PRCI Project Ref: ENV-1

QUARTERLY PUBLIC REPORT

Pipeline Integrity Management for Ground Movement Hazards

Date of Report: September 15, 2007

Contract No: DTPH56-06-000015

Prepared For: United States Department of Transportation
Pipeline and Hazardous Materials Safety Administration
Office of Pipeline Safety

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For Period Ending: September 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
Task 5: Hazard Mitigation Strategies

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

Technical Status

Work this quarter focused on Tasks 1.4, 1.5, and 1.6. Tasks 1.4 and 1.5 were completed this quarter.

Results and Conclusions

- Task 1.4: Assess current capabilities with needs for pipeline design

USGS delivered summary reports on landslide and subsidence hazard definition last quarter. These reports were reviewed by topic area experts on the DGHC team and were the subject of discussion at a meeting with USGS on July 12 and 13, 2007 at the USGS offices in Golden, CO. Some results from these discussions are as follows:

— Some site investigation methods (e.g., large boreholes to accommodate direct visual observation of subsurface soil conditions) were identified as impractical for pipeline applications
— Need for additional material on estimating subsidence induced by coal mining
— Clarification of resolution capabilities for remote sensing (aircraft and satellite)
— More specific conclusions and recommendations are needed related to the ability to quantify the amount of expected ground displacement
— More specific conclusions and recommendations are needed relate to the ability eliminate the potential for large rapid episodic slide displacements for slides that are observed to be undergoing creep
— Pipeline applications do not typically require detailed landslide morphological descriptors; key information is limited to the size of the area with a potential for movement and the direction and distribution of movement relative to the pipeline alignment
— Several areas were identified where reviewers agreed to provide additional information to USGS (e.g., correlating precipitation events with movement, use of remote sensing to identify potential for cavity collapse in karst terrain)

Comments on the USGS reports were assigned to one of two categories: issues that were within the USGS scope and would be addressed in revised drafts prepared by USGS and issues that were within the broader scope of DGHC tasks and would be addressed by the DGHC team.

- Task 1.5: Provide recommendations for determining hazard assessment approach

One of the key outcomes from the assessment of current capabilities in hazard definition was a preliminary list of guiding statements to be used in developing guidance on recommended practice.

- Task 1.6: Prepare second draft of recommended practice for hazard definition

Preparation of a second draft of recommended practices for hazard definition has been delayed pending receipt of revised USGS documents. In addition, substantial modification of the preliminary working version of the revised draft is necessary to incorporate the basic concepts from Task 1.5. Delivery of USGS documents is anticipated by the end of September which should permit a revised draft to be distributed for review by mid October.

A preliminary process diagram that lays out the design and assessment process for pipelines in landslide and subsidence hazard areas is provided in Figure 1.1. Most of the effort to date has been related to providing information necessary for the hazard definition (i.e., the steps before an assessment of potential pipeline vulnerability in Figure 1.1).

Figure 1.1: Preliminary Process for Design and Assessment of Pipelines in Landslide and Subsidence Hazard Areas

