C-FER Technologies

200 Karl Clark Road
Edmonton, Alberta
Canada T6N 1H2
Tel 780.450.3300
Fax 780.450.3700
www.cfertech.com

Final Report

Effectiveness of Prevention Methods for Excavation Damage

Confidential to
PRCI and PHMSA

Prepared by
Qishi Chen, PhD, PEng
Mohamed R. Chebaro, EIT

Reviewed by
Maher Nessim, PhD, PEng

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L110

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PROFESSIONAL ENGINEER OF ALBERTA
QISHI CHEN
2006-12-8

PERMIT TO PRACTICE
C-FER Technologies
Signature
Date 15/12/06
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L110

PROJECT TEAM

Effectiveness of Prevention Methods for Excavation Damage	C-FER Project: L110
Name	**Responsibility**
Qishi Chen, PhD, PEng	Project management, model development, conclusions, report preparation
Mohamed R. Chebaro, BSc, EIT	Surveys, basic event probabilities, analysis, part of report preparation
Theresa Casey, EIT	Survey of contractors

REVISION HISTORY

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3	December 8, 2006	Final	QC, MC	MAN	MAN

NOTICE

PRCI understands that the Department of Transportation ("DOT") is providing funding in support of the Project. C-FER is authorized to disclose reports required under this Agreement to DOT. C-FER shall make its best efforts to provide reports to be disclosed to DOT to PRCI at least thirty (30) days in advance of the disclosure to DOT.

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EXECUTIVE SUMMARY

This report has been prepared to summarize the results of the second phase of a two-phase project carried out by C-FER Technologies. It describes the development, validation and application of a fault tree model that estimates the frequency of mechanical damage events. The intended application of this model is to quantify the effectiveness of damage prevention methods in terms of their potential for reducing impact frequency, and to assist with the selection of damage prevention methods.

Basic event probabilities that define the model inputs were developed based on survey data, experiment results and simple probabilistic models. Validation of the fault tree model demonstrated that failure causes identified by the tree structure were plausible and common causes reported in past incidents were represented. The comparison between historical data and analysis results showed a general agreement in terms of hit frequency and distribution of leading causes.

The evaluation of prevention effectiveness led to the following conclusions:

- Increasing the rate of notification remains the highest priority for damage prevention, as about half of damage incidents occur without one-call notifications. In addition to promoting public awareness, key factors include enforcement and access to one-call services.

- Implementing procedures for safe excavation and promoting awareness of these procedures were identified as important issues. Continuous site supervision throughout excavation is an essential element of excavation procedures.

- Despite their effectiveness, most construction-related damage measures are costly even for new pipelines. However, warning tape or mesh is a cost effective method of reducing hits that result from unreported excavations and should be considered for new construction.

The following recommendations were developed for data collection and future work:

- The fault tree model described in this report can be used to guide data collection efforts by government agencies and the industry. By doing so, the collected data can be used to identify areas where improvement is most needed and quantify the associated key factors.

- Incident data collected in recent years show that 80 to 90% of incidents fall into two leading categories, namely lack of one-call notification and excavation error on marked lines. This suggests that the cause categories could be reorganized by further dividing the major categories and merging the minor ones. For example, if the *lack of notification* category is divided into a few subcategories based on the reasons for lack of notification, the incident data would offer more insight regarding how to increase notifications.

- The tree structure and basic event probabilities need to be updated based on new data from incidents and ongoing government and industry surveys. An example of ongoing surveys is the one conducted by API, INGAA and AOPL in connection with the implementation of API RP 1162. With respect to incident data, this study has utilized data reported to OPS and CGA, but has not utilized data gathered by local governments and the pipeline industry. Incident or survey data in other countries (e.g. Canada, Australia and Europe) can be included as well.

- The fault tree model needs to be modified for distribution systems. This requires that the model and input probabilities be revised based on data regarding the operating environment and prevention practices specific to distribution operators.

- Additional experiments are needed to gather data on prevention effectiveness. Reliable data can be gathered from experiments such as those conducted by British Gas. Areas in which experimental data are needed include the effectiveness of excavation procedures, alignment makers, and locating and marking methods.

ACKNOWLEDGEMENTS

The work of evaluating prevention effectiveness described in this report was jointly sponsored by PRCI, GRI and PHMSA. The authors thank Kimbra Davis of PHMSA for her advice during the second phase of this study.

1. INTRODUCTION

1.1 Terms of Reference

This report has been prepared to summarize the results of the second phase of a two-phase project carried out by C-FER Technologies (1999) Inc. (C-FER). The project was jointly sponsored by the Pipeline Research Council International (PRCI), Gas Research Institute (GRI) and the U.S. Pipeline and Hazardous Materials Safety Administration (PHMSA). The work performed in the first phase was presented in a report submitted to PRCI and GRI, under the title of “Assessment Model for Damage Prevention Effectiveness” (Chen and Stephens 2005).

The overall objective of the project was to develop and validate a model that can be used to estimate the frequency of impact due to third-party excavations based on right-of-way condition information and damage prevention practices. The intended application of this model is to quantify the effectiveness of damage prevention methods in terms of their potential for reducing impact frequency and to assist with the selection of damage prevention methods that will meet safety improvement or cost optimization objectives. In addition, the model can be incorporated into quantitative risk and reliability assessment tools, providing pipeline operators and regulators with the ability to assess the risk of third-party damage and evaluate risk mitigation alternatives.

1.2 Tasks

This project involved the execution of four technical tasks:

1. Data gathering;
2. Development of a fault tree model;
3. Development of basic event probabilities; and
4. Analysis of selected cases.

Tasks 1 and 2 were completed in the first phase of the project. This report, which is based on Phase 2, describes Tasks 3 and 4.

1.3 Report Organization

Section 2 presents the fault tree model that was developed in Phase 1 of this study, which has since undergone minor modifications in Phase 2. Section 3 describes the development of basic event probabilities based on survey data, experiment results and simple probabilistic models. In Section 4, validation of the fault tree model through examination of minimal cut sets and comparison of the results with incident data is described. This is followed by Section 5, in which the effectiveness of construction, maintenance, one-call, regulatory and public awareness measures are evaluated. Finally, conclusions and recommendations are outlined in Section 6.

2. FAULT TREE MODEL

2.1 Fault Tree Method

A damage prevention program is a complex process that involves pipeline operators, planners and developers, one-call centres, excavation contractors, and the general public. Such a program can be seen as a "system" that consists of individual components including dig notification, locating and marking, and right-of-way surveillance. Similar to any engineering system that consists of mechanical or electrical components, the collective effect of component failures in the prevention system could lead to a system failure, which is defined as a contact between digging equipment and the pipeline.

The logical relationship between system malfunction and the performance of individual components can be described by a fault tree that uses a deductive approach to identify the combination of component failures necessary to cause system failure (McCormick 1981). The fault tree method was developed in the aerospace industry in the early 1960s and has since been utilized for applications in risk and reliability analysis of nuclear facilities, chemical plants, and offshore oil and gas systems.

Table 2.1 summarizes the symbolic notation commonly employed in graphic representations of a fault tree model, in which failure of a component or a system is referred to as an event (or a fault event). Development of a fault tree for a given application begins by identifying the system failure of concern (referred to as the top event). Input events leading to the top event are then identified and the necessary relationships between them modelled. Basic events, shown in circles, are the most fundamental input events that cannot be broken down further.

Two types of logical relationships (referred to as gates), AND and OR, are commonly used to connect an output event with the associated input events. The AND relationship means that the input events must coexist for the output event to occur, whereas the OR relationship means that any one (or more) of the input events could cause the output event to occur.

In addition to identifying the critical combinations of component failures that cause the system to fail, the tree structure provides a framework for estimating the probability of system failure (i.e. top event probability) from the probabilities of the underlying component failures (i.e. basic event probabilities). This is achieved by computing the probability of each output event using equations representing the AND or OR relationship.

By assuming independence between all basic events in the fault tree, the probability, p_o, associated with the output event of an AND gate can be calculated from

$$p_o = p_{i1}\, p_{i2}\, p_{i3} \;\ldots\ldots \qquad [2.1]$$

where p_{i1}, p_{i2}, p_{i3}, are the probabilities of the input events, on the basis that all input events have to coexist for the output event to happen.

For an OR gate, the probability of the output event is given by

$$p_o = 1 - [(1 - p_{i1})\,(1 - p_{i2})\,(1 - p_{i3})\ldots\ldots] \qquad [2.2]$$

The quantity in the square brackets in Equation [2.2] gives the probability that none of the input events will occur. Subtracted from 1, the result represents the probability that at least one of these events will occur, which is a sufficient condition for the output event to take place.

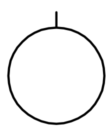
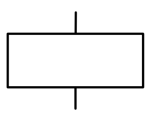
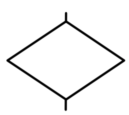
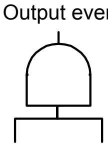
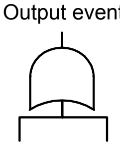
Symbol	Name	Description	Probability
	Basic fault event	A primary fault event that does not require further development into more basic event.	Probability of occurrence is obtained by observation. It may be affected by a number of attributes.
	Intermediate or top fault event	A secondary event which is the result of a logical combination of other events.	Probability of occurrence is calculated based on the logical relationship (AND gate or OR gate) with input events.
	Undeveloped fault event	A fault event which is not fully developed as to its input events. It is only an assumed primary fault event.	Probability of occurrence is estimated similar to that of basic events.
Output event  Input events	AND gate	The output event occurs if **all** input events occur.	The probability of the output event is the product of the probabilities of all input events.
Output event  Input events	OR gate	The output event occurs if **one or more** of input events occur.	The probability of the output event is calculated by [3.2].

Table 2.1 Fault Tree Symbols

2.2 Condensed Model

Building on previous fault tree models developed by C-FER (Chen and Nessim 1999) and on recent information regarding regulatory initiatives and industry approach to damage prevention, a more comprehensive fault tree model that reflects a broad range of elements found in various damage prevention programs was developed in this project in two steps. A condensed, high-level fault tree that uses a few undeveloped events to represent groups of basic events was developed first. Since the condensed fault tree contains fewer events, it is less cumbersome to ensure that the basic tree structure correctly represents the relationships between different components of a prevention program. Once this was verified, the condensed version was then expanded into a detailed fault tree by breaking each undeveloped event into a set of underlying basic events.

The development of this fault tree took into account the typical preventative process during an excavation activity and the different categories of prevention methods. In addition, care was taken to identify factors that influence the performance of each component of the prevention process. Potential interactions between the various components of the damage management process were clarified to ensure that these relationships were correctly reflected in the structure.

Figure 2.1 shows the condensed fault tree, in which the ends of each branch consist of basic events (shown in circle nodes) and undeveloped events (shown in diamond-shaped nodes). The top event of a pipeline being hit by excavation equipment (E11) results from excavation taking place on the pipeline alignment (E21), failure of the prevention methods (E22), failure of the physical protection (E23) and insufficient soil cover for the applicable excavation depth (E24). The prevention failure event (E22) is the outcome of an OR gate connecting two input events: one representing ineffective excavation procedures that fail to prevent equipment from interfering with a properly marked line (E31); and the other for an unmarked or incorrectly marked alignment, in which case the actual pipeline location is unknown to the third party (E32).

The branch associated with ineffective alignment markers (E32) is further broken down into ineffective permanent and temporary markers (E44 and E45, respectively), and interference on an unmarked or incorrectly marked alignment (E46). Ineffective temporary markers (E45) are attributed to the following: a) the operator being unaware of the excavation (E53); b) ineffective response by the operator to a one-call notification (E54); or c) errors in locating or marking the pipeline (E55). Furthermore, the pipeline operator is assumed to be unaware of the excavation if the operator is not notified by the one-call centre (E61) and the right-of-way surveillance fails to detect the excavation activity in time (E62).

Input events leading to E61 (operator not notified) represent potential failures in the dig notification process. These failures can be caused by the third party being unaware of the notification requirement (E71), the third party's decision not to notify (E72) or the one-call centre's ineffective response to a notification by the third party (E73). Event E71 (third party unaware of dig notification) occurs if public awareness is inadequate (E81) and right-of-way signs fail to induce the third party to notify of the intent to excavate (E82).

Fault Tree Model

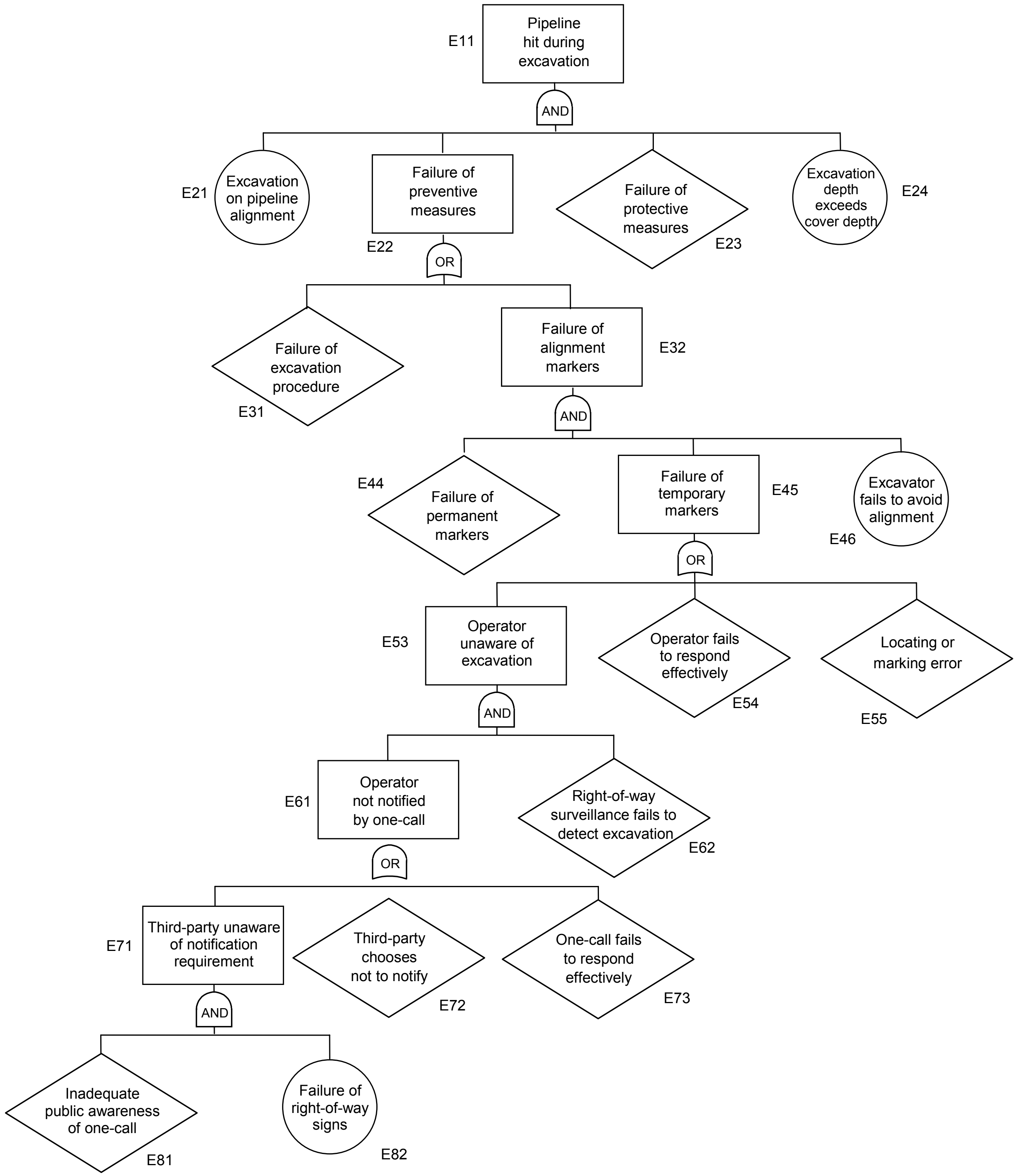


Figure 2.1 Condensed Fault Tree Model

2.3 Detailed Model

As presented in Figure 2.2, the fully-developed, detailed fault tree model consists of the tree structure in Figure 2.1 and the basic events under each of the ten undeveloped events. The new model includes a number of damage prevention methods (e.g. physical protection) that were not addressed in the previous model by Chen and Nessim (1999). In addition, for prevention methods that were shown to be effective based on previous studies such as public awareness, one-call notification and excavation procedures, additional basic events have been introduced to more fully account for all contributing factors.

