ground displacement.

The issue of reliable estimates of likelihood and severity will be a main focus of refinements to the draft documents provided by USGS.

Task 2: Improved Pipeline-Soil Interaction Models

Technical Status

Progress on Task 2 continued this quarter and focused on subtasks 2.3, 2.4, 2.5, and 2.6.

Results and Conclusions

- Task 2.3: Centrifuge Modeling of Oblique Pipeline/Soil Interaction (Clay)

Preliminary preparations have been made for these tests, which will commence in earnest on the completion of Task 2.3. The clay bed for these tests will be consolidated from a silty clay slurry over the next month.

- Task 2.4: Calibrate numerical models (clay) and conduct parametric study

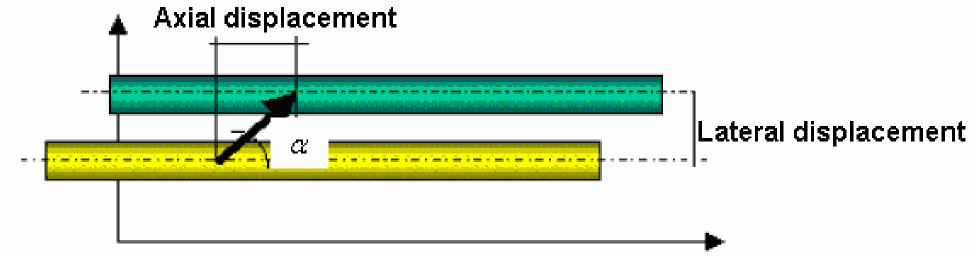

Figure 2 - Buried pipeline subject to oblique movement.

Analyses similar to those reported last quarter under Task 2.6 are progressing, except for cohesive (clay) rather than frictional (sand) soils. Examples of some of the results are shown in Figure 3 for two different burial depths, and for a range of oblique loading angles, α as defined in Figure 2.