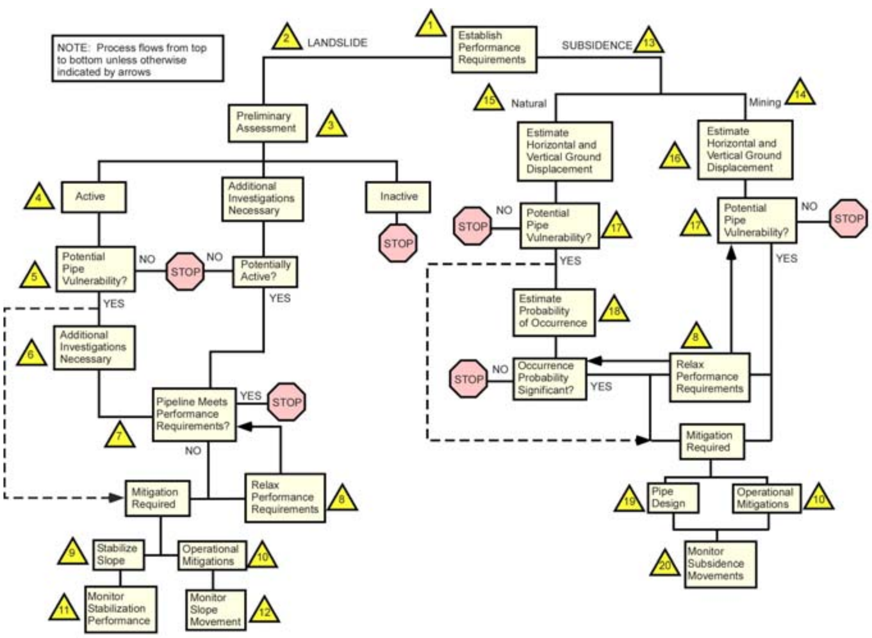


Table A: General Descriptors to Assess Annual Probability of Landslide Hazard

Description	Likelihood Over Design Life	Annual Probability			FS (± 0.075)	Activity State	Process Category
Frequent	Imminent	greater than 0.1	or	1 in 10	1	Active, reactivated, or historic; Main scarp sharp and unvegitated	Active
Probable	Expected	greater than 0.01	or	1 in 100	1.2		
Occasional	Possible	greater than 0.001	or	1 in 1,000	1.3	Dormant-young to mature: Main scarp sharp and partly vegetated to smooth and vegetated	Potentially Active
Remote	Unlikely	greater than 0.0001	or	1 in 10,000	1.35		
Improbable	Extremely Unlikely	greater than 0.00001	or	1 in 100,000	1.4	Dormant-old; Main scarp vaguely discernable	Inactive
Negligible	Not Possible	less than 0.00001	or	1 in more than 100,000	1.5		

No.	ADVISORY NOTES
1	The level of performance required is expected to be stated in terms of an acceptable annual likelihood of exceeding a particular outcome (e.g., loss of pressure integrity, local pipe wall wrinkling) and may involve multiple requirements (e.g., annual probability of 10% for pipe wall wrinkling and 0.1% for loss of pressure integrity). These requirements will depend upon various safety, economic, and operational factors and are typically pipeline specific.
2	"LANDSLIDE" is used as a general term to refer to any down-slope soil movement.
3	Preliminary assessments will primarily be based upon desk-top studies with the goal to identify the credibility of the landslide hazard and conservatively define the hazard for preliminary pipeline vulnerability assessment.
4	Examples of what constitutes active, potentially active, and inactive is provided in Table A.
5	The purpose of these pipeline assessments is to determine whether or not the severity of the hazard can be dismissed on the basis that it is not severe enough to cause unacceptable performance, assuming no limit on landslide displacement.
6	Additional investigations will focus on improving estimates of landslide likelihood (e.g., through comparisons with landslide inventories, perhaps correlated with slope stability estimates) and hazard severity (e.g. slide dimensions, depth)
7	Pipeline vulnerability relative to performance requirements is reassessed, assuming no limit on landslide displacement, considering refined likelihood and severity of landslide hazard.
8	In cases where desired performance requirements can not be met, some relaxation may be acceptable. For example, an initial goal of 0.1% annual chance of pipe damage might be relaxed to a goal of 1% annual chance of loss of pressure integrity.
9	Slope stabilization will generally consist of combinations of a) increasing internal resistance through drainage, b) reducing driving forces through grading, or c) providing additional external resistance through buttressing, retaining walls, or tie-backs.
10	Operational measures will generally consist of a) periodically alleviating pipe stresses through relocation or removal of backfill and/or b) providing means to minimize the consequences of pipe damage through containment and/or rapid shut-in of damaged pipe section.
11	Sufficient monitoring to confirm effectiveness of slope stabilization methods is required.
12	Operational mitigation measures require periodic, long-term slope monitoring.
13	"SUBSIDENCE" is used as a general term to refer to the formation of any surface depression.
14	"Mining" is used as a general term to refer to any removal of solid or liquid subsurface material (e.g., water, salt, coal, oil). All other forms of subsidence are considered "Natural".
15	Natural occurrences of subsidence (e.g., collapse in karst terrain) will generally be based upon observations of typical subsidence features in the region.
16	Mining subsidence will generally be based upon analytical models (typical for subsidence from coal mining) or historical measurements (typical for subsidence from ground water or oil withdrawal).
17	Pipe vulnerability will typically be assessed using analytical models that explicitly account for non-linear soil-pipeline interaction.
18	The probability of occurrence for natural subsidence events will typically be based upon observations of the variation in event occurrence over some historical record.
19	Pipe design changes can include increasing pipe wall thickness or material grade and reducing soil loading through pipeline coatings or specialized backfill specifications
20	Monitoring is required to identify the occurrence of natural subsidence events and confirm that subsidence related to mining is consistent with expectations.

Task 2: Improved Pipeline-Soil Interaction Models

Technical Status

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

Results and Conclusions

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

The clay bed for these tests is now being consolidated from a silty clay slurry. These 4 tests will be conducted within a month.

- Task 2.5: Centrifuge Modeling of Oblique Pipeline/Soil Interaction (Sand)

The four centrifuge model tests in sand have been completed following the procedures and techniques described in the previous quarterly report. The results of the finite element analyses will be reported against data from reduced scale physical model tests under Task 2.7. A 20" diameter steel pipe was modeled at 1/12.32 scale using a 1 5/8" (41.3mm) C-1026 cold drawn seamless tube. The pipe section was displaced purely laterally, axially and at 60 and 20 degrees to the pipe axis in tests 1 to 4. The displacement exceeded one pipe diameter to fully mobilize the peak resistances in normal to and along the pipe axis.