For example, public awareness of one-call systems (E81) is further broken down into four basic events representing message coverage (E91), delivery frequency (E92), delivery method (E93) and message content (E94). These are identified as the four key elements of public awareness communication in the recommended practice published by API RP 1162. Also included is the adequate use of explicit excavation procedures as recommended by API RP 1166 (E41) and the associated awareness among contractors (E42).

The event of the third party choosing not to notify (E72) is further developed into ineffective one-call services due to limited participation or multiple call centres (E83) and ineffective enforcement of notification (E84).

New and emerging damage prevention technologies (Muradali et al. 2003), such as the use of buried electronic markers, real-time surveillance of the right-of-way and automated one-call notification systems, were incorporated into the basic events corresponding to the respective prevention methods. For instance, the benefit of electronic buried markers, in comparison to conventional remote sensing locating technologies, was reflected in the basic event probabilities assigned to event E67.

Encroachment management was identified earlier in the Phase 1 report (Chen and Stephens 2005) as one of the proactive damage prevention methods used by pipeline companies to influence future development near pipelines and to manage pending development activity. The effects may include a controlled increase in excavation activities in some cases and the opportunity to introduce enhanced preventative measures in anticipation of new developments. Because the benefits will be realized in the future, encroachment management can be incorporated into the fault tree by assigning appropriate future probabilities to relevant basic events such as excavation activity (E21), right-of-way signage (E96) and patrol frequency (E74).

Fault Tree Model

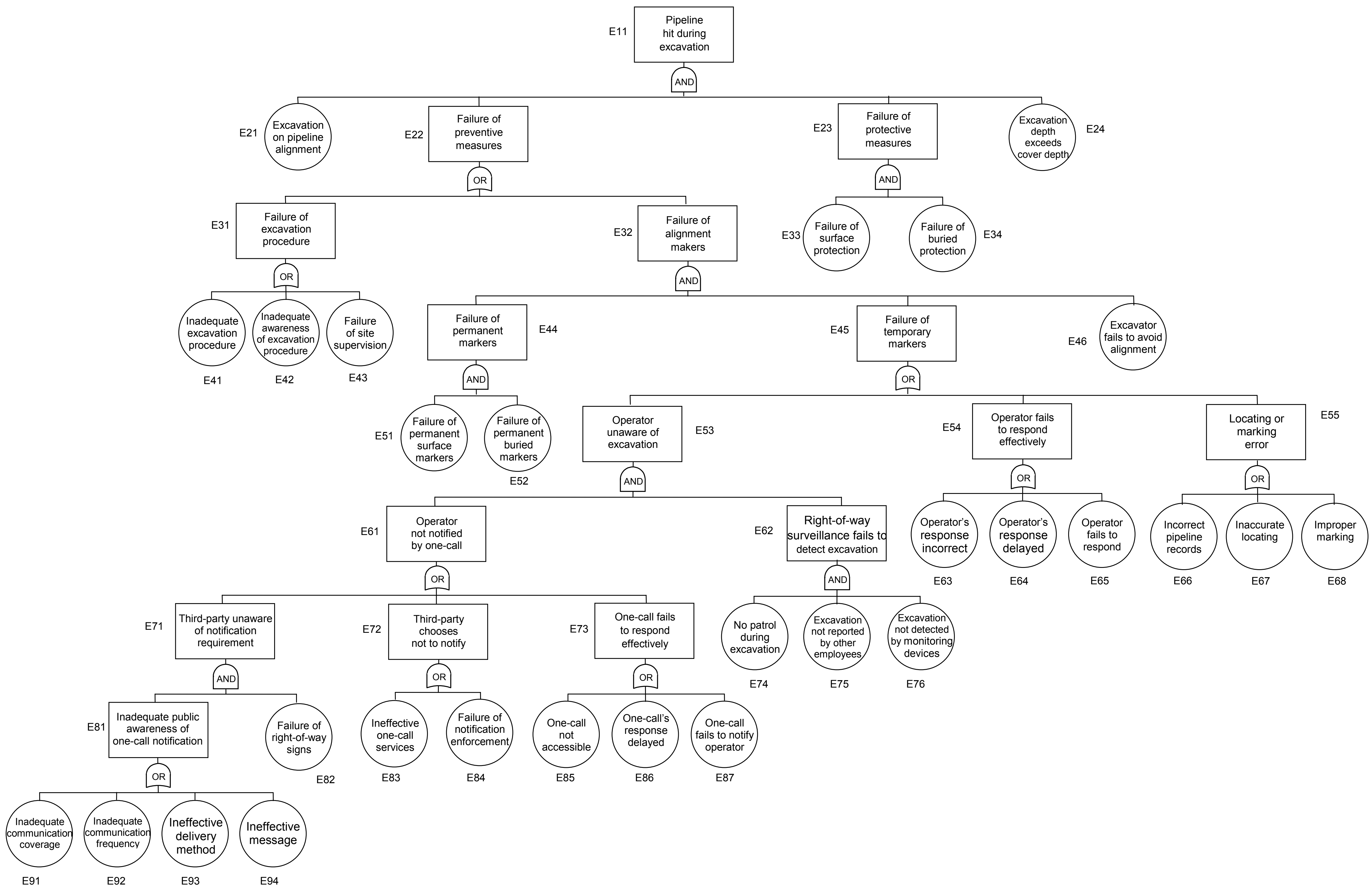


Figure 2.2 Detailed Fault Tree Model

2.4 Basic Events

Probability of a basic event, which represents the probability of a component fault in the prevention system, is defined as a function of variables representing right-of-way conditions and prevention practices. For example, the frequency of excavation activity (E21) could be a function of land use or population density in adjacent areas, and the probability of detecting unauthorized excavations (E74) varies with patrol frequency. As a result, several discrete probability values corresponding to different line attributes or effectiveness of prevention measures are assigned to each basic event.

Table 2.2 presents all 29 basic events considered in the detailed fault tree model. Probability definition and governing variables are also listed for each basic event.

Number	Basic Event	Probability Definition	Control Variables
E21	Excavation on pipeline alignment	Annual frequency of excavations on pipeline alignment	Land use type, population density
E24	Excavation depth exceeding cover depth	Probability that excavation depth exceeds the depth of soil cover	Excavation depth and pipeline cover depth
E33	Failure of surface protection	Probability that surface protective devices fail to stop an ongoing excavation	Type of surface protection
E34	Failure of buried protection	Probability that buried protective devices fail to stop an ongoing excavation	Type of buried protection
E41	Inadequate excavation procedure	Probability that an inadequate procedure causes mechanical interference to the marked alignment	Completeness, clarity and practicality
E42	Inadequate awareness of excavation procedure	Probability that low awareness and lack of training cause mechanical interference to the marked alignment	Promotion of awareness/ training of contractors
E43	Failure of site supervision	Probability that insufficient site supervision causes mechanical interference to the marked alignment	Site supervision criteria and duration
E46	Third party fails to avoid pipeline alignment	Probability that a third party fails to avoid unmarked and incorrectly marked pipeline alignment.	Excavation procedure of third parties
E51	Failure of permanent surface markers	Probability that permanent surface markers fail to indicate pipeline location	Type of permanent surface markers
E52	Failure of permanent buried markers	Probability that permanent buried markers fail to indicate pipeline location	Type of permanent buried markers
E63	Operator's response incorrect	Probability that operator's response to dig notification is incorrect	Staff training, quality control, and notification processing technologies
E64	Operator's response delayed	Probability that excavation takes place before operator's response to dig notification	Response time by one-call and operator, and the time between third party's notification and excavation
E65	Operator fails to respond	Probability that the operator fails to respond to a notification	Resources and technologies
E66	Incorrect pipeline records	Probability that records of pipeline location are incorrect	Records keeping and updating
E67	Inaccurate locating	Probability that a pipeline is not correctly located	Locating equipment and staff training
E68	Improper marking	Probability that temporary markers fail	Marking method and staff training

Table 2.2 Summary of Basic Events

Number	Basic Event	Probability Definition	Control Variables
E74	No patrol during excavation	Probability that right-of-way patrols do not detect an ongoing activity before the interference on the alignment	Patrol frequency, and the time between third party's moving on ROW and starting excavation
E75	Excavation not reported by other employees	Probability that other employees do not detect an ongoing activity before the interference on the alignment	Likelihood of employee present at the site
E76	Excavation not detected by monitoring devices	Probability that right-of-way monitoring devices do not detect the activity before the interference on the alignment	Type of monitoring equipment
E82	Failure of right-of-way signs	Probability that right-of-way signs fail to prompt third party to notify	Spacing and type of signs
E83	Ineffective one-call services	Probability that third party chooses not to notify because of ineffective one-call services	One-call participation and exemption
E84	Failure of notification enforcement	Probability that third party chooses not to notify due to ineffective enforcement	Notification requirements and enforcement measures
E85	One-call not accessible	Probability that a third party abandons the attempt to notify because one-call is not accessible	Access method, coverage and availability
E86	One-call response delayed	Probability that one-call fails to respond to the notification in time	One-call resource and technology
E87	One-call fails to notify operator	Probability that one-call fails to notify the operator due to operational errors	Quality control, technologies, and staff training
E91	Inadequate communication coverage	Probability that a third party does not notify one-call due to inadequate coverage of public awareness communication	Coverage among all target groups
E92	Inadequate communication frequency	Probability that a third party does not notify one-call due to infrequent public awareness communication	Annual communication frequencies
E93	Ineffective delivery methods	Probability that a third party does not notify one-call due to ineffective public awareness communication methods	Different delivery methods
E94	Ineffective message	Probability that a third party does not notify one-call due to ineffective public awareness message	Completeness and clarity of communication message

Table 2.2 Summary of Basic Events (continued)

3. PROBABILITY OF BASIC EVENTS

3.1 Data Sources

In the context of the fault tree model described in Section 2, the probability of each basic event represents the likelihood that a damage prevention activity (e.g. notification, patrol) will fail to achieve its intended purpose. In most cases, a basic event probability is defined as a function of prevention methods, with discrete probability values associated with the effectiveness of these methods.

Different approaches including direct data gathering and derivation by simple probabilistic models were used to develop basic event probabilities. The development used data from several sources:

- a survey of one-call centres conducted by C-FER during this study;
- a survey of excavation contractors conducted by C-FER during this study;
- a survey of pipeline operators conducted by C-FER in 1997; and
- data from past incidents, tests, other surveys and literature sources.

There are a few basic events (E63, E65, E66 and E91 in Figure 2.2) for which user's input is required to define the probability based on the operator's experience. Additionally, assumed values were adopted for two basic events (E51 and E76) where the attributes can be defined, but data or models to develop the corresponding probabilities were not available.

Table 3.1 presents the probability values developed using the above-mentioned processes for all basic events. The development of basic event probabilities is explained in detail in the following subsections.

It is expected that ongoing work by the pipeline industry and government bodies to evaluate prevention methods will provide additional data for the probabilities discussed here. For example, API, INGAA and AOPL plan to conduct surveys among pipeline operators in 2007 to evaluate the effectiveness of public awareness programs recommended by API RP 1162. Once these surveys are completed, the data can be used to improve the probabilities of relevant basic events.

Probability of Basic Events

Number	Basic Event	Probability Definition	Condition	Probability	Data Source
E21	Excavation on pipeline alignment	Annual frequency of excavations on pipeline alignment (per km.year)	Commercial / Industrial	0.52	Derived from operator survey data (North American members)
			Residential	0.36	
			Agricultural	0.076	
			Remote	0.06	
E24	Excavation depth exceeds cover depth	Probability that excavation depth exceeds the depth of soil cover	**For populated area or cold region, cover depth =**		Derived from operator survey data of excavation depth
			0.8 m (2.5 ft)	0.87	
			0.9 m (3 ft)	0.83	
			1.2 m (4 ft)	0.50	
			1.5 m (5 ft)	0.30	
			1.8 m (6 ft)	0.10	
			For other areas, cover depth =		
			0.8 m (2.5 ft)	0.42	
			0.9 m (3 ft)	0.25	
			1.2 m (4 ft)	0.08	
			1.5 m (5 ft)	0.07	
			1.8 m (6 ft)	0.06	
E33	Failure of surface protection	Probability that surface protective devices fail to stop an on-going excavation	Surface protective devices not availlable	1.00	Inferred from tests on buried protection
			Protective devices installed without warning signs	0.20	
			Protective devices installed with clear warning signs	0.05	
E34	Failure of buried protection	Probability that buried protective devices fail to stop an on-going excavation	Buried mechanical protective not availlable	1.00	Based on tests
			Mechanical protection installed without warning signs	0.20	
			Mechanical protection installed with clear warning signs	0.05	
E41	Inadequate excavation procedure	Probability that an inadequate procedure causes mechanical interference with the marked alignment	Documented excavation procedure not available	0.54	Based on excavator survey data
			An excavation procedure consisting of general guidelines	0.28	
			An excavation procedure that requires site supervision for digging within a buffer zone	0.10	
			An excavation procedure that requires hand or hydraulic digging within a tolerance zone	0.10	
			Both site supervision and soft digging are required	0.08	
E42	Inadequate awareness of excavation procedure	Probability that low awareness of excavation procedure causes mechanical interference with the marked alignment	**Training provided to all excavators:**		Based on data of excavator categories and memory tests
			Training not available	1.00	
			Once every five years	0.42	
			Once every two years	0.06	
			Once a year	0.02	
			Training provided to 50% of contractors:		
			Training not available	1.00	
			Once every five years	0.74	
			Once every two years	0.49	
			Once a year	0.44	