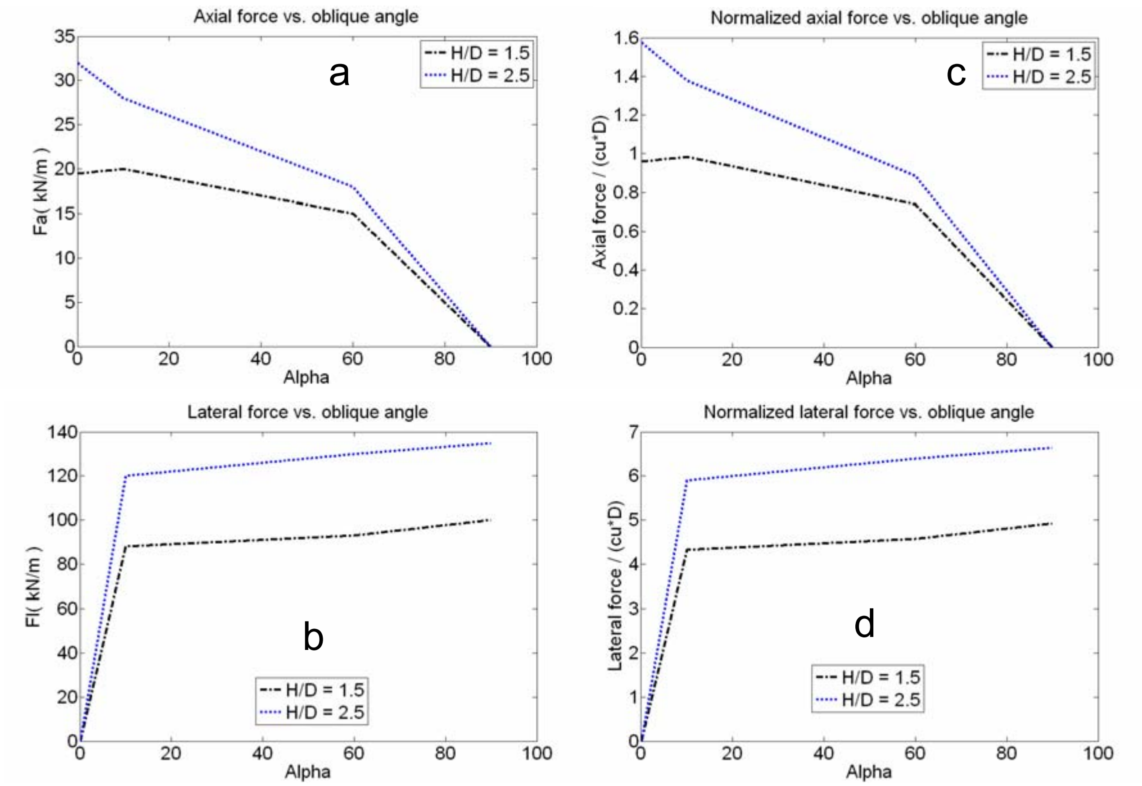

Figure 3 - Interaction forces in clay for H/D =1.5 and H/D = 2.5: (a) Axial force vs. oblique angle, and (b) lateral force vs. oblique angle. Figs. 3c to 3d represent dimensionless forces corresponding to Figs. 3a to 3b.

- Task 2.5: Centrifuge Modeling 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.

Fine dry silica sand is being used in the model tests at 80% relative density. One test-bed has been prepared to contain 4 or more buried pipe sections. A 20” diameter steel pipe is modeled at 1/12.32 scale using a 1 5/8” C-1026 cold drawn seamless tube.

The load cells have been redesigned, built and calibrated. The delay in signing the contract also delayed material procurement, causing the initial 3 months slip in schedule. The new servo controlled load actuator has been used to translate a buried pipe section through the sand bed. The data from the first test is being processed. The pipe loads and displacements were measured. Three more tests will be conducted over the next few weeks in the sand bed.

- Task 2.6: Parametric Analysis of Oblique Pipeline/Soil Interaction (Sand)

Progress on this task was reported in the last quarterly report. This task is currently on hold waiting for the physical model tests results against which the analyses will be calibrated.

Task 3: Improved Pipeline Response Modeling

Technical Status
Efforts have begun on Task 3 looking at alternative soil and pipeline formulations.

Results and Conclusions

- Task 3.1: Evaluate alternative soil formulations

The software interface to the Abaqus finite element program has been developed using Fortran subroutines. Preliminary ‘simple’ soil formulations have been coded. Initial analyses are now being conducted on single pipe elements to test the new interface and the Fortran code. These analyses will become progressively more complex as preceding simpler tests are completed satisfactorily.

- Task 3.2: Evaluate alternative pipeline formulations

Options for alternative pipeline formulations within the element suite provided within the Abaqus software are being identified. A series of shell elements in place of a single Pipe31 element is certainly a candidate for an alternative formulation. Shell elements will provide the ability to simulate more localized behavior, such as local buckling, within the pipeline discretisation.

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

Technical Status
An algorithm for deducing the longitudinal strain in a displaced pipeline from curvature measurements that might be established from geometry pig measurements has been developed. The efficacy of the algorithm was tested by comparing the strains deduced from surrogate curvature measurements provided by PIPLIN with the strains calculated directly with PIPLIN for vertical subsidence and right lateral fault crossing displacement scenarios, the latter representing a more severe test of the algorithm. In general, the comparisons are considered very favorable and appear to improve with increasing deformation. The algorithm provided a conservative (over) estimate for the maximum tensile strain which has the more ominous impact on the structural integrity of the displaced pipeline. While Eq. (4.3) is based upon first principles, more favorable agreement could be attained, if deemed necessary, by calibrating this equation; e.g., multiplying the second term of the equation by an appropriate calibration factor. Nevertheless, the very favorable comparisons and the simplicity of the algorithm attest to its potential usefulness for estimating the total longitudinal strains in a displaced pipeline from ILI data.

Results and Conclusions

Axial Strain Development

Central to the development of a method for estimating the axial and flexural strains is the measurement; e.g., as might be accomplished with a geometry-pig, of the variation of the *X-Y-Z* coordinates, pitch, or curvature of the displaced pipeline as function of position along the pipeline. In this development the displacement of the pipeline is assumed to be confined to a plane; e.g., the *X-Y* plane. The pipeline is considered to be initially straight or if it is not, the initial strains produced by any deviation from the straight configuration are taken to be much smaller than those induced by the subsequent pipeline displacement.

The most highly strained fibers in the pipe's cross section are the ones furthest from the neutral axis and whose total longitudinal or axial strain ε can be expressed as

$$\varepsilon = \varepsilon_e \pm \varepsilon_f \tag{4.1}$$

where ε_e is the extensional strain and ε_f is the maximum flexural strain given by

$$\varepsilon_f = D|K|/2; \tag{4.2}$$

in which D is the pipe diameter and K is the change in curvature of the pipeline. Since the curvature is assumed to be measured directly or derivable from geometry pig data, the development of an estimate for the longitudinal strain rests with the determination of an effective means for evaluating the extensional strain from ILI data.