Task 3: Improved Pipeline Response Modeling

Technical Status

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

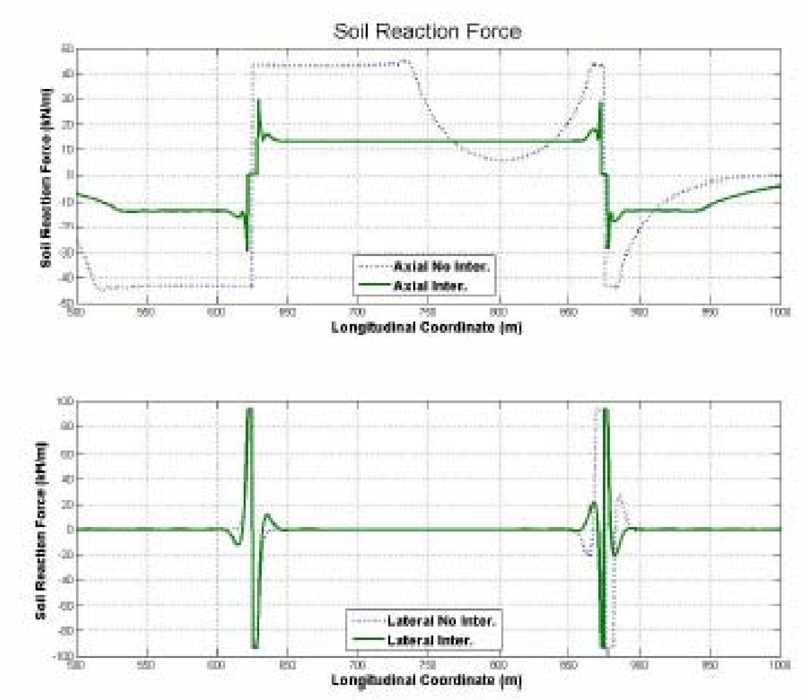
Results and Conclusions

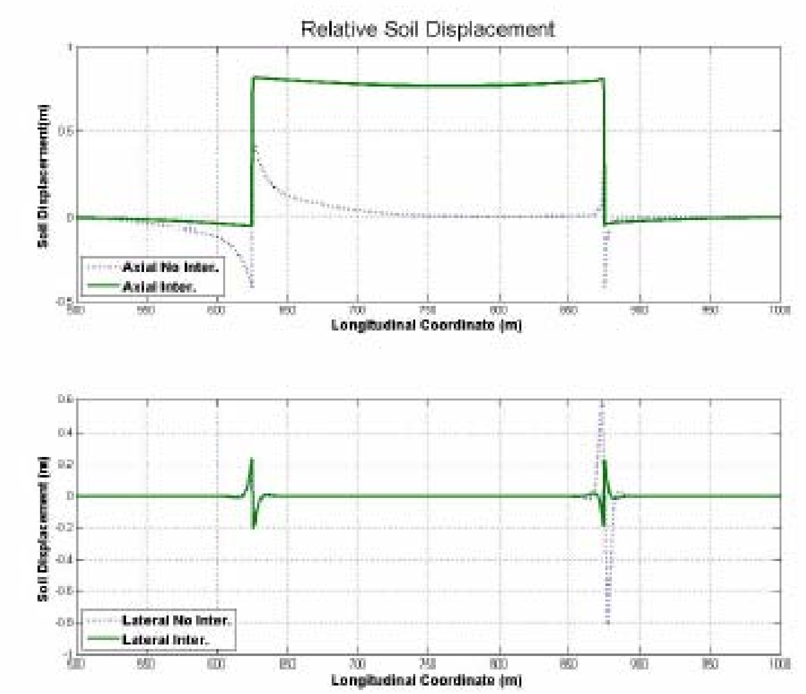
Preliminary results are presented in this section. These results are unverified and are currently undergoing review by the project team.