Table 3.1 Probability Values for Basic Events

Probability of Basic Events

Number	Basic Event	Probability Definition	Condition	Probability	Data Source
E43	Failure of site supervision	Probability that insufficient site supervision causes mechanical interference with the marked alignment	Site supervision not available	0.36	Based on excavator survey data
			Site visit by pipeline company staff	0.26	
			Site supervision provided during part of the excavation	0.16	
			Site supervision provided throughout excavation	0.09	
E46	Failure of avoiding pipeline alignment			0.50	
E51	Failure of permanent surface markers	Probability that permanent surface markers fail to indicate pipeline location	No surface markers	1.00	Assumed values
			Surface markers that are not visible in all weather conditions	0.50	
			All-weather, discontinuous surface markers with warning signs	0.30	
			All-weather and continuous surface markers with warning signs	0.05	
E52	Failure of permanent buried markers	Probability that permanent buried markers fail to indicate pipeline location	No buried markers	1.00	Based on tests on buried warning tape
			Single warning tape	0.60	
			Dual warning tapes	0.35	
			Warning meshes or multiple tapes	0.20	
E63	Operator's response incorrect	Probability that operator's response to dig notification is incorrect	Varying with staff training, quality control and technologies	N/A	User's input
E64	Operator's response delayed	Probability that excavation takes place before operator's response to dig notification	Response in more than three days	0.50	Derived from operator survey data
			Response within three days	0.20	
			Response within two days	0.11	
			Response during the same day	0.02	
E65	Operator fails to respond	Probability that the operator fails to respond to a notification	Varying with human resource availability and ticket-management technologies	N/A	User's input
E66	Incorrect pipeline records	Probability that records of pipeline location are incorrect	Varying with records quality and updating practices	N/A	User's input
E67	Inaccurate locating	Probability that a pipeline is not correctly located	Site locating not provided	1.00	Based on operator survey data
			By ground penetration radar	0.38	
			By magnetic tools	0.09	
			By buried electronic markers	0.02	
			By pipe locators/probe bars	0.01	
E68	Improper marking	Probability that temporary markers fail to indicated the pipeline location	No temporary markers	1.00	Inferred from damage incident data
			Temporary markers that do not meet marking standards	0.50	
			Standard temporary markers without maintenance	0.15	
			Using pre-marking, following marking standards and maintaining markers throughout the excavation	0.05	

Table 3.1 Probability Values for Basic Events (continued)

Probability of Basic Events

Number	Basic Event	Probability Definition	Condition	Probability	Data Source
E74	No patrol during excavation	Probability that right-of-way patrols do not detect an ongoing activity before the interference on the alignment	Semi-daily patrols	0.13	Derived from a simple model and operator survey data
			Daily patrols	0.30	
			Bi-daily patrols	0.52	
			Weekly patrols	0.80	
			Biweekly patrols	0.90	
			Monthly patrols	0.95	
			Semi-annually patrols	0.99	
			Annually patrols	0.996	
E75	Excavation not reported by other employees	Probability that other employees do not detect an ongoing activity before the interference on the alignment	Employees do not detect an ongoing activity before the interference on the alignment	0.97	Based on operator survey data
E76	Excavation not detected by monitoring devices	Probability that right-of-way monitoring devices do not detect the activity before the interference on the alignment	Continuous monitoring devices not available	1.00	Assumed values
			Continuous monitoring devices with limited reliability	0.25	
			Continuous monitoring devices with high reliability	0.05	
E82	Failure of right-of-way signs	Probability that right-of-way signs fail to prompt an excavator to notify	Signs at selected crossings	0.23	Based on operator survey data
			Signs at all crossings	0.19	
			All crossings plus intermittently along route	0.17	
E83	Ineffective one-call services	Probability that third-party chooses not to notify because of ineffective one-call services	Low company participation in the one-call system (exemption available)	0.54	Based on one-call survey data
			Intermediate company participation in the one-call system	0.36	
			High company participation in the one-call system	0.17	
E84	Failure of notification enforcement	Probability that third-party chooses not to notify due to ineffective enforcement	Voluntary	0.51	Based on survey data of one-call centers and operators
			Mandatory without enforcement	0.33	
			Enforced by civil penalties	0.21	
			Enforced by administrative penalties	0.15	
			Enforced by criminal prosecution	0.13	
			Right-of-way agreement	0.11	
E85	One-call not accessible	Probability that a third-party abandons the attempt to notify because one-call is not accessible	One-call service not available	1.00	Based on one-call survey data
			One-call service not available 24/7, with long waiting time	0.49	
			One-call service available 24/7 only by phone	0.24	
			One-call service available 24/7 by phone, fax, email and voice message	0.15	
E86	One-call's response delayed	Probability that one-call fails to respond to the notification in time	One-call center is under-staffed and uses a grid based, manual/semi-automated procedure for location search and ticket processing	0.52	Based on one-call survey data
			One-call center is under-staffed and uses a polygon based, fully-automated procedure for location search and ticket processing	0.40	
			One-call center is fully-staffed and uses a polygon based, fully-automated procedure for location search and ticket processing	0.10	

Table 3.1 Probability Values for Basic Events (continued)

Probability of Basic Events

Number	Basic Event	Probability Definition	Condition	Probability	Data Source
E87	One-call fails to notify operator	Probability that one-call fails to notify the operator due to operational errors	One-call center does not follow guidelines or standards, has no employee training and no quality assurance	0.58	Based on one-call survey data
			One-call center does not follow any guidelines or standards, has some employee training and some quality assurance	0.47	
			One-call center follows standards, has extensive employee training and high quality assurance	0.04	
E91	Inadequate communication coverage	Probability that an excavator does not notify one-call center due to inadequate coverage of public awareness communication	Varying with the coverage of public awareness education	N/A	User's input
E92	Inadequate communication frequency	Probability that an excavator does not notify one-call center due to infrequent public awareness communication	Twice a year	0.003	Bade on test data
			Annual	0.02	
			Once every 2 years	0.06	
			Once every 3 years	0.16	
			Once every 4 years	0.25	
			Once every 5 years	0.42	
E93	Ineffective delivery methods	Probability that an excavator does not notify one-call center due to ineffective public awareness communication methods	Advertising via community meetings with direct mail-outs and promotion among contractors	0.10	Based on operator survey data
			Advertising via direct mail-outs and promotion among contractors	0.24	
			Advertising via community meetings only	0.50	
E94	Ineffective message	Probability that an excavator does not notify one-call center due to ineffective public awareness message	Message does not clearly mention calling before digging	0.55	Based excavators survey data
			Message mentions calling before digging without providing details	0.42	
			Message provides one-call number and an overview of one-call operation	0.20	
			In addition to the above, the message mentions that notification is free and required by law	0.14	
E95	Failure of right-of-way signs	Probability that right-of-way signs fail to prompt an excavator to notify	Signs at selected crossings	0.23	Based on operator survey data
			Signs at all crossings	0.19	
			All crossings plus intermittently along route	0.17	

Table 3.1 Probability Values for Basic Events (continued)

3.2 Probabilities Based on Survey of Pipeline Operators

A survey of pipeline operating companies was carried out by C-FER in 1997 for a study commissioned by PRCI (Chen and Nessim 1999). The survey questionnaire was designed based on an earlier fault tree model, with the objective of gathering data to estimate basic event probabilities. The questionnaire consisted of 21 questions in four categories: frequency of excavation on pipeline alignment; awareness of pipeline and notification system; right-of-way surveillance and response to notifications; and excavation activity and incidents.

A total of 15 responses were received, representing data from gas transmission systems with a combined distance of 59,000 km. The responses came from five continents: six from the United States, three each from Canada and Europe, and one each from Argentina, Australia and Japan.

Probabilities of events E21, E46, E64, E67, E75, E82 and E93 (as shown in Table 3.1) are directly based on the average values of probabilities estimated by survey respondents. For event E67, the probability related to buried electronic markers was added based on results of field tests (Muradali et al. 2003).

Probabilities of basic events E24 and E74 were derived from the survey data using simple probabilistic models.

Excavation Depth Exceeding Cover Depth (E24)

Excavation depth data obtained from the survey was used to construct the two probability distributions shown in Figure 3.1: one for developed areas and cold regions and the other for all other areas. The excavation depth in the former category is greater than that in the latter because utility lines are buried deeper in developed areas for additional soil protection and in cold regions to avoid frost damage.

In Figure 3.1, the probability of excavating over a given depth represents the likelihood that the excavation equipment will reach a buried pipe if the soil cover is shallower than the given depth. In this context, the curves based on survey data shown in Figure 3.1 define the probability of basic event E24. As an example, an uncontrolled excavation over a pipeline buried one metre (3.3 feet) deep in "other areas" has a 20% chance of hitting the pipe. Note that a depth of one metre corresponds to the average cover depth estimated by survey respondents for Class 1 locations.

In verifying the survey data in Figure 3.1, it was found that the slope of the middle section (which deals with the common range of cover depths) is similar to those derived from pipeline incident data (shown in the figure as dashed curves and plotted against the y-axis on the right side). Since the historical trend curves are based on the relative decrease in damage incidents as cover depth increases, they can be used to evaluate the slope of survey curves, but cannot verify the absolute probability values. This is because the frequency of damage incidents is proportional to the probability of basic event E24, according to the fault tree model described in Section 2.

The historical trends are based on the incident data collected by Gasunie (Jager et al. 2003) and British Gas (Corder 1995). This Gasunie trend reported by Jager et al. (2003) was obtained by analyzing the influence of cover depth on the frequency of excavation damage for Gasunie's pipelines. The analysis utilized data regarding damage frequency as a function of cover depth and the distribution of cover depth throughout Gasunie's system. Jager et al. concluded that, on average, the damage frequency decreases by a factor of ten when the cover depth increases by 0.96 m.

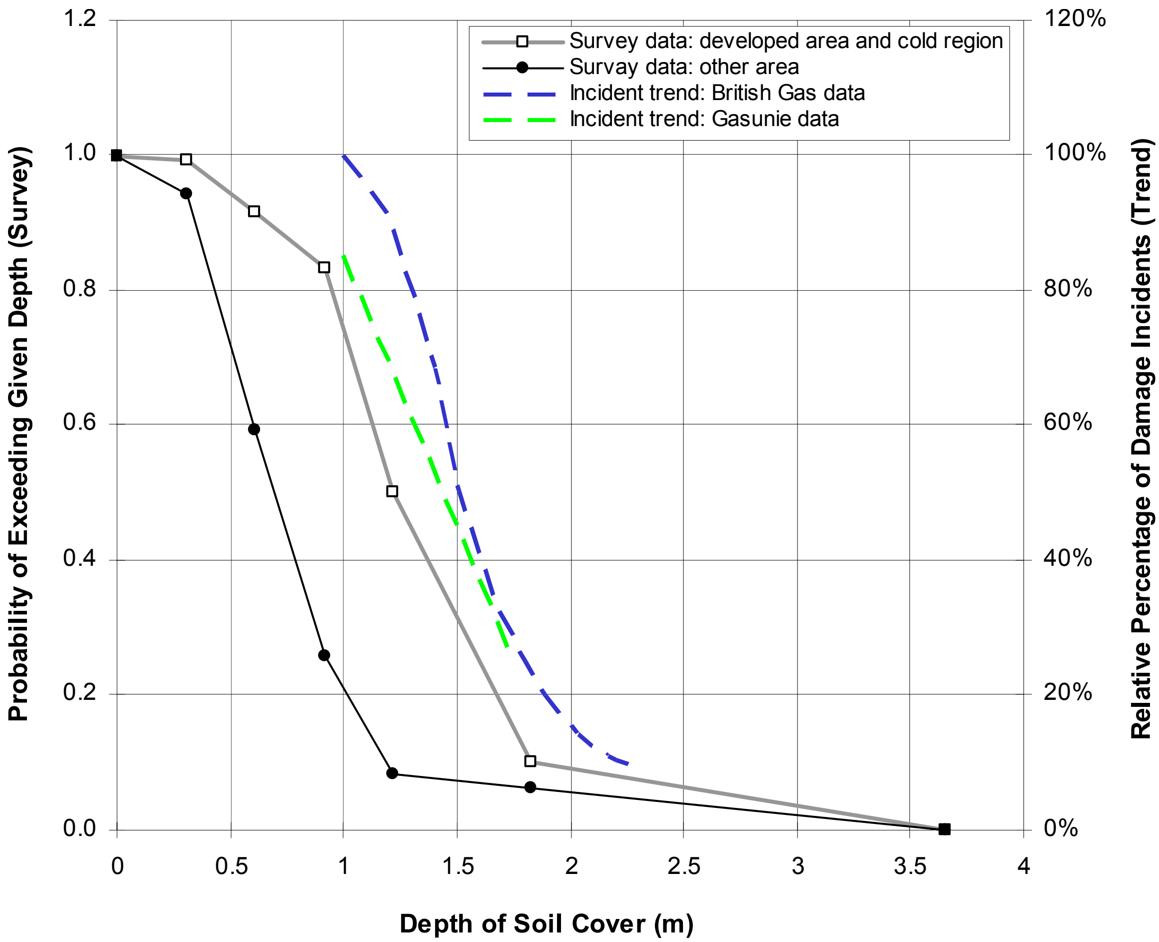


Figure 3.1 Probability Distribution of Excavation Depth Exceeding Cover Depth

No Patrol during Excavation (E74)

The key variable to the derivation of this basic event probability is the time to excavate, or the time between a third party moving onto a pipeline right-of-way (i.e. the activity becomes visible and detectable) and starting to excavate on the pipeline alignment. Once excavation starts, the third party may hit the pipeline and a patrol taking place after this point is considered ineffective.

An activity will not be detected if the time to the next patrol exceeds the time to excavate, or

$$p\text{ (activity not detected)} = p\text{ (time to excavate < time to next patrol)} \qquad [3.1]$$

where p ( ) denotes the probability of the event described in the brackets.

The survey included a question designed to gather data on the "time to excavate". Based on survey responses, it was estimated that the probability of time to excavate has cumulative probability values of 10%, 50% and 90% corresponding to 2 hours, 6 hours and 2 business days, respectively. This probability is denoted as $p_{t\_ext}(t)$ and is plotted in Figure 3.2.

It is recognized that the probability of detection failure is the probability of p_{t_ext} conditional upon the probability of a third party moving onto the right-of-way (p_{t_ROW}). If the time interval between patrols is denoted as t_o and a third party moves onto the right-of-way at time t from the previous patrol, the remaining time to the next patrol is $(t_o - t)$. The probability that the excavation will start before next patrol (or that it will not be detected in time) is $p_{t\_ext}(t_o - t)$. By assuming that a third party may move onto the right-of-way randomly at any time between patrols (or $p_{t\_ROW}(t) = t_o^{-1}$), Equation [3.1] becomes

$$p\text{ (activity not detected)} = \int_0^{t_o} p(\text{time to excavate} < t_o - t)\, dp(\text{third party moves to ROW at } t)$$

$$= \int_0^{t_o} p_{t\_ext}(t_o - t)\; d[p_{t\_ROW}(t)] \;=\; \int_0^{t_o} p_{t\_ext}(t_o - t)\, t_o^{-1}\, dt \qquad [3.2]$$

The resulting probability curve is shown in Figure 3.2 and the probability values corresponding to typical patrol frequencies are listed in Table 3.1. Based on these results, a patrol frequency of less than once per month will detect less than 5% of unreported excavations. The effectiveness of periodic patrols does not improve significantly unless the patrol is carried out on a daily basis, when 70% of unreported excavations can be detected.