If the loading in the region of the laterally displaced pipeline is predominately transverse; i.e., the work done by the axial frictional forces in this region is negligible compared to the work done by the transverse loading, it can be readily shown via the principle of virtual work that the axial load in this region is a constant. Assuming that plane cross sections remain plane during the lateral displacement, that the lateral displacement is sufficient to produce moderate plastic strains; e.g., on the order of a few percent, and that the pipe material can be modeled as an elastic-perfectly plastic material, it can be shown that to first order the axial strain can be simply expressed as

$$\varepsilon_e = D|K|/\pi + c \tag{4.3}$$

The constant of integration c is determined such that ε_e equals the measured extensional strain in the straight length of the pipe joint immediately adjacent to the displaced region of the pipeline; e.g., by measuring the change in length from the known initial pipe joint length.

It is clear from Eqs. (4.1) through (4.3) that an estimate for the longitudinal strain depends upon the measurement of the curvature of the displaced pipe; e.g., via a geometry or curvature pig. The deduction of the longitudinal strain from curvature measurement using these equations provides an estimate for the strain demand that can be compared with the strain capacity to facilitate a rational basis for whether or not remedial action is necessary.

PIPLIN Buried Pipe Deformation Analyses

A series of buried pipeline deformation analyses is being undertaken to support the effort to establish the axial extensional strain in a pipeline from measurements of its displaced geometry. The purpose of these analyses is to provide a rational basis for validating/benchmarking and evaluating the efficacy of the extensional strain estimate in Eq. (4.3). The analyses are performed using the PIPLIN [1] computer program, which is a special-purpose program developed for deformation analysis of buried pipeline systems. The program considers several nonlinear aspects of pipeline behavior, including pipe steel plasticity, large-displacement effects, and nonlinear soil support.

To date, pipe-soil interaction analyses have been carried out for two different permanent ground displacement (PGD) scenarios: vertical subsidence over abrupt block settlement profiles and right lateral movement at a pipeline-fault crossing with a crossing angle of 90 degrees. The analysis cases consider a 16-inch diameter by 0.375-inch thick X60 gas pipeline with an internal pressure of 725 psi. The pipeline has a uniform cover depth of 6 feet in a cohesionless sand material with an in-situ density of 120 pcf and a soil friction angle of 35^{o}. The pipe is assumed to have a coal tar external coating. Bilinear (elastic-perfectly plastic) pipe-soil springs were developed for the models based on industry standard procedures (e.g., see References [2] and [3]). An isotropic X60 pipe steel stress-strain relationship is assumed. Pipe plasticity effects are considered for biaxial stress conditions using the von Mises yield criterion with multi-linear kinematic hardening [4]. The pipeline model mesh is refined to provide a grid of 1-foot long pipe elements that extend well beyond the region where significant bending deformation and transverse pipe-soil spring engagement occurs.

In each analysis the pipeline is first pressurized to 725 psi and then subjected to the PGD profile which is imposed through the base of the pipe-soil springs using PIPLIN's settlement profile option. In all cases, the results are verified to make sure that the length of the model boundary sections extend beyond the location of the longitudinal virtual anchor. The ground movement profile is imposed in small steps and the nonlinear solution is established using an event-to-event solution strategy for obtaining the resulting pipe-soil deformation state at selected levels of imposed displacement. The pipe state includes the along-the-pipe distribution of pipe axial force, bending moment, curvature, compression and tension stresses and strains, as well as the forces and deformations in the pipe-soil springs. For the purposes of these "pilot studies," the key results are the extreme fiber total axial strains, the pipeline curvature and the pipe centerline extensional strains.

For the vertical subsidence analysis case, the length of the settlement span was selected to be 100 feet. For this model, the output state was provided in Excel format for two different subsidence levels; namely; State A at 4 feet of subsidence and State B at 7 feet of subsidence. Note that at approximately 7 feet of imposed settlement, the pipeline "bridged" through the uplift pipe-soil springs such that additional settlement did not change the pipe state. For the right lateral fault crossing analysis case, the output state was also provided in Excel format for two levels of fault offset; specifically, State A at 6 feet of fault offset and State B at 9 feet of fault offset.