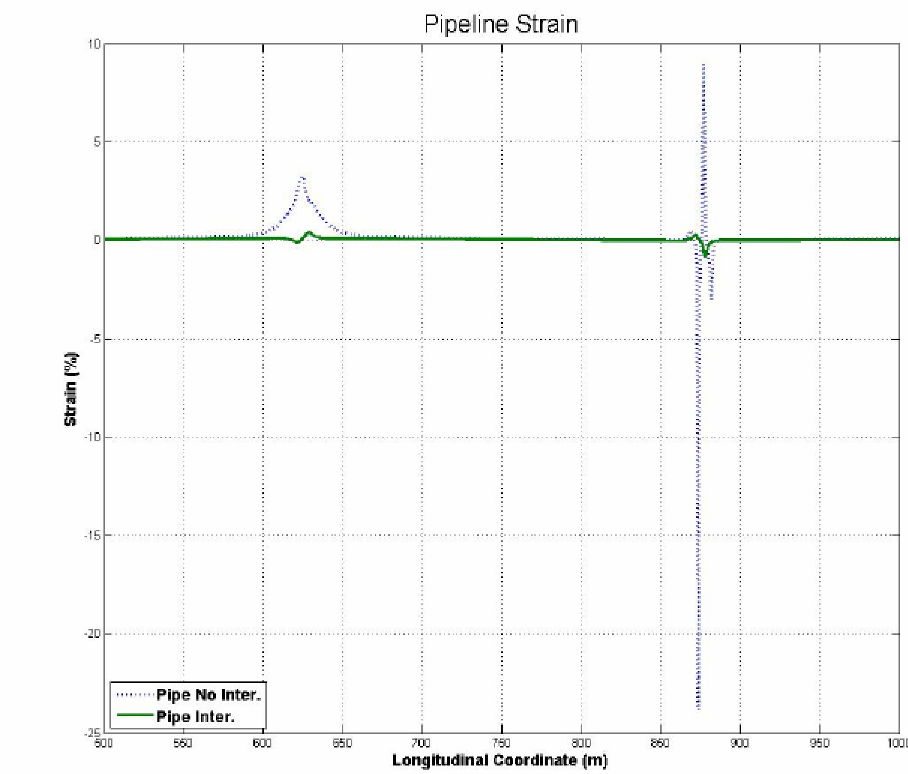
The software interface to the Abaqus finite element program has been developed using Fortran subroutines. This note shows the importance of accounting for the interaction between axial and lateral soil resistance in a pipe-soil (beam-spring) structural analysis for aseismic ground movement. The current practice soil spring formulation is shown to be overly conservative with respect to strains developed in the pipeline.

The analysis was done on a X60, 20" pipeline with a wall thickness of 8mm buried to a depth of one meter. No vertical movement of the pipe was considered. An analysis was carried out with for an abrupt mid slope soil displacement of 1m magnitude at 30 degrees with respect to pipe centerline over a 250m length. The soil was considered to have an undrained strength, Cu of 30 kPa, a unit weight, γ of 8 kN/m3 and a soil-pipe interface friction angle, δ of 20 deg.

The results show that, by accounting for the interaction between elements, the strain developed in the pipeline is reduced. The maximum compressive strain considering interaction is about 0.8%. The following figures are a summary of results:







- Task 3.2: Evaluate alternative pipeline formulations

Options for alternative pipeline formulations within the element suite provided within the Abaqus software have been identified and are now being tested. 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

As discussed in Reference [1], an algorithm for deducing the total longitudinal strain in a displaced pipeline based on curvature that might be established from geometry pig measurements has been developed.

Since the previous quarterly report [1], the matrix of test cases has been expanded to consider additional right lateral fault crossing angles as well as a range of block landslide scenarios for pipe diameters of 8, 16, 24, 36 and 48 inches. In addition to using the nodal curvatures output from PIPLIN to compute the deduced strain profiles, strain calculations were performed using curvature profiles established based on the results from a simulation of a “digital pig” run over the PIPLIN model deflected shapes. Consideration of digital pig curvatures is important because geometry pigs measure the pipe orientation over a finite “pig length” and the curvatures computed from the geometry pig orientation are computed over a gage length which is normally significantly longer than the typical 1-foot element length used in the refined portion of the

PIPLIN model mesh (e.g., typical geometry pig curvature calculation gage lengths range from 2D to 10 feet).

Additional PIPLIN Buried Pipe Deformation Analyses

The series of buried pipeline deformation analyses described in [1] has been extended to consider additional ground movement cases for a wide range of pipe diameters to provide a rational basis for validating/benchmarking and evaluating the efficacy of the deduced strain calculations. The analyses are performed using the PIPLIN [2] computer program, which considers several nonlinear aspects of pipeline behavior, including pipe steel plasticity, large-displacement effects, and nonlinear soil support.

The columns on the left side of Table 4.1 summarize the current matrix of pipe-soil interaction analysis cases in terms of the analysis case number, the pipe diameter, wall thickness, internal pressure, cover depth, and the ground movement profile and its amplitude. Several cases were run for a pipeline crossing a right-lateral fault with different fault crossing angles β. β values ≥ 90^o result in a net longitudinal tension in the pipe while β values < 90^o result in a net longitudinal compression. Additional cases were run for vertical subsidence over abrupt block settlement profiles as well as for horizontal landslide movements across abrupt block landslide profiles.