3.3 Probabilities Based on Survey of One-call Centres

A survey of one-call centres was carried out during this study as a data gathering effort to quantify probabilities for basic events E83 to E87. In the survey questionnaire, respondents were asked to select the range of probability (e.g. 10 to 20%) that is most applicable to the likelihood of an occurrence, which was essentially a condition for one of the five basic events. In total, there were 19 such choices in the questionnaire, corresponding to 19 conditions for these five basic events.

Over 50 one-call centres in the United States and Canada were contacted during this survey. Fifteen responses were received from centres that cover 15 states in the U.S. and two provinces in Canada. These were Arizona, California, Colorado, Connecticut, Hawaii, Illinois, Mississippi, Montana, Nevada, New Mexico, Ohio, South Carolina, South Dakota, Texas, Washington, Alberta and Quebec.

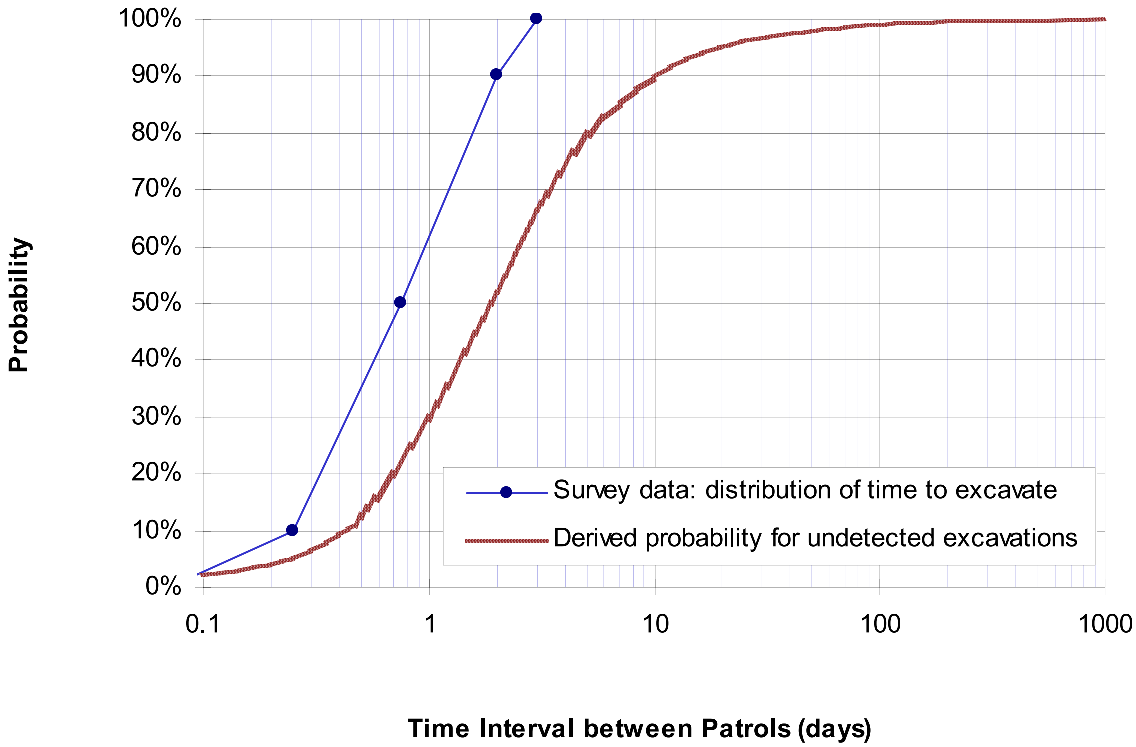


Figure 3.2 Probability Distributions Related to the Effectiveness of Right-of-Way Patrol

Following a review of survey responses, several one-call centres were contacted for clarifications and comments. This follow-up communication provided insights into the factors that influence prevention effectiveness. Survey results were complied and are included in Appendix A.

Probability of Basic Events

Ineffective One-call Services (E83)

This basic event deals with the failure of a third party to notify the one-call centre due to ineffective one-call services in the area. This could result from low company participation in the one-call membership or exemption of utility and transportation workers from being required to notify one-call.

The majority of survey respondents agreed that third parties are more likely to notify one-call centres if they know that exemption of notification is limited and that participation in one-call membership is high. In areas where exemptions cover a very narrow range of activities, such as graveyards, non-pressurized drains or water lines, and sewer line applications, survey participants indicated that exemption has little effect on the one-call notification rate. However, some survey participants argued that notifying the one-call centre is not affected because third parties may not be aware of one-call participation or exemption of notification.

Table 3.1 shows the average probabilities corresponding to three participation levels, based on the survey results. Reponses for low company participation has the highest spread with a standard deviation of 28%, while those for the intermediate and high participation have a smaller standard deviation of about 15%.

An additional question regarding multiple one-call centres in the same state/province was included in this survey. Five out of thirteen one-call centres in the U.S. indicated that there was more than one centre in their states, but that these centres tend to cover different parts of the same state.

Failure of Notification Enforcement (E84)

This basic event concerns failure of a third party to notify the one-call centre due to ineffective enforcement. The level of enforcement varies from voluntary notification to criminal prosecution for excavating and damaging pipelines without notifying one-call. Survey participants regarded criminal prosecution as the most effective enforcement method, followed by civil penalties with corrective actions.

Many participants commented that even though state laws stipulate severe penalties for third parties who fail to notify one-call centres, the lack of resources to enforce such laws reduces their effectiveness. It was learned from participants that, in some areas, corrective measures are applied to repetitive offenders.

Table 3.2 illustrates the four levels of enforcement and their corresponding probabilities based on the average of the survey responses. Note that the standard deviation for the estimated probabilities of all questions did not exceed 18%.

Probability of Basic Events

Level of Enforcement	Probability that a Third Party Fails to Notify One-call
Voluntary	0.44
Civil penalties (monetary penalties)	0.27
Civil penalties with corrective action	0.21
Criminal prosecution	0.19

Table 3.2 Results from One-call Survey

In developing the probabilities for this basic event, additional results from a survey addressed to pipeline operators were considered (see Table 3.3). While both groups agreed that enforcement by civil penalties will significantly reduce the probability of not notifying, operators had a higher level of confidence in the effectiveness of this measure than did one-call centres. In addition, operators indicated that enforcement levels designated as voluntary, mandatory without enforcement and civil penalties were equally likely in areas covered by the survey. A right-of-way agreement between the pipeline operator and a third party was regarded as the most effective method, although it is only commonly used for major utility companies.

Level of Enforcement	Probability That a Third party Fails to Notify One-call
Voluntary	0.58
Mandatory without enforcement	0.33
Mandatory plus civil penalties	0.14
Right-of-way agreement	0.11

Table 3.3 Results from Operator Survey

Probabilities from Tables 3.2 and 3.3 were consolidated into the six values displayed in Table 3.1. The resulting probabilities reflect the average of those reported by the two survey groups, and the probability reductions estimated by one-call centres for different levels of enforcement.

Even though notification enforcement has been widely regarded as an important issue, data on enforcement effectiveness are not readily available. In many cases, the reported effectiveness data resulted from a number of factors. For example, a reduction in hits per 1,000 locates by a factor of three has been reported in Virginia and Minnesota over a ten-year period, during which enforcement programs and levy fines were implemented (Hereth et al. 2006). However, this reduction could be partly attributed to factors other than the increase of notification due to enforcement. For instance, it could be influenced by an increase in notification rate due to increased public awareness, or by a decrease in hits due to improved locating practices or enhanced excavation procedures.

One-call Centre Not Accessible (E85)

When one-call is not accessible due to limited operating hours, long waits on the phone, or lack of alternative notification methods, the third party may abandon the attempt to notify. Although the vast majority of one-call centres can receive notifications 24 hours a day, 7 days a week, through websites and faxes, these are generally processed during office hours only. Figure 3.3 illustrates the various hours of operation for 66 one-call centres in North America. It was found that more than 40 centres (over 60%) operate 24 hours a day. Furthermore, many participants commented that most one-call centres ensure that the waiting time on the phone does not exceed one to two minutes.

Survey participants indicated that most notifications are received through phone and Internet. Fax notifications are less common because they often require follow-up with the third party to provide additional information on the dig location. Many one-call centres reported that there are a growing number of third parties that send electronic notifications. In some areas, one-quarter of notifications are received through the Internet.

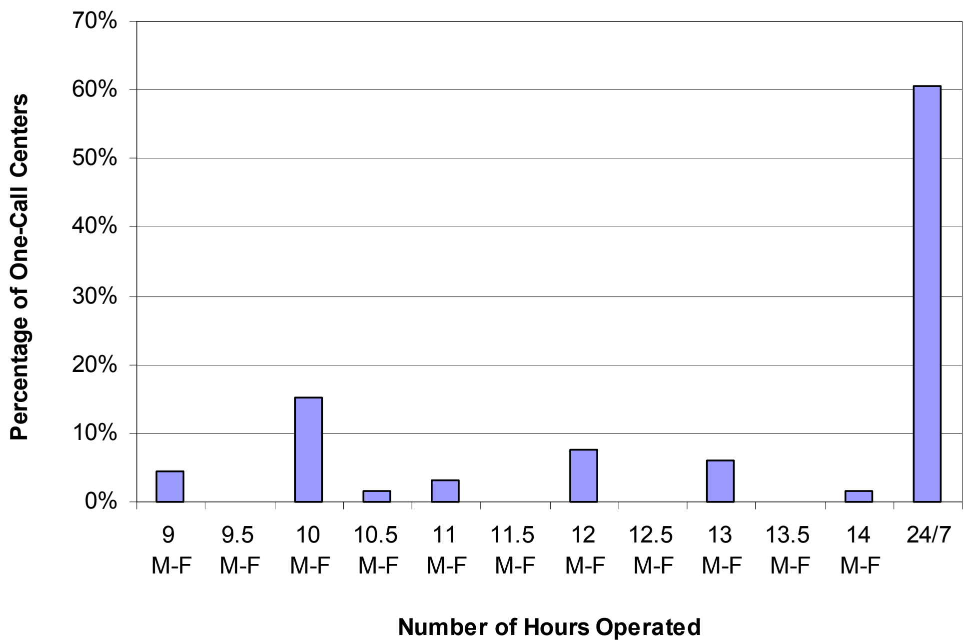


Figure 3.3 Hours of Operation for One-call Centres in the U.S. and Canada

The four levels of accessibility considered in this study and their corresponding average probabilities obtained from the survey are included in Table 3.1. For each level, probability estimates had a standard deviation of less than 25%.

One-call Response Delayed (E86)

Nearly 50% of one-call centres involved in this study issue 5 to 7 tickets for each locate request. This ratio is 3 to 5 for 33% of the centres and 9 to 11 for 17% of the centres. Timely processing of locate requests and notification of affected facility owners depends on the level of staffing, the technology used to search the excavation site and affected utilities, and the method used to generate and deliver one-call tickets. For instance, in comparison to conventional grid-based systems (Figure 3.4) in which all companies having facilities within the same grid of the excavation site are notified, a polygon-based database is perceived to be more efficient as it considerably reduces the number of one-call tickets. In addition, it is believed that automated technologies to prepare and deliver one-call tickets can further reduce the time required to process locate requests.

Even with a large spread in probability estimates, the survey responses show that, on average, participants believe polygon- or grid-based systems do not significantly reduce the delay in processing locate requests. It was also pointed out that accurate polygon-based information is not yet available for most buried facilities including oil and gas pipelines. As shown in Table 3.1, the probability estimated by one-call centres drops from 52% for the first condition (understaffed, grid-based, manual or semi-automated processing) to 10% for the third (fully-staffed, polygon-based, fully-automated processing).

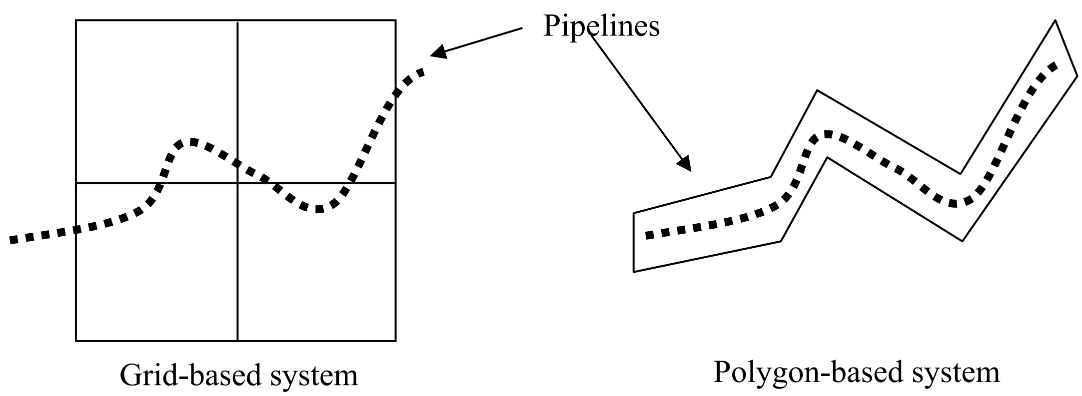


Figure 3.4 Grid- and Polygon-based Systems

One-call Fails to Notify Operator (E87)

This basic event deals with failure of a one-call centre to notify the pipeline operator due to operational errors related to staff training and quality assurance. The survey results showed that most participants believe that the chance of one-call error is relatively high when staff training and quality assurance are inadequate, and that this probability drops significantly when adequate training is provided to ensure that guidelines and standards are followed. All one-call centres contacted asserted that they follow guidelines and/or standards. The majority follow the Common Ground Alliance (CGA) Best Practices, but there are many that follow their own call guidelines along with those of CGA.

The three conditions considered in the survey and their corresponding probabilities are listed in Table 3.1. The spread in probability estimates was relatively large for the first two conditions, as some respondents believed that one-call centres always notify pipeline operators regardless of their operational standards, staff training and quality assurance.

3.4 Probabilities Based on Survey of Excavating Contractors

In order to define the probabilities of basic events E41, E43 and E94, C-FER designed a 13-question survey based on the 13 conditions considered for these basic events. Questions were answered by personnel from 17 excavation and construction companies from Canada and the United States. Detailed results of this survey are shown in Appendix B.

Inadequate Excavation Procedure (E41)

This basic event deals with mechanical interference with a marked pipeline alignment (without necessarily resulting in a hit) due to inadequate excavation procedures. There were five levels considered for this basic event, ranging from the absence of an excavation procedure to the most rigorous requirement of soft digging under site supervision.

In most cases, survey responses had a low standard deviation. For probabilities associated with three levels, the standard deviations were equal or lower than 12%. It was found that the absence of an excavation procedure could drastically increase the risk of interference with the pipeline alignment, while site supervision and soft digging could decrease this risk by a factor of over five. The probability displayed in Table 3.1 varies from 8% to 54%.