Evaluation of the Strain Algorithm

The evaluation of the efficacy of the above algorithm for deducing the axial strain distribution from curvature measurement used the PIPLIN analyses to provide realistic surrogate curvature measurements as might be provided by a geometry or curvature pig. These curvatures along with an estimate for the extensional strain in the pipe joint immediately adjacent to the region of displaced pipe serve as inputs to Eqs. (4.2) and (4.3) for estimating the flexural and extensional strains, respectively. The deduced strains are compared with those computed from PIPLIN to establish the efficacy of the algorithm.

References

[1] SSD, Inc., "*PIPLIN: Stress and Deformation Analysis of Pipelines*", Version 4.56, User Reference and Theoretical Manual, Reno, Nevada, May, 2007.

[2] American Lifelines Alliance, *"Guidelines for the Design of Buried Steel Pipe",* www.americanlifelinesalliance.org, July 2001.

[3] ASCE, "*Guidelines for the Seismic Design of Oil and Gas Pipeline Systems*", Committee on Gas and Liquid Fuel Lifelines, 1984.

[4] Mroz, Z., "*On the Description of Anisotropic Work-Hardening*", Journal of Mechanics, Physics and Solids, Vol. 15, pp. 163-175, 1967.

Plans for Future Activity

Activities for Tasks 1, 2, 3, and 4 will continue in the next quarter (milestone period). In addition, work will initiate on Task 5, Hazard Mitigation Strategies. Planned activities for these four tasks are presented below.

Task 1: Definition of Large Ground Displacement Hazards

Technical Progress
A review of the USGS draft on the state-of-practice for defining slope movement and subsidence hazards is underway and scheduled to be complete by the end of June. The focus of the review is to identify areas requiring additional clarification and "gaps" in the topic area coverage. These review comments will be the topic of a meeting in mid-July.

A revised draft of guidelines for identifying slope movement and subsidence hazards will be prepared and reviewed during the next quarter. In addition, efforts will begin to focus on preparing draft guidelines on mitigation measures (Task 5) during the next quarter.

Meeting and Presentations
A meeting is scheduled with the DGHC team members and USGS personnel at the USGS offices in Golden, CO on July 12 and 13. The goals of this meeting include the following:

- Review comments on USGS reports related to defining landslide and subsidence hazards for pipelines
- Identify topics and writing assignments to address comments

- Discuss criteria to be used in recommending the level of effort for hazard definition (e.g., higher safety, environmental, operational, and financial consequences of pipeline damage should).

Task 2: Improved Pipeline-Soil Interaction Models

Technical Progress
The planned activities for next two months include:

- Task 2.3: Centrifuge Modeling of Oblique Pipeline/Soil Interaction (Clay)
  - Complete centrifuge experiments in sand (frictional) test bed.
- Task 2.4: Parametric Analysis of Oblique Pipeline/Soil Interaction (Clay)
  - Conclude parametric analysis based on numerical procedures from Task 2.2 with calibration of modeling procedures
- Task 2.5: Centrifuge Modeling of Oblique Pipeline/Soil Interaction (Sand)
  - These tests will commence on the completion of Task 2.3.
- Task 2.6: Calibrate numerical models (Sand) and conduct parametric study
  - Complete preliminary analyses. Parametric analyses will be undertaken on completion of Task 2.5.

Meeting and Presentations

- No related meetings, conferences, or presentations are planned for upcoming quarter.

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
  - Continue developing more complex pipeline systems to initially rather simple soil formulations. The complexity of the formulation will be increased as required to capture the essence of the soil interaction.
- Task 3.2:Evaluate alternative pipeline formulations
  - Initial alternative pipeline formulations will be evaluated over the next 2 months.

Meeting and Presentations

- No related meetings, conferences, or presentations are planned for upcoming quarter.

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

Technical Progress

- Continue work on Excel implementation of extensional strain algorithm.
- Apply algorithm to additional benchmark test cases.
- Expect to complete Task 4.1 within next 30 days.
- Expect to initiate work on Task 4.2 within the next 30 days.

Task 5: Hazard Mitigation Strategies

Technical Progress

The following subtasks will be initiated during the next quarter:

- Task 5.1: Summarize current state-of-practice on mitigation through pipeline design
- Task 5.2: Summarize current state-of-practice on mitigation through geotechnical design
- Task 5.3: Summarize current state-of-practice on mitigation through operational measures
- Task 5.4: Prepare initial draft of recommendations on appropriate mitigation measures

Meeting and Presentations

No meetings or presentations planned.