In all cases, the pipeline has a uniform cover depth in a typical 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 since this will maximize the longitudinal pipe-soil resistance. Bilinear (elastic-perfectly plastic) pipe-soil springs were developed for the models based on industry standard procedures (e.g., see References [3] and [4]). 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 [5]. The pipeline model mesh is refined to provide a grid of short (e.g. 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 and then subjected to the ground displacement 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 to obtain the 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. The key PIPLIN output results are the extreme fiber total axial strains, the pipeline curvature and the pipe centerline extensional strains. For the purposes of this work, the PIPLIN results are considered to be the "exact" results.

The deduced strain estimates can be computed using the PIPLIN nodal curvatures. However, because the deduced strains will eventually be developed based on geometry pig data, it is desirable that the PIPLIN results be "mapped" into the corresponding profiles of geometry pig "signals". As previously stated, consideration of digital pig curvatures is important because geometry pigs measure the pipe orientation over a finite "pig length" and the curvatures computed from geometry pig orientation are computed over a finite gage length. In order to accomplish this mapping, the concept of a "digital pig" was applied to the PIPLIN deflected shapes. The digital pig calculations are performed as a post-processing operation on the PIPLIN deflected shape for the output state of interest. A first-pass calculation loop is used to compute the rotation angle $\theta_{pig}(S)$ at the current station (pitch angle for vertical profiles and azimuth angle for horizontal profiles) over the length of the pig (L_{pig}). A second-pass calculation loop is then used to compute the curvature of the deflected pipe $\Psi(S_{current})$ at the current station over a user-selected gage length (L_{gage}). For more information on digital pigging, see Reference [6]. The pig lengths and curvature gage lengths used for the calculations were selected based on previous project experience and discussions with geometry pig vendors. For all cases, curvature gage lengths of 2D and 10 feet were considered.

Results and Conclusions

Evaluation of the Strain Algorithm

As previously noted, the total extreme fiber strains computed by PIPLIN were taken as the "exact" strains for comparison with the deduced strains from the algorithm. Three different deduced strain profiles were computed; namely, the deduced strains based on the PIPLIN nodal curvature and the deduced strains based on the digitally "pigged" curvatures for gage lengths of 2D and 10 feet. Although detailed profile plot comparisons were developed for each test case, only the maximum governing strains are presented herein. The columns on the right side of Table 4.1 summarize the maximum exact strains, and the maxima for the three different deduced strain measures for imposed displacements at States A and B (see middle columns of Table 4.1).

Observations

The matrix of test cases has been extended to consider additional ground displacement patterns and a wide range of pipe diameters, and additional processing of the results has been undertaken to map the deformation analysis results into information that is consistent with ILI geometry pigs. Although testing of the proposed algorithm is ongoing, several observations can be made:

(1) The comparison between the deduced strains and the exact strains tends to be better for State B than for State A (i.e., at higher strains).

(2) For the case with a block landslide moving along the pipe with no transverse component (i.e., with a crossing angle of zero, Case 22), the deduced strains provide a poor comparison with the exact strains since there was no transverse displacement of the pipe.

(3) When the deduced strains are computed based on the PIPLIN nodal curvatures, the deduced strain tends to over-predict the governing strain (e.g., the tension strain when the gross strain field is tensile or the compression strain when the gross strain field is compressive). However, the deduced strains computed based on the PIPLIN nodal curvatures tend to underestimate the non-governing strains (e.g., the tension strain when the gross strain field is compressive or the compression strain when the gross strain field is tensile).

(4) For all pipe sizes, deduced strains computed based on the PIPLIN nodal curvatures underestimate exact strain for the fault crossing cases with $\beta=100^o$ and with $\beta=110^o$.

(5) When the deduced strains are computed based on the digitally pigged curvatures for a gage length of 2D, the deduced strain tends to under-predict the governing strain. The degree of under-prediction increases when the deduced strains are computed using the pigged curvatures for a gage length of 10 feet.

(6) Mapping of the PIPLIN analysis results into "digital pigged" results is important because the pigged rotations tend be less than the PIPLIN nodal rotations and the pigged curvatures tend to be less than the PIPLIN nodal curvatures, especially for longer gage lengths. This implies that curvatures from geometry pigs should be developed using as short a gage length as possible. However, due to the inevitable presence of low amplitude noise in actual pig rotation data, curvature profiles calculated using shorter gage lengths tend to have a high signal-to-noise ratio and it may be necessary to utilize digital filtering (see References [6] and [7]) in order to reduce the noise.

(7) Both components of the total deduced strain depend on the pipeline curvature. Therefore, when the deduced strain is computed from digitally pigged results the effect of longer gage lengths will tend to reduce both of these terms.