A few Canadian participants noted that there could be differences between excavation requirements stipulated in federal and provincial regulations. Thus, the probability in question could vary with location depending on whether the pipeline is within federal or provincial jurisdiction. Furthermore, several companies noted that their workers are asked not to dig if they are not provided with clear excavation procedures.

Failure of Site Supervision (E43)

Site supervision within a buffer zone is considered an important safety measure in API RP 1166, in which a site visit (called excavation monitoring in API RP 1166) is required for digs within 25 feet of pipeline, and continuous site supervision (called excavation observation in API RP 1166) is required for digs within a buffer zone of 5 feet. Site supervision was categorized into five conditions with varying supervision frequencies and durations. It was found that the probability of equipment interference with a marked pipeline is vastly dependent on site supervision.

Survey responses to all conditions show a similar pattern: they all have a small spread and the same probability range of 10 to 20% was selected by the highest percentage of participants (see Appendix B, Question #2, Selection #1). The tendency of selecting the small probability was related to the belief that very few third parties interfere with marked pipeline alignment regardless of the level of supervision. However, others observed that site supervision could reduce the probability of interference with pipeline alignment, which causes the average probabilities to decrease from 0.36 to 0.09 as shown in Table 3.1. It is noted that the pipeline operators in the 1997 survey estimated that the probability corresponding to the last condition to be 0.06.

Ineffective Communication Message (E94)

This basic event deals with the likelihood that a third party fails to notify a one-call centre because of low public awareness associated with ineffective communication messages.

The public awareness message should be conveyed in the languages spoken by the majority of the intended audience and should contain very specific, clear and concise information. According to API RP 1162, the messages should

- emphasize that every person must contact the one-call centre before digging;
- explain what happens when the one-call centre is notified by the third party;
- provide the local or toll-free number (as well as the fax number and e-mail address, if available) for the one-call centre;
- emphasize the fact that one-call centre services are free for the caller (some exceptions might apply in certain areas); and
- remind the equipment operator that calling before digging is required by law (when applicable).

As an example, Figure 3.5 shows the Dig Safely logos developed by the Office of Pipeline Safety. These simple, eye-catching and recognizable graphics communicate four simple points to third parties: call before digging, wait the required time for marking, respect the marks and dig with care.

Figure 3.5 Examples of "Dig Safely" Awareness Graphics (from www.digsafely.com)

Four different types of communication messages were considered for this basic event. For the two cases related to messages lacking clarity and details, there was a significant spread in the survey responses (standard deviation of 25 to 30%) since many of them believe that the vast majority of third parties notify the one-call centre regardless of the content of the communication message. However, other participants believe that the notification level is directly related to communication efficiency, resulting in average probabilities varying from 14% to 55%.

3.5 Probabilities Based on British Gas Tests

British Gas conducted a total of 53 tests to study the effectiveness of protective measures (Corder 1995). At the testing site, the pipes were buried underneath warning tape with or without mechanical protection consisting of concrete slabs or steel plates. Contractors unaware of the pipes were hired to excavate trenches at depths greater than the cover depth, while researchers observed through a hidden video to determine whether or not mechanical protection and warning tape prevented third parties from hitting the pipe. Results of these tests were used to derive the probabilities of basic events E33, E34 and E52.

Probability of Basic Events

The probability that mechanical protection will fail to protect the pipeline (basic event E34) is related to whether or not it is used in conjunction with warning tape. The experiments by British Gas indicated that with unmarked, three-metre wide concrete slabs, contractors in 13 out of 16 tests terminated excavation or at least continued with great care. Only in three cases were the pipes damaged after the contractors removed the slab and continued to excavate, leading to a probability of 19% for hitting the pipeline. However, no damage occurred in any of the 30 tests involving yellow-striped concrete slabs or steel plates in combination with warning tape. This indicates that the hit frequency in this case is smaller than 1 in 31 or 3.2% (assuming conservatively that damage would occur in the 31st test). Based on the test results, a conservative probability of 0.20 is adopted in E34 for mechanical protection installed without warning signs and 0.05 for protection with clear warning signs (Table 3.1). Similar probabilities were used for ground surface protection represented by basic event E33.

Buried warning tape (Figure 3.6) is commonly used by utility companies to prevent damage when the activity is not reported or the line is not properly marked. This tape is typically made from low-density polyethylene for durability in an underground environment, and is colour coded according to the standard set by American Public Works Association (APWA).

During the same series of tests conducted by British Gas, warning tape used without mechanical protection deterred the contractors in two of five tests. Pipes were damaged in the other three tests because the tape was not detected by the equipment operator or was obscured from view by site conditions. As shown in Table 3.1, a failure probability of 0.6 was assumed for basic event E52 for single warning tape. In lieu of test data for multiple tapes, it was assumed that each tape has an independent probability of not being seen during an excavation. Consequently, a probability of 0.36 was adopted for a dual tape configuration. Similarly, 0.18 was assumed for cases that involve three tapes or a warning mesh (shown in Figure 3.7).

Figure 3.6 Buried Warning Tapes

Figure 3.7 Underground Warning Mesh

3.6 Probabilities Related to Communication Frequency

In addition to the message content, delivery method and coverage of public awareness education, communication frequency is regarded as a vital parameter in API RP 1162. To address this key factor, memory test results and the breakdown of third parties with respect to different communication frequencies were used to derive probabilities for basic events E42 and E92.

Inadequate Communication Frequency (E92)

Effectiveness associated with the frequency of public awareness education is influenced by the composition of the target audience, communication frequency for each audience group and the likelihood to retain information over time.

Table 3.4 shows a breakdown of third-party groups excavating on pipelines, based on 21,688 facility damage incidents reported to the DIRT database in 2004 from 32 U.S. states (CGA 2005). As expected, contractors are by far the largest group.

Probability of Basic Events

Third Party Group	Percentage
Contractors	80 %
Residents	13 %
Public Workers	5 %
Emergency Workers	2 %

Table 3.4 Breakdown by Third Party Groups

Communication frequencies applicable to various third-party groups are recommended in API RP 1162, as shown in Table 3.5. When weighted by the breakdown of third party groups, the average recommended communication intervals are 1.2 years for third parties near most pipelines and 1.1 years for those near gas distribution pipelines.

Third Party Group	Communication Frequency
Contractors	Annual
Residents	Once every two years *(Annual for gas distribution lines)*
Public Workers	Once every three years
Emergency Workers	Annual
Weighed average for all groups	**Once every 1.2 years** ***(1.1 years for gas distribution lines)***

Table 3.5 Frequency of Public Awareness Communication

The findings of two studies in cognitive psychology were used to define the probability of not notifying one-call centres as a function of the frequency of public awareness education. Both studies recorded the percentage of correct recall as a function of time, and provided analytical descriptions of memory decay over five to six years. The results from these studies were complied (shown in Figure 3.8) and adopted here to predict the percentage of third parties that will forget to notify one-call. As shown in the figure, this probability increases approximately linearly with time.

In deriving the probability for E92, it was assumed that each excavation decision involves at least two individuals, and the probabilities that these individuals will forget to notify are independent. Consequently, if the probability of forgetting is p_1 for one person, then the combined probability is p_1^2. The resulting probability values corresponding to varying communication frequencies are listed in Table 3.1. It is noted that the 1.1 year average frequency recommended by API RP 1162 corresponds to a probability of about 2%, and is thus adequate to ensure retention of the information communicated.

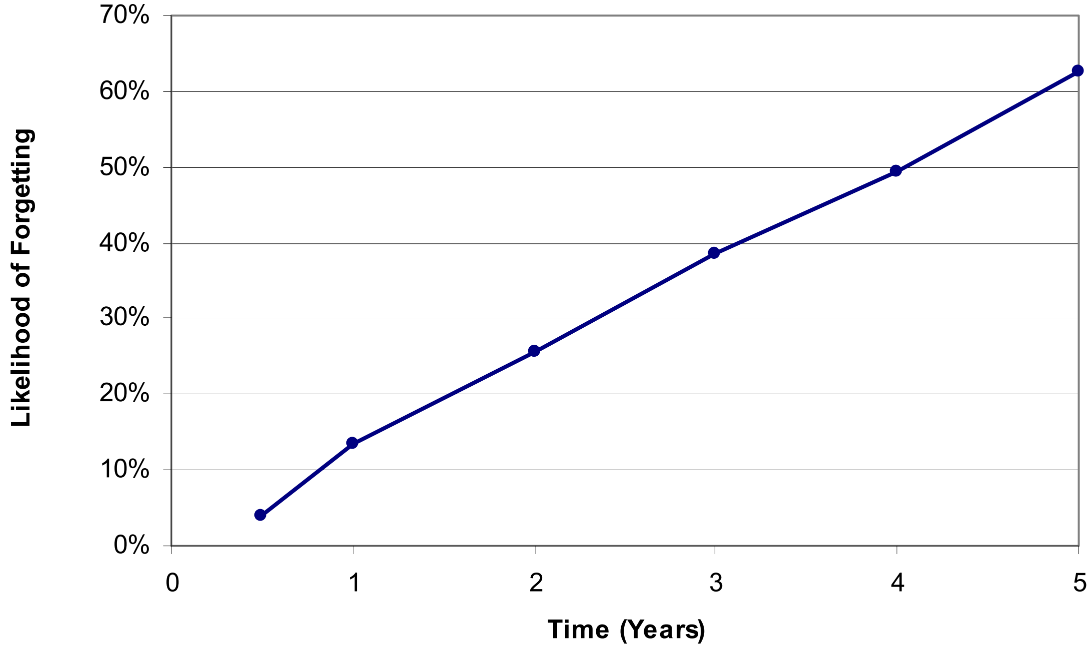


Figure 3.8 Probability of Failing to Retain Information

Inadequate Awareness of Excavation Procedure (E42)

This basic event addresses the accidental interference on a marked pipeline alignment due to low awareness of existing excavation procedures. Since the associated probability is affected by the coverage and frequency of education programs related to safe excavation, eight conditions based on two coverage scenarios and four communication frequencies were considered (Table 3.1).

The first coverage scenario assumes that training is provided to all third parties including contractors, residents, public workers and emergency staff, while the second one limits training to 50% of contractors.

Derivation of the probabilities shown in Table 3.1 utilized the probability of failing to retain long-term memory (Figure 3.8). For a given frequency, the probability of each individual being unaware of the excavation procedure is estimated by weighting the probability shown in the figure by the percentages corresponding to the selected coverage scenario. By assuming that each excavation involves at least two individuals and that their probabilities of not recalling excavation procedures are independent, the final probability values shown in Table 3.1 were obtained by multiplying the (equal) probabilities for two individuals.

3.7 Probabilities from Other Sources

Failure of Permanent Surface Markers (E51)

Above-surface markers, such as paved walkways, concrete barriers and fences, can be used to identify the location of buried pipelines and warn third parties. The effectiveness of surface markers is further enhanced if explicit warning signs are incorporated. However, the effect of surface markers can be diminished in some weather conditions (e.g. snow on the ground).

This basic event deals with the failure of permanent surface markers to indicate the pipeline location. Four conditions that reflect the presence of surface markers, the use of warning signs and the visibility in different weather conditions were implemented for this event. Probability values assumed for these four conditions are presented in Table 3.1.

Ineffective Marking (E68)

Incidents related to marking errors are usually caused by incorrect temporary markers (wrong markers for the facility or markers that do not cover the excavation area) or markers that fade away before the excavation is completed. In this context, key factors for establishing reliable temporary markers include following marking standards that employ symbols to convey information about buried facilities, maintaining markers throughout the excavation and pre-marking the excavation area to ensure that facilities are properly located and marked. Important facility information that can be conveyed by temporary makers includes the type of facility (by following a standard colour code), change of direction, presence of multiple lines and width of the facility.

Damage incident data collected by DIRT (CGA 2005) suggest that for gas pipelines, the number of incidents caused by marking errors is comparable to those associated with locating errors. Based on experience with the frequency of locating errors, it is assumed that the failure probability for typical marking practice (proper marking without maintenance) is 15%. By examining the DIRT data in terms of the breakdown between visible and invisible markers, it is assumed that a more rigorous approach (e.g. pre-marking and maintenance of temporary markers) could reduce the probability of failure to 5%.

Ineffective Monitoring Devices (E76)

This basic event deals with the continuous monitoring of activities on the right-of-way. (Periodic detection such as patrol or satellite monitoring is dealt with in E74.) Examples of continuous monitoring devices include video monitors and microwave motion detectors.

Once excavation has started, detection is unlikely to lead to impact prevention and is therefore no longer considered effective. For this reason, devices that rely on vibration signals generated by excavation equipment (e.g. seismic or acoustic signals) to detect ongoing excavations are not included in this basic event at this time.

The ability to detect equipment movement may vary with weather conditions and the reliability of the chosen technology. The probabilities listed in Table 3.1 include an upper value (1.0 for monitoring devices not available) and a lower value (0.05 for monitoring technologies that are highly reliable in all conditions). In lieu of field data, an intermediate value of 0.25 was assigned based on the assumption that the effectiveness of the monitoring device decreases to 50% for 50% of the time.

4. MODEL VALIDATION

4.1 Minimal Cut Sets of Condensed Model

By definition, a cut set is a group of basic events that are sufficient to cause the top event. Each minimal cut set is unique, containing only those basic events that are necessary for the top event to occur. For instance, while all 13 basic and undeveloped events in the condensed model (Figure 2.1) form a cut set, only a few of them are required for a minimal cut set. As an example, a combination of events E21, E23, E24 and E31 is sufficient for the top event (E11) to take place, and therefore forms a minimal cut set

In order to qualitatively validate the structure of the fault tree model, minimal cut-set analyses were performed to verify if the model adequately addresses common causes associated with excavation damage, and if each cut set represents a plausible cause for such damage.

Analysis results for the condensed model are shown in Table 4.1. By listing the cut sets and then eliminating unnecessary basic events, six minimal cut sets are formed as shown in the table. Each cut set corresponds to an event combination that could conceivably cause an impact event.

Cut Set	Basic Events	Cause Description	Cause Reported in Past Incidents
M1	E21, E23, E24, E44, E62, E81, E82	Third party does not notify due to low public awareness and ineffective right-of-way signs.	No one-call
M2	E21, E23, E24, E44, E62, E72	Third party chooses not to notify.	No one-call
M3	E21, E23, E24, E44, E62, E73	One-call fails to effectively respond to the notification by the third party.	Not located
M4	E21, E23, E24, E44, E55	Locating or marking error.	Locating/marking error
M5	E21, E23, E24, E44, E54	Operator fails to effectively respond to the one-call ticket.	Not located
M6	E21, E23, E24, E31	Third party accidentally hits a marked line due to errors in excavation procedure.	Digging error

Table 4.1 Minimal Cut Sets of Condensed Fault Tree

It is noted that events E21, E23 and E24 (excavation on pipeline alignment, failure of protection and excavation depth exceeding cover depth, respectively) appear in all minimal cut sets in Table 4.1 because they are connected to the top event by an AND gate as shown in Figure 2.1. In addition to these three basic events, each minimal cut set contains a different group of other basic events that represents a way in which preventative measures fail (E22).

The validity of the model was further examined by comparing the causes represented by the minimal cut sets with those reported in incident data (e.g. CGA 2005). In order to identify leading causes for mechanical damage, incident data are often reported in certain major cause categories, such as *no one-call*, *not located*, *digging error* and *locating/marking error*. The right column of Table 4.1 shows that these categories are represented by the six minimal cut sets.

4.2 Minimal Cut Sets of Detailed Model

Table 4.2 presents the minimal cut sets for the detailed model shown in Figure 2.2. In the column that lists the basic events for each minimal cut set, events E21, E24, E33 and E34 are omitted to avoid repetition. These four basic events are connected to the top event with an AND gate and thus appear in every minimal cut set.

In total, there are 18 minimal cut sets for the detailed model. The cause description in Table 4.2 shows that each set represents a specific root cause of impact. The minimal cut sets are classified into six main categories corresponding to commonly reported causes of excavation damage. These main categories are consistent with the six minimal cut sets shown in Table 4.1 for the condensed model.

The tree structures for both the condensed and detailed models are confirmed by the findings that failure causes identified by minimal cut-sets are plausible and common causes reported in past incidents are represented.

Cut Set	Basic Events *(in addition to E21, E24, E33, E34)*	Cause Description	Main Cause Category
C1	E46, E51, E52, E74, E75, E76, E82, E91	Inadequate communication coverage	Third party unaware of one-call and signs
C2	E46, E51, E52, E74, E75, E76, E82, E92	Inadequate communication frequency	
C3	E46, E51, E52, E74, E75, E76, E82, E93	Ineffective delivery method	
C4	E46, E51, E52, E74, E75, E76, E82, E94	Ineffective message	
C5	E46, E51, E52, E74, E75, E76, E83	Low one-call participation	One-call ignored
C6	E46, E51, E52, E74, E75, E76, E84	Inadequate enforcement	
C7	E46, E51, E52, E74, E75, E76, E85	One-call not accessible	Error in one-call's response
C8	E46, E51, E52, E74, E75, E76, E86	Response delayed	
C9	E46, E51, E52, E74, E75, E76, E87	Incorrect response	
C10	E46, E51, E52, E63	Incorrect response	Error in operator's response
C11	E46, E51, E52, E64	Response delayed	
C12	E46, E51, E52, E65	No response	
C13	E46, E51, E52, E66	Incorrect records	Locating or marking error
C14	E46, E51, E52, E67	Inaccurate locating	
C15	E46, E51, E52, E68	Improper marking	
C16	E41	Inadequate procedure	Error during excavation
C17	E42	Inadequate awareness of excavation procedure	
C18	E43	Inadequate site supervision	

Table 4.2 Minimal Cut Sets of Detailed Model

4.3 Baseline Case

In order to evaluate the fault tree model by comparing analysis results with historical data, a baseline case was selected for which the line attributes and damage prevention practices represent those corresponding to typical pipelines in the United States and Canada. Once the model had been validated, the baseline case was subsequently used in the evaluation of prevention effectiveness described in Section 5.

Table 4.3 displays the selected activity frequency and prevention measures for the baseline case, as well as the corresponding probabilities for all 29 basic events. For the six basic events that require user input, typical probability values were adopted.

Both undeveloped and developed areas were considered in selecting the baseline case. For basic event E21, the activity frequencies in agricultural and residential areas were adopted for undeveloped and developed cases, respectively. Based on the responses of the operator survey (Chen and Nessim 1999), the respective average cover depths were assumed to be 1 m and 1.2 m for undeveloped and developed areas. The values chosen for developed areas are shown in brackets. Probabilities for other basic events are assumed to be identical for both undeveloped and developed cases.

Number	Basic Event	Condition	Probability
E21	Excavation on pipeline alignment	Agricultural *(Residential)*	0.076/km-yr *(0.36/km-yr)*
E24	Excavation depth exceeding cover depth	Cover depth = 1 m *(Cover depth = 1.2 m)*	0.2 *(0.5)*
E33	Failure of surface protection	Surface protection not available	1.00
E34	Failure of buried protection	Buried protection not available	1.00
E41	Inadequate excavation procedure	Site supervision within a tolerance zone by excavation procedure	0.10
E42	Inadequate awareness of excavation procedure	Training provided to all third parties once a year	0.023
E43	Failure of site supervision	Site supervision provided throughout excavation	0.09
E46	Third party fails to avoid alignment	Industry average	0.50
E51	Failure of permanent surface markers	No surface markers	1.00
E52	Failure of permanent buried markers	No buried markers	1.00
E63	Operator's response incorrect	Typical user input	0.05
E64	Operator's response delayed	Response within two days	0.11
E65	Operator fails to respond	Typical user input	0.01
E66	Incorrect pipeline records	Typical user input	0.02
E67	Inaccurate locating	By magnetic tools	0.09
E68	Improper marking	Using pre-marking, following marking standards and maintaining markers throughout excavation	0.05
E74	No patrol during excavation	Biweekly patrols	0.90
E75	Excavation not reported by other employees	Industry average	0.97
E76	Excavation not detected by monitoring devices	Continuous monitoring devices not available	1.00

Table 4.3 Basic Event Probabilities for Baseline Case

Number	Basic Event	Condition	Probability
E82	Failure of right-of-way signs	Signs at all crossings	0.19
E83	Ineffective one-call services	High company participation in the one-call system	0.17
E84	Failure of notification enforcement	Mandatory without enforcement	0.33
E85	One-call not accessible	Notifications can be placed 24/7 by phone, fax, email and voice recording	0.15
E86	One-call response delayed	One-call centre is fully-staffed and uses a polygon based, fully-automated procedure for location search and ticket processing	0.10
E87	One-call fails to notify operator	One-call centre follows standards, has extensive employee training and high quality assurance	0.04
E91	Inadequate communication coverage	Typical user input	0.10
E92	Inadequate communication frequency	Annual	0.02
E93	Ineffective delivery methods	Advertising via community meetings with direct mail-outs and promotion among contractors	0.10
E94	Ineffective message	Message provides one-call number and an overview of one-call operation	0.20

Table 4.3 Basic Event Probabilities for Baseline Case (continued)

4.4 Comparison with Distribution of Damage Causes

In addition to the qualitative validation described in Sections 4.1 and 4.2, the fault tree model was evaluated by comparing the analysis results of the baseline case with historical data on the distribution of common causes for excavation damage incidents and the frequency of such incidents. Here, the distribution refers to the relative percentage by damage causes, and the frequency refers to the number of incidents on a per km-year basis.

Comparison of damage cause distribution was performed using the minimal cut sets described in Section 4.3. While any single minimal cut set is sufficient to cause the top event to occur (an OR relationship), it is noted that all basic events in a minimal cut set must coexist for the top event to occur (an AND relationship). Therefore, the original fault tree can be represented by linking the top event to all minimal cut sets via an OR gate and then connecting the basic events within each minimal cut set by an AND gate. Such a representation allows the probability of top event (p_{E11}) for all causes to be calculated by (see Equation [2.2])

$$p_{E11} = 1 - [(1 - p_{C1})\,(1 - p_{C2})\,(1 - p_{C3}) \cdots\cdots (1 - p_{C18})] \qquad [4.1]$$

where p_{Ci} is the probability of the ith minimal cut set and equals to the product of the probabilities of all basic events included in that minimal cut set. When calculating p_{E11} of a given cause, only those minimal cut sets related to the cause were included in [4.1]. The percentage of incidents attributed to each cause is determined by the ratio between p_{E11} for that cause and p_{E11} for all minimal cut sets. Note that even though the probability obtained from minimal cut sets represents an upper bound value, the estimated distribution by this approach is considered to be sufficiently accurate for the intended purpose.

Historical data regarding damage causes can be obtained from the incident data collected by the Office of Pipeline Safety (OPS) in the United States. The new OPS pipeline incident reporting form provides additional information on causes leading to excavation damage incidents. Table 4.4 presents the 2003 to 2005 pipeline incident data reported to OPS and analyzed by Hereth et al. (2006). As shown in the table, the causes are classified into four categories including all common causes, except errors in excavating on correctly marked pipelines. Note that the percentages shown in the table indicate that more than half of the incidents occurred because operators were not notified.

Also presented in Table 4.4 are the minimal cut sets corresponding to the identified causes and the percentage breakdown based on the fault tree model. Since a considerable fraction of damage incidents were related to excavation errors, and it is possible that such errors caused most incidents in the "other" category, the percentage of excavation error from fault tree analysis is compared to that of the "other" category. While the overall trend is similar for both historical data and analysis results, the comparison with incident data shows that the fault tree model underestimates the frequency of "operator not notified" and overestimates that of the "other" category.

Cause Category	Distribution in Incident Data		Fault Tree	
	Gas Transmission	Hazardous Liquid Transmission	Cut Sets	Distribution
Operator not notified	62%	66%	C1-C10	52%
Pipeline not marked	17%	8%	C10-C12	11%
Mark incorrect	6%	11%	C13-15	10%
Other	15%	15%	C16-C18 (digging errors)	27%

Table 4.4 Causes of Reportable Pipeline Incidents

Information concerning causes of excavation damage is also available from incident data for utility damage. Table 4.5 presents the relative frequencies of different outage causes reported in the DIRT data (CGA 2005), which included incidents in gas and liquid pipelines, telecommunication and power cables, waterlines, and other underground facilities.

Another source of relevant historical data is reportable outages of buried communications cables, which were reported to the U.S. Federal Communications Commissions (USDOT 1993). Both the DIRT and FCC data show that over 50% of incidents occurred because third parties did not notify one-call. In addition, data from both sources suggest that hitting a marked utility line is the second-leading cause of excavation damage. Two other important causes are locating/marking errors and notification without response. Together these four categories make up over 98% of excavation incidents. The comparison with fault tree analysis in Table 4.5 shows a general agreement regarding the relative contributions of the major causes.

Cause Category	Distribution in Incident Data		Fault Tree	
	DIRT 2004	DOT 1993	Cut Sets	Distribution
No notification made to one-call	58%	51%	C1-C7	43%
Insufficient excavation practices	29%	20%	C16-C18	28%
Insufficient locating/marking practices	8%	18%	C14,C15	9%
Facility not located/marked	4.3%	9%	C8,C10-C12	17%
Incorrect facility records/maps	0.5%	N/A	C13	1%
One-call centre error	0.1%	N/A	C9	2%
Other	N/A	2%	N/A	N/A

Table 4.5 Causes of Utility Damage

4.5 Comparison with Frequency of Damage Incidents

Table 4.6 presents the analysis results of the baseline case in terms of hit frequency and failure frequency for both undeveloped and developed areas. The frequencies of hits were calculated from the fault tree model using the basic event probabilities defined in Table 4.3. The frequencies of pipeline failures were obtained by multiplying the hit frequencies by the probability of immediate failure given a hit. On average, the conditional failure probability was estimated by Fuglem et al. (2001) to be 0.05 in Class 1 areas and 0.008 in Class 3 areas. These values represent weighted averages for gas transmission pipelines regulated by DOT, with different diameters, wall thicknesses and steel grades.

Location Type	Hits to Pipelines (per km-year)	Pipeline Failures (per km-year)
Undeveloped areas	7.1E-03	3.6E-04
Developed areas	8.4E-02	6.7E-04

Table 4.6 Incident Frequencies based on Fault Tree Model

The data collected from pipeline operators by the Gas Research Institute (Doctor et al. 1995) contain information regarding hit frequencies for gas transmission and distribution pipelines. While the average hit frequency for transmission operators was 3E-3 per km-year, this rate was as high as 6E-3 per km-year for the operator who reported the majority of the hits. For local distribution companies, the hit frequencies varied from 1.2E-2 to 1.1E-1 per km-year, with an average of 4E-2 per km-year. The frequencies by fault tree analysis shown in Table 4.6 are within the range of the GRI data, even though they are higher than average values.

Table 4.7 presents leak frequencies due to third party damage reported to OPS in 2002 and 2003 for gas transmission pipeline in the United States (Hereth et al. 2006). Only the four states with the total distance greater than 15,000 km were included. The reported leak rates vary from 1E-4 to 6E-4 per km-year. The analysis results shown in Table 4.6 are in general agreement with those of Table 4.7.

State	Pipeline Distance (km)	Number of Leaks (2002 to 2003)	Leak Frequency (per km-year)
Texas	84632	34	2.0E-04
Louisiana	33308	9	1.4E-04
California	19744	16	4.1E-04
Mississippi	16327	18	5.5E-04

Table 4.7 Leaks due to Excavation Damage for Gas Transmission Lines

4.6 Application to Gas Distribution Systems

In principle, the fault tree model and input probabilities are applicable to gas distribution systems. The baseline case for developed areas (Section 4.3) illustrates application to distribution pipelines.

However, it is recognized that the model development work described in Sections 2 and 3 was primarily based on information related to transmission pipelines. This was particularly evident in two aspects:

- The data gathered in Phase 1 regarding prevention practices were obtained from several transmission companies (Chen and Stephens 2005). This data set was used to develop the structure of the fault tree model.
- The probabilities of about one-third of the basic events were derived from a survey of gas transmission companies (Chen and Nessim 1999).

Operators of distribution pipelines indicated that some of their prevention practices are different from those used by transmission operators. In this context, modifications to the fault tree model may be required for distribution systems. Such modifications are to be based on data regarding the operating environment and prevention practices specific to distribution operators.

5. EFFECTIVENESS EVALUATION

5.1 Selection of Analysis Scenarios

The effectiveness of a given prevention method can be measured by the resulting reduction in pipeline impact frequency. The evaluation of these methods was carried out for four categories of prevention measures:

- Construction measures that can be used when building new pipelines (e.g. use of buried or surface protection, greater cover depth);
- Operation and maintenance measures that are applicable to existing pipelines (e.g. patrol, right-of-way signs, supervision of excavation site);
- Regulatory and public education measures that require joint government-industry efforts (e.g. message delivery method, communication frequency, enforcement of dig notification); and
- One-call system measures that concern response to dig notifications and have a direct impact on excavation activities (e.g. one-call's accessibility, one-call's efficiency).

The fault tree model described in previous sections was used to assess the effectiveness of commonly used damage prevention measures. The baseline case used in the analysis of undeveloped areas is described in Section 4 of this report. The probability of each event was modified individually while maintaining all other basic events at the baseline probability. Using this method, the impact of each of the 22 basic events on the hit rate frequency was examined. When possible, two conditions were considered for each basic event: above and below the baseline probability. However, when the baseline condition was at a maximum/minimum value, the sensitivity analysis was conducted by considering a lower/higher probability only.

While the methodology and analysis procedure described in this report are generic, it is noted that the different scenarios implemented in the fault tree model are based on research and survey results and should be representative of the majority of pipelines.