References

[1] PRCI, "Pipeline Integrity Management for Ground Movement Hazards", Quarterly Report, June 2007.

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

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

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

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

[6] Hart, J.D., Zulfiqar, N., Moore, D.H., and Swank, G.R., "*Digital Pigging as a Basis for Improved Pipeline Structural Integrity Evaluations"*, IPC06-10349, Proceedings of the International Pipeline Conference, Calgary, Alberta, Canada, September 25-29, 2006.

[7] Hart, J.D., Powell, G. H., Hackney, D., and Zulfiqar, N., *"Geometry Monitoring of the Trans-Alaska Pipeline",* Proceedings of the ASCE Cold Regions Conference, Anchorage, Alaska, May 20-22, 2002.

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Table 4.1. Pipe Soil-Interaction Analysis Cases and Results

Case Number	Model Description	Diameter (inches)	Thickness (inches)	Pressure (psi)	Cover (feet)	Imposed Displ. State A (feet)	Imposed Displ. State B (feet)	State A Exact (%)	State A Deduced Strains From PIPLIN (%)	State A Deduced Strains From Lgage=2D (%)	State A Deduced Strains From Lgage=10’ (%)	State B Exact (%)	State B Deduced Strains From PIPLIN (%)	State B Deduced Strains From Lgage=2D (%)	State B Deduced Strains From Lgage=10’ (%)
1	100' Block Subsidence	8.625	0.322	1500	6	6.0	9.0	4.62	5.36	2.93	1.54	4.60	5.19	2.83	1.89
2	200' Block Subsidence	8.625	0.322	1500	4	6.0	9.0	3.00	3.56	2.29	1.21	2.99	3.48	2.23	1.44
3	Fault; Beta=70°	8.625	0.322	1500	3	1.0	1.5	-0.80	-0.95	-0.86	-0.54	-5.33	-5.76	-2.48	-1.02
4	Fault; Beta=80°	8.625	0.322	1500	3	1.0	2.0	-1.32	-1.56	-1.27	-0.63	-7.13	-8.72	-4.29	-1.38
5	Fault; Beta=90°	8.625	0.322	1500	6	6.0	9.0	2.81	3.30	2.16	1.72	2.76	2.95	1.83	1.55
6	Fault; Beta=100°	8.625	0.322	1500	6	5.0	7.0	2.01	2.01	1.65	1.43	2.50	2.04	1.57	1.54
7	Fault; Beta=110°	8.625	0.322	1500	6	4.0	6.0	1.83	1.80	1.54	1.43	4.24	1.97	1.64	1.59
8	100' Block Landslide; 90°	8.625	0.322	1500	6	6.0	9.0	2.18	2.46	1.96	1.57	2.68	1.97	1.70	1.61
9	100' Block Landslide; 45°	8.625	0.322	1500	6	6.0	9.0	2.39	3.04	2.39	1.62	2.35	2.88	2.23	1.73
10	100' Block Subsidence	16.0	0.375	725	6	4.0	7.0	4.08	4.86	2.93	1.49	5.12	5.71	3.90	2.16
11	200' Block Subsidence	16.0	0.375	725	4	4.0	6.0	2.36	2.98	1.95	1.11	3.36	3.94	2.58	1.49
12	Fault; Beta=70°	16.0	0.375	725	3	1.0	2.0	-0.43	-0.53	-0.53	-0.45	-3.18	-3.33	-2.24	-1.30
13	Fault; Beta=80°	16.0	0.375	725	3	2.0	3.0	-1.57	-1.86	-1.40	-0.97	-4.82	-5.71	-3.37	-1.76
14	Fault; Beta=90°	16.0	0.375	725	6	6.0	9.0	3.06	3.58	2.73	2.25	3.02	3.45	2.60	2.24
15	Fault; Beta=100°	16.0	0.375	725	6	5.0	8.0	2.39	2.33	2.01	1.81	2.38	2.25	2.01	1.90
16	Fault; Beta=110°	16.0	0.375	725	6	5.0	8.0	2.17	2.08	1.88	1.81	4.99	2.35	2.17	2.11
17	100' Block Landslide; 90°	16.0	0.375	725	6	6.0	9.0	2.65	2.98	2.51	2.09	2.62	2.70	2.29	1.98
18	100' Block Landslide; 45°	16.0	0.375	725	6	6.0	9.0	2.65	3.22	2.74	1.95	2.73	3.24	2.74	2.23