5.2 Effectiveness of Construction Measures

Figure 5.1 illustrates the effectiveness of five basic events and their impact on the pipeline hit rate:

- Basic events E51 and E52 have four conditions each that describe surface and buried permanent markers. By using all-weather continuous surface markers or installing a warning mesh or multiple warning tape, the top event probability decreases by 55% and 46%, respectively.

- Basic events E33 and E34 have three conditions each that describe surface and buried protection. It was found that using surface protective devices with warning signs or marked underground mechanical protection reduces the hit rate by 95% in each case.

- Basic event E24 corresponds to several cover depth values. The analysis showed that cover depth has a significant effect on the hit rate. Increasing the cover depth in undeveloped areas from 1.0 to 1.2 m achieves a reduction of 60%, while decreasing it to 0.8 m results in an increase of 110%.

Construction measures were found to have a substantial effect on the hit probability. However, achieving such reductions in the hit frequency could be expensive and labour-intensive. Installing buried and surface protection mechanisms or increasing the soil cover depth is costly for existing lines, but they could be considered for new pipelines.

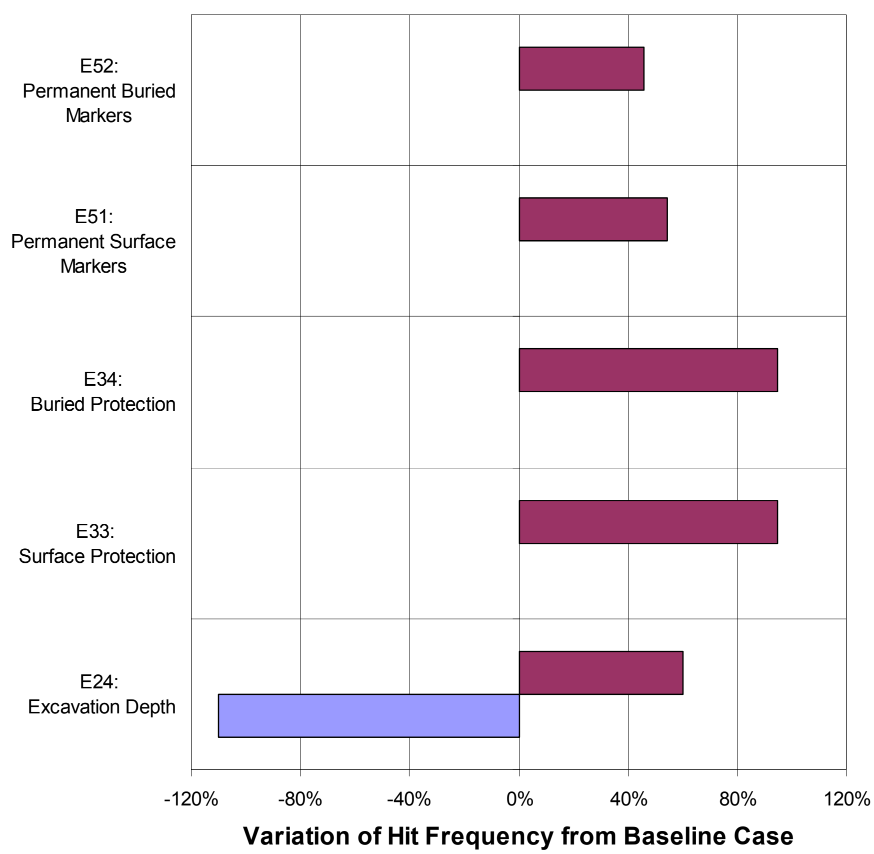


Figure 5.1 Effectiveness of Five Construction Measures

5.3 Effectiveness of Operation and Maintenance Measures

Figure 5.2 shows the effectiveness of eight measures related to basic events and their influence on the probability of pipeline hit:

- Basic event E41 has five different conditions describing various excavation procedures. The condition chosen in the baseline model represents supervised excavation within a buffer zone, which has a relatively low hit rate. Enhancing this condition to include site supervision and soft digging only achieves a hit rate reduction of 3%. An unsupervised excavation lacking documented procedures would result in a 54% increase in the hit probability.

- Basic event E43 has four conditions dealing with site supervision. When site supervision is provided during part of the excavation only, the hit frequency increases by 9% compared to the case for which supervision covers the entire duration of the excavation.

- Basic event E64 is influenced by four conditions specifying the operator's response time (ranging from over three days to less than one day). Shortening the response time from two days to one day reduces the hit rate by 3%, while extending it to three days increases it by 3%.

- Basic event E67 has five conditions describing various levels of locating accuracy. Switching from the use of magnetic tools to ground penetration radar increases the hit probability by 9%, while using buried electronic markers decreases it by 2%.

- Basic event E68 has four types of pipeline temporary markers. Switching from well maintained temporary markers installed according to standards to ones that do not meet standards increases the pipeline hit rate by 13%.

- Basic event E74 deals with the probability that right-of-way patrols fail to detect an ongoing excavation activity before interference with the pipeline alignment. Eight patrol frequencies ranging from semi-daily to annually were considered. Replacing biweekly patrols with monthly patrols increases the hit rate by 2% while implementing weekly patrols reduces it by 4%.

- Basic event E76 has three conditions representing different monitoring devices. Use of continuous monitoring devices with high reliability reduces the hit rate by 31% compared to the baseline case, which assumes that monitoring devices were not used.

- Basic event E82 deals with the presence of right-of-way signs. The hit frequency would increase by less than 0.5% if right-of-way signs were only present at selected crossings as a substitute for all crossings.

As shown in Figure 5.2, using an adequate excavation procedure could have a considerable impact on the hit frequency. In addition, effective monitoring of the right-of-way achieves further enhancement. Variations in factors influencing the probabilities of the remaining basic events proved to have a limited influence on the pipeline hit rate.

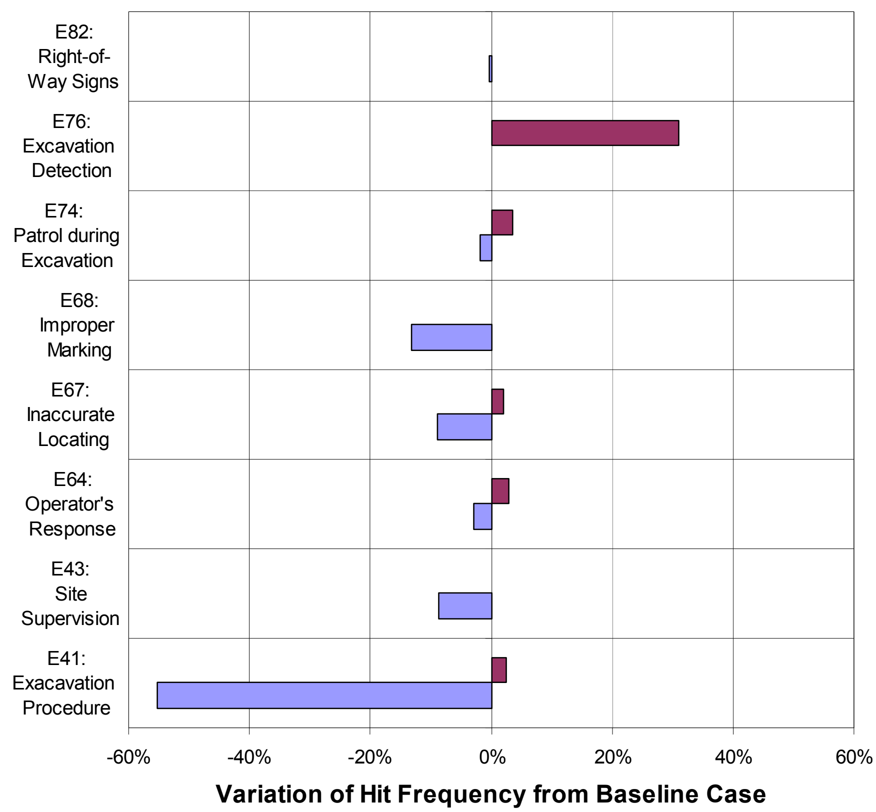


Figure 5.2 Effectiveness of Eight Operation and Maintenance Measures

5.4 Effectiveness of Regulatory and Public Education Measures

Figure 5.3 shows the effect of five basic events on the top event probability describing the pipeline hit rate:

- Basic event E42 has four different conditions describing various types of awareness of excavation procedures. The baseline condition assumed that training was provided annually to all third parties. Decreasing this frequency to once every two years (biennially) would increase the hit probability by almost 5%.

- Basic event E84 has six conditions corresponding to different enforcement levels for one-call centre notifications. If notifications are voluntary, the hit rate increases by over 5%; however, if they are enforced by administrative penalties, the rate drops by 5%.

Effectiveness Evaluation

- Basic event E93 deals with the efficiency of different public awareness delivery methods; three conditions were considered. The baseline condition assumed that public awareness consisted of advertisement via community meetings with direct mail-outs and promotion among contractors. Limiting communication to advertisement via community meetings increases the hit rate by 1% only.

- Basic event E94 deals with public awareness message efficiency and has three conditions. It was found that if a message fails to provide details such as one-call contact information, the hit frequency increases by about 1%.

Awareness of excavation procedures and effective notification enforcement are potentially effective methods to decrease pipeline hit frequency. Alternatively, variation of events dealing with the communication frequency, delivery method and communication message had a limited effect on the top event probability.

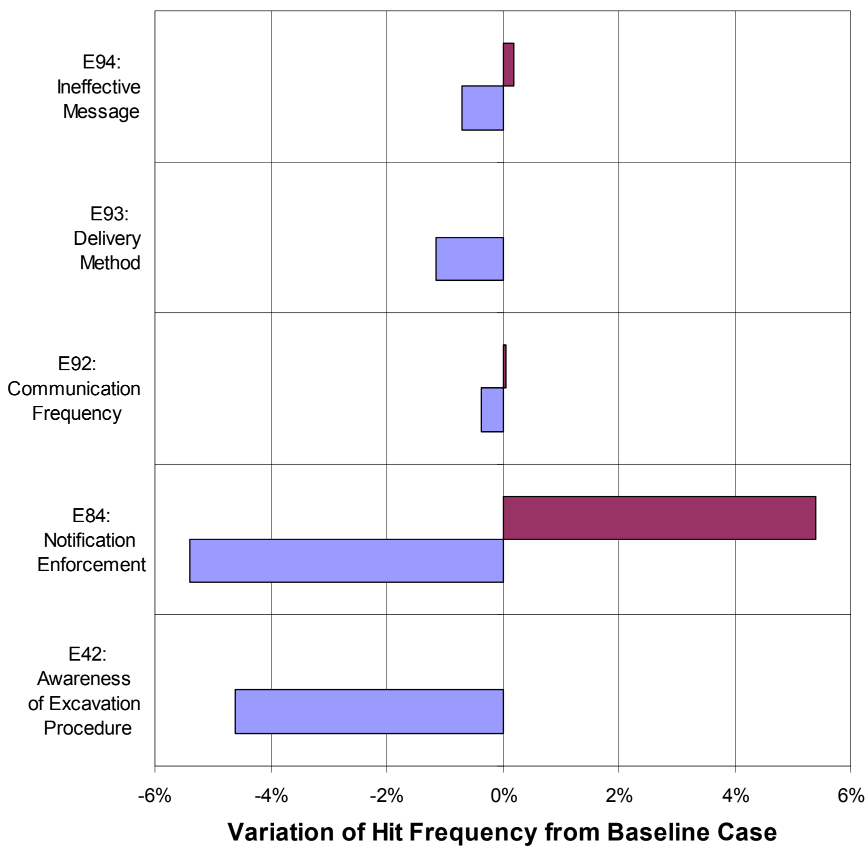


Figure 5.3 Effectiveness of Five Regulatory and Public Education Measures

5.5 Effectiveness of One-call System Measures

The baseline model described in Section 4 implemented the best conditions for basic events E83, E85, E86 and E87 as shown in Figure 5.4:

- Basic event E83 has three conditions describing different levels of company participation in the one-call system. If this participation level is intermediate as opposed to high, the pipeline hit rate increases by almost 5%.

- Basic event E85 has four scenarios illustrating the accessibility of one-call. If excavators are not able to send their notifications to one-call centres 24 hours a day, 7 days a week, and are required to wait on the phone to reach an agent, the hit rate increases by 8%.

- Basic event E86 deals with the possibility that a one-call centre fails to process the notification in time. If a one-call centre is under-staffed, but uses an automated procedure for location search and ticket processing, the hit rate is 7% higher.

- Basic event E87 has three conditions related to the ability of one-call centres to notify operators. It was found that if a one-call centre does not follow guidelines, has some employee training and a limited quality assurance level, the pipeline hit rate increases by 9%.

As shown in Figure 5.4, improvements in one-call measures were found to be effective in reducing pipeline hit frequency between 5% and 9%.

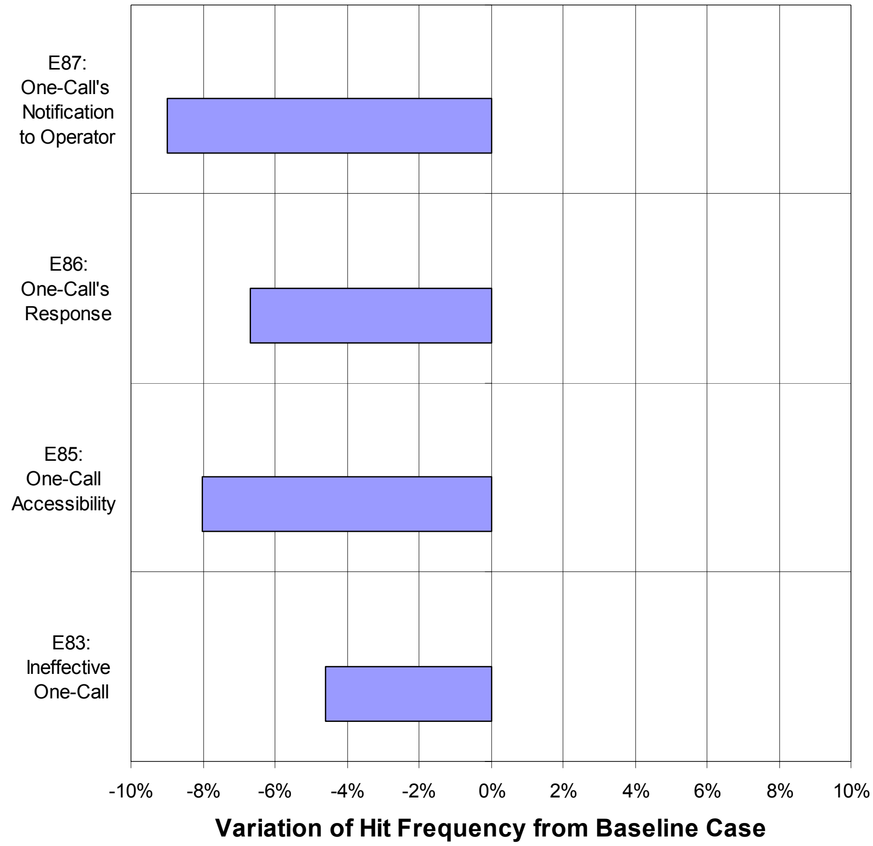


Figure 5.4 Effectiveness of Four One-call System Measures

6. CONCLUSIONS AND RECOMMENDATIONS

6.1 Effectiveness of Prevention Methods

By using the fault tree model described in Section 2 and the input probabilities defined in Section 3, damage prevention effectiveness was evaluated for four types of measures: construction, operation and maintenance, regulatory and public awareness education, and one-call. The evaluation was based on the change in pipeline hit frequency, resulting from variations in individual basic event probabilities relative to the baseline probabilities.