19	100' Block Landslide; 30°	16.0	0.375	725	6	6.0	9.0	2.10	2.73	2.36	1.52	2.70	3.26	2.82	2.01
20	200' Block Landslide; 15°	16.0	0.375	725	6	6.0	9.0	0.86	1.46	1.23	0.82	1.65	2.67	2.18	1.30
21	400' Block Landslide; 7.5°	16.0	0.375	725	7	6.0	9.0	0.43	0.66	0.60	0.47	0.87	1.61	1.18	0.79
22	1000' Block Landslide; 0°	16.0	0.375	725	7	2.0	5.0	0.53	0.13	0.06	0.05	0.53	0.13	0.06	0.05
23	100' Block Subsidence	24.0	0.562	725	6	4.0	7.0	2.36	2.99	2.09	1.36	3.20	3.84	2.66	1.67
24	200' Block Subsidence	24.0	0.562	725	4	4.0	7.0	0.94	1.30	1.12	0.86	2.37	2.83	2.14	1.45
25	Fault; Beta=70°	24.0	0.562	725	3	2.0	3.0	-0.90	-1.02	-0.92	-0.79	-3.46	-3.58	-2.61	-1.76
26	Fault; Beta=80°	24.0	0.562	725	3	4.0	6.0	-3.30	-3.85	-2.99	-2.01	-6.28	-7.70	-5.47	-3.33
27	Fault; Beta=90°	24.0	0.562	725	6	6.0	9.0	2.48	2.98	2.56	2.16	2.61	3.01	2.60	2.39
28	Fault; Beta=100°	24.0	0.562	725	6	6.0	9.0	2.11	2.09	1.86	1.78	2.10	2.09	1.86	1.81
29	Fault; Beta=110°	24.0	0.562	725	6	6.0	9.0	2.04	1.95	1.75	1.69	2.41	2.18	1.95	1.92
30	100' Block Landslide; 90°	24.0	0.562	725	6	6.0	9.0	2.33	2.68	2.35	2.03	2.35	2.62	2.29	2.10
31	100' Block Landslide; 45°	24.0	0.562	725	6	6.0	9.0	1.80	2.26	2.08	1.68	2.39	2.78	2.49	2.14
32	100' Block Subsidence	36.0	0.500	1000	6	3.0	4.0	1.58	2.27	1.56	1.25	2.52	3.39	2.26	1.72
33	200' Block Subsidence	36.0	0.500	1000	4	4.0	7.0	1.06	1.54	1.22	1.02	2.79	3.47	2.47	1.91
34	Fault; Beta=70°	36.0	0.500	1000	3	2.0	2.5	-1.66	-1.66	-1.49	-1.27	-3.23	-3.13	-2.50	-1.98
35	Fault; Beta=80°	36.0	0.500	1000	3	3.0	4.0	-2.78	-2.96	-2.43	-1.90	-4.57	-4.87	-3.94	-2.97
36	Fault; Beta=90°	36.0	0.500	1000	6	6.0	9.0	3.50	4.41	3.72	3.19	4.09	4.85	4.16	3.78
37	Fault; Beta=100°	36.0	0.500	1000	6	6.0	9.0	3.36	3.25	2.86	2.69	3.47	3.35	2.91	2.82
38	Fault; Beta=110°	36.0	0.500	1000	6	6.0	9.0	3.25	3.00	2.63	2.56	3.74	3.36	3.14	3.06
39	100' Block Landslide; 90°	36.0	0.500	1000	6	6.0	9.0	3.36	4.00	3.60	3.09	3.87	4.39	3.95	3.59
40	100' Block Landslide; 45°	36.0	0.500	1000	6	6.0	9.0	2.49	3.33	2.92	2.41	3.55	4.34	3.87	3.30
41	100' Block Subsidence	48.0	0.562	1000	6	6.0	9.0	0.33	0.53	0.51	0.49	0.33	0.53	0.51	0.49
42	200' Block Subsidence	48.0	0.562	1000	4	6.0	9.0	1.97	2.62	1.76	1.61	3.14	3.86	2.63	2.37
43	Fault; Beta=70°	48.0	0.562	1000	3	2.0	3.0	-1.19	-1.22	-1.10	-1.05	-3.51	-3.37	-2.71	-2.47
44	Fault; Beta=80°	48.0	0.562	1000	3	3.0	5.0	-1.95	-2.08	-1.72	-1.62	-5.13	-5.44	-4.17	-3.78
45	Fault; Beta=90°	48.0	0.562	1000	6	6.0	9.0	3.30	4.29	3.46	3.24	4.32	5.21	4.36	4.18
46	Fault; Beta=100°	48.0	0.562	1000	6	6.0	9.0	3.47	3.38	2.88	2.81	3.89	3.68	3.14	3.11
47	Fault; Beta=110°	48.0	0.562	1000	6	6.0	9.0	3.50	3.18	2.78	2.73	3.64	3.29	2.93	2.91
48	100' Block Landslide; 90°	48.0	0.562	1000	6	6.0	9.0	3.16	3.90	3.41	3.19	4.19	4.81	4.28	4.07
49	100' Block Landslide; 45°	48.0	0.562	1000	6	6.0	9.0	2.11	3.01	2.52	2.35	3.29	4.28	3.70	3.45

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Task 5: Options to Mitigate Risks of Large Ground Displacement

Technical Status

Work was initiated this quarter on Tasks 5.1 through 5.3.

Results and Conclusions

- Tasks 5.1: Summarize current state-of-practice on mitigation through pipeline design

Mitigation through pipeline design focuses on analytical methodologies to incorporate soil-pipeline interaction into an assessment of pipeline response. The basic approach in this regard is developed in PRCI seismic design guidelines published in 2004. Efforts related to Task 5.1 during this quarter have focused on identifying new research findings related to soil-pipeline interaction and coordination with C-CORE efforts under this project to improve soil-pipeline interaction models.

Ongoing research into soil-pipeline interaction at Cornell University and Rensellaer Polytechnic Institute is being monitored to determine what findings could be incorporated into the pipeline guidelines. An important aspect of this research that is being monitored relates to the effects of moisture content on the differences in maximum horizontal soil resistance on pipelines in sandy soils. Research published by Cornell in 2004 indicated that moist sand resistance could be twice as high as for dry sand although this finding has not been confirmed in tests performed at RPI and at the University of British Columbia as part of a past PRCI project.

- Task 5.2: Summarize current state-of-practice on mitigation through geotechnical design

Mitigation through geotechnical design will consist of standard practices for assuring slope stability: altering slope topography, controlling surface and subsurface drainage, providing additional sliding resistance through walls or buttresses. Efforts initiated on Task 5.2 during this quarter have focused on determining the level of detail on engineering methodologies for implementing these practices that is needed and identifying the key issues that need to be noted with respect to implementation for pipeline applications.

- Task 5.3: Summarize current state-of-practice on mitigation through operational measures

Only limited efforts related to Task 5.3 were initiated this quarter. The issue of what operational measures can be considered as effective mitigation strategies is highly dependent upon the rate and amount of landslide displacement.

Plans for Future Activity

Activities for Tasks 1, 2, 3, 4, and 5 will continue in the next quarter (milestone period). In addition, work will initiate on Task 6: Comprehensive Guidance Document. Planned activities for these six tasks are presented below.

Task 1: Definition of Large Ground Displacement Hazards

Technical Progress

Efforts will focus on completing the following subtasks during the next quarter:

- Task 1.6: Prepare second draft of recommended practice for hazard definition
- Task 1.7: Obtain review comments from outside experts

A revised draft of guidelines for identifying slope movement and subsidence hazards will be prepared and reviewed during the next quarter. This review will be performed by direct contributors to the writing of the document as well as three experts that have not been involved in the development of the draft.

Meeting and Presentations

A working meeting of the DGHC team is anticipated during the next quarter to discuss comments from the second draft of the hazard definition guidelines. However, the need for a meeting will largely depend upon the level of comments received from review of the second draft. Given that the meeting will need to occur near the holidays, consideration will be given to resolving review comments via e-mail and conference call if practical.

Task 2: Improved Pipeline-Soil Interaction Models

Technical Progress

The planned activities for next three months include:

- Task 2.5: Centrifuge Modeling of Oblique Pipeline/Soil Interaction (Clay)
  - These tests will be completed.

- Task 2.6: Calibrate numerical models (clay) and conduct parametric study
  - 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 2.5 above.

Task 3: Improved Pipeline Response Modeling

Technical Progress

- Task 3.1:Evaluate alternative soil formulations
  - This task will be completed

- Task 3.2:Evaluate alternative pipeline formulations
  - Alternative pipeline formulations will continue to 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

Testing of the deduced strain algorithm is ongoing. The effects of the gage length used to compute curvature from geometry pig data will be given additional attention. Additional simulations are planned to consider less abrupt ground displacement profiles. The effects of noise in the curvature profiles will also be investigated.

Task 5: Hazard Mitigation Strategies

Technical Progress

Efforts will focus on completing the following subtasks 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
- Task 5.5: Prepare initial draft of recommendations on appropriate mitigation measures
- Task 5.6: Assess recommendations with constraints typical of pipeline construction

Meeting and Presentations

A working meeting of the DGHC team is anticipated during the next quarter to discuss comments from the second draft of the hazard definition guidelines.

Task 6: Comprehensive Guidance Document

The following subtasks will be initiated during the next quarter:

- Task 6.1: Assemble 1st draft of guideline from task reports

Meeting and Presentations

No meetings or presentations are planned.