Construction Measures

Construction measures considered included soil cover depth, permanent surface or buried markers that clearly identify the presence and location of a buried pipeline, and surface or buried physical protection that provides a barrier between the excavating equipment and the pipeline. It was found that all construction measures can significantly reduce hit frequency, with physical protection combined with warning signs achieving the highest reduction.

Construction measures are generally more suitable for new pipelines than existing ones because it is more cost effective to implement these measures during construction. Even for new pipelines, measures such as physical protection, increased cover depth and permanent surface makers are likely to raise the construction costs considerably; therefore, they are only suitable for locations where the risk associated with excavation damage is high (e.g. in developed areas or at road crossings). Conversely, buried permanent markers (i.e. warning tape or mesh) are less expensive and could be considered as a generic option for new construction.

Operation and Maintenance Measures

The eight items analyzed in this category consisted of five measures that deal with notifications made through one-call (response time, locating, marking, excavation procedure and site supervision) and three measures that address unreported excavations (right-of-way signs, patrols and continuous monitoring).

In the first group, the influence of site supervision was found to be more significant than the other measures that deal with locating and marking. This can be explained by the incident data and fault tree analysis results, both of which have identified mistakes during excavation on marked alignment as the second-leading cause for damage incidents.

With respect to unreported excavations, analysis results suggest that increasing patrol frequency or adding more signs have a limited effect. In spite of the high cost, continuous monitoring of right-of-way activity is potentially effective and could be considered at critical locations.

Additionally, buried warning tape is an effective method for reducing hits resulting from unreported excavations.

Regulatory and Public Awareness Education Measures

Regulatory and public awareness measures that require joint government-industry efforts include enforcement of one-call notification, awareness and training related to excavation procedure, and three measures related to the public awareness of the requirement to call before digging (communication frequency, delivery method and message content).

Enforcement of notification was identified as the most influential factor. This outcome suggests that the number of pipeline hits tends to be more sensitive to variations in enforcement level than to the changes associated with other measures, including public awareness education. This sensitivity could be attributed to the fact that awareness of one-call requirements has improved considerably after decades of continuing effort in public education.

The fault tree analysis also showed the importance of public awareness and contractor training regarding safe excavation procedures. Essential elements of such procedures have been established by the Common Ground Best Practices (CGA 2004) and API RP 1166.

One-call Measures

Data from a survey of one-call centres were collected and analyzed for three basic events related to accessibility, response time and participation in one-call membership. Of these three basic events, the accessibility of one-call centres appears to be relatively important. In addition to a telephone service during normal operation hours, this requires that one-call centres be able to receive notifications at any time by Internet, email, fax and voice messages.

6.2 Recommendations

The following recommendations were developed based on the findings of this study:

Prevention Methods

- Increasing notification remains the highest priority for damage prevention because approximately half of the damage incidents occur without one-call notification. In addition to promoting public awareness, key factors identified based on the analysis results included enforcement and access to one-call services.

- Implementing procedures for safe excavation and promoting the awareness of such procedures among third parties were identified as important issues. Continuous site supervision throughout excavation is considered an essential element of excavation procedures. API RP 1166 recommends that continuous site supervision be provided for excavation within 5 feet of the pipeline.

- The use of buried warning tape was found to be more effective than traditional prevention methods (e.g. periodic patrols and right-of-way signs) in reducing the risks associated with unreported excavations.

Data Collection

- The fault tree model described in this report can be used to guide data collection efforts by government agencies and the industry. By doing so, the collected data can be used to identify areas where improvement is most needed, and quantify the associated key factors.

- The new OPS incident reporting form and the DIRT database have adopted a logical structure. Information regarding the cause of excavation damage is now based on exclusive subsets (i.e. not notified, unmarked but notified, and notified and marked). Data collected in recent years show that 80 to 90% of incidents fall into two leading categories, namely lack of one-call notification and excavation error on marked lines. This suggests that the cause categories could be reorganized by further dividing the major categories and merging the minor ones. For example, if the category of *lack of notification* is divided into a few new categories based on the reasons for lack of notification, the incident data would offer more insight concerning how to increase notifications.

Future Work

- The tree structure and basic event probabilities need to be updated based on new data from incidents and ongoing government and industry surveys. An example of ongoing surveys is the one conducted by API, INGAA and AOPL in connection with the implementation of API RP 1162. With respect to incident data, this study has used data reported to OPS and CGA, but has not used data gathered by local governments and the pipeline industry. Incident or survey data in other countries (e.g. Canada, Australia and Europe) can be included as well.

- The fault tree model needs to be modified for distribution systems. This requires that the fault tree model and input probabilities be revised based on the operating environment and prevention practices specific to distribution operators.

- Additional experiments are needed to gather data on prevention effectiveness. Reliable data can be gathered from experiments such as those conducted by British Gas. As shown in Section 3.5, these experiments have provided essential data on the effectiveness of mechanical protection. Areas in which experimental data are needed include the effectiveness of excavation procedures, alignment makers, and locating and marking methods.

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APPENDIX A – SURVEY OF ONE-CALL CENTRES

C-FER Technologies

One Call Centre Survey

This survey is part of a study conducted by C-FER Technologies (Edmonton, Alberta) for the Pipeline Research Council International Inc. (PRCI) and the Office of Pipeline Safety (OPS). PRCI is a non-profit corporation consisting of energy pipeline companies (including: Chevron Pipe Line Company, Duke Energy Gas Transmission, ConocoPhillips, Enbridge Pipelines, ExxonMobil Pipeline Company, BP, Rosen, Shell Pipeline Company LP, Texas Gas Transmission, TransCanada Pipelines Limited, and TransGas Limited).

The main purpose of this survey is to quantify four different probabilities defined below. The collected data will be processed and presented in summary format to ensure that One Call centres participating in the survey remain anonymous. This information, along with the final results of the study, will be incorporated in a technical report that will be submitted to PRCI and OPS.

Please define probabilities as a percentage value representing the likelihood of occurrence of the event. **To answer the questions, you can rely on your experience and judgment or on statistical data that you may possess.** If you are unfamiliar with some of these cases or if the question does not apply to your area of operation, please provide answers only for the cases that you are familiar with. If you believe that the cases provided are incomplete or if you have additional comments, please use the space in the comments box.

Thank you for your participation in this survey.

One Call centre name and location: ________

Name and contact of participant (Optional): ________

For the scenarios described below, please enter the corresponding probabilities for an excavator <u>to call</u> before digging:

Indicator	1	2	3	4	5	6	7	8	9	10
Probability	0-10%	11-20%	21-30%	31-40%	41-50%	51-60%	61-70%	71-80%	81-90%	91-100%
	Excavator very **unlikely** to call	← Excavator may call with varying likelihood →								Excavator very **likely** to call

1- One Call Service with Limited

1.1 For a state/province with a single One Call centre: What is the probability for an excavator to call in an exempted area (an area where some workers from the public work and transportation sectors are exempted from calling before digging) if the company participation in the One Call system is low?

○ 1 ○ 2 ○ 3 ○ 4 ○ 5 ○ 6 ○ 7 ○ 8 ○ 9 ○ 10

1.2 For a state/province with a single One Call centre: What is the probability for an excavator to call if there is an intermediate company participation in the One Call system?

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7 ☐ 8 ☐ 9 ☐ 10

1.3 For a state/province with a single One Call centre: What is the probability for an excavator to call if there is a high company participation in the One Call system (nearly all companies with buried facilities are One Call members)?

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7 ☐ 8 ☐ 9 ☐ 10

Comments related to company participation or exemptions in your area:

1.4 Does your province/state have more than a single One Call centre? ☐ Yes ☐ No ☐ I don't know

If a province/state has more than a single One Call centre, according to you, what percentage of operators would call before digging?

Comments:

For the scenarios described below, please enter the corresponding probabilities for an excavator <u>to call</u> before digging:

Indicator	1	2	3	4	5	6	7	8	9	10
Probability	0-10%	11-20%	21-30%	31-40%	41-50%	51-60%	61-70%	71-80%	81-90%	91-100%
	Excavator very **unlikely** to call	← Excavator may call with varying likelihood →								Excavator very **likely** to call

2- Level of

2.1 What is the probability that an excavator calls the One Call centre if calling before digging is a voluntary action?

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7 ☐ 8 ☐ 9 ☐ 10

2.2 What is the probability that an excavator calls the One Call centre if failing to call before digging is subject to criminal prosecution?

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7 ☐ 8 ☐ 9 ☐ 10

2.3 What is the probability that an excavator calls the One Call centre if failing to call before digging is subject to civil penalties (monetary penalty against a person for wrongdoing)?

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7 ☐ 8 ☐ 9 ☐ 10

2.4 What is the probability that an excavator calls the One Call centre if failing to call before digging is subject to administrative penalties (monetary penalty with corrective action against person for wrongdoing)?

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7 ☐ 8 ☐ 9 ☐ 10

2.5 Please describe the level/type of enforcement in your area:

Comments:

For the scenarios described below, please enter the corresponding probabilities that an excavator is <u>able to notify</u> the One Call centre when he/she <u>intends to notify</u>:

Indicator	1	2	3	4	5	6	7	8	9	10
Probability	0-10%	11-20%	21-30%	31-40%	41-50%	51-60%	61-70%	71-80%	81-90%	91-100%
	Excavator very **unlikely** to be able to notify	← Excavator may be able to notify with varying likelihood →								Excavator very **likely** to be able to notify

3- One Call Service Accessibility

3.1 What is the probability that an excavator notifies the pipeline operator before digging if no One Call centre is available in the area?

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7 ☐ 8 ☐ 9 ☐ 10

3.2 What is the probability that an excavator notifies the One Call centre if it does not operate 24 hours a day, 7 days a week (i.e. notifications can not be placed 24/7). Callers are often required to wait on the line or to call several times due to busy signals?

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7 ☐ 8 ☐ 9 ☐ 10

3.3 What is the probability that an excavator notifies the One Call centre if it operates 24 hours a day, 7 days a week including holidays, waiting time on the line is acceptable but excavators can only send their notifications by phone?

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7 ☐ 8 ☐ 9 ☐ 10

3.4 What is the probability that an excavator notifies the One Call centre if it operates 24 hours a day, 7 days a week including holidays and excavators can send their notifications through One Call website, fax, email or voice recording?

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7 ☐ 8 ☐ 9 ☐ 10

3.5 Describe the hours of operation and methods of notification at your One Call centre:	
Comments:	

For the scenarios described below, please enter the corresponding probabilities for a One Call centre to notify the operator in time:

Indicator	1	2	3	4	5	6	7	8	9	10
Probability	0-10%	11-20%	21-30%	31-40%	41-50%	51-60%	61-70%	71-80%	81-90%	91-100%
	One Call centre very **unlikely** to notify operator in time	← One Call centre may be able to notify operator in time with varying likelihood →								One Call centre very **likely** to notify operator in time

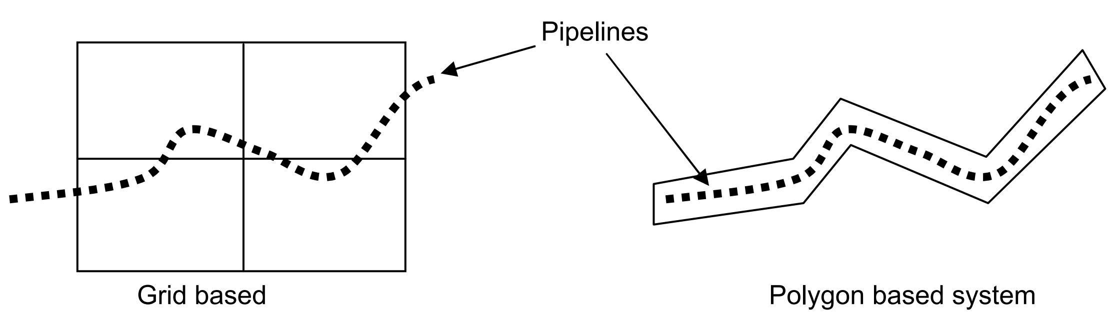
4- Response of One Call Centre

4.1 What is the probability that a One Call centre transmits notifications in time to the operator if its employees are unable to process calls in a timely fashion, has a grid based system and has a manual/semi-automated procedure to track and notify operators?

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7 ☐ 8 ☐ 9 ☐ 10

4.2 What is the probability that a One Call centre transmits notifications in time to the operator if its employees are unable to process calls in a timely fashion, but has a polygon based system and a fully automated procedure to track and notify operators?

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7 ☐ 8 ☐ 9 ☐ 10



4.3 What is the probability that a One Call centre transmits notifications in time to the operator if its employees are able to process all received notifications in a timely fashion, has polygon based system and a fully automated procedure to track and notify operators?

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7 ☐ 8 ☐ 9 ☐ 10

4.4 Average number of notifications received by the One Call centre per year:	
4.5 Average number of tickets issued by the One Call centre per year:	
Comments:	

In some cases, a One Call centre does not notify the affected utility companies due to errors in the process. For the scenarios described below, please enter the corresponding probabilities for a One Call centre to notify the operator:

Indicator	1	2	3	4	5	6	7	8	9	10
Probability	0-10%	11-20%	21-30%	31-40%	41-50%	51-60%	61-70%	71-80%	81-90%	91-100%
	One Call centre very **unlikely** to notify operator	← One Call centre may be able to notify operator with varying likelihood →								One Call centre very **likely** to notify operator

5- One Call Centre's Ability to Notify Operator

5.1 What is the probability that a One Call centre notifies the operator if it does not follow One Call guidelines/standards, has no employee training and no quality assurance?

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7 ☐ 8 ☐ 9 ☐ 10

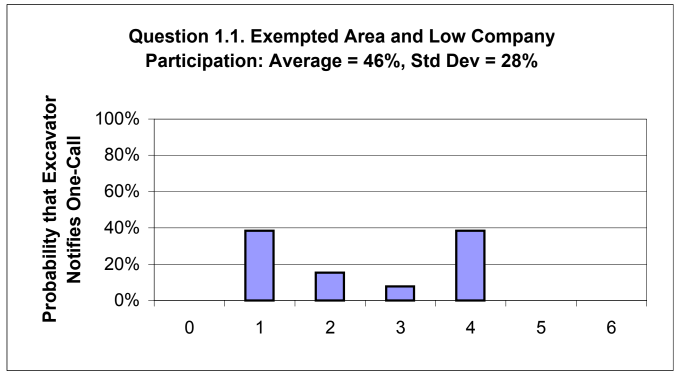
5.2 What is the probability that a One Call centre notifies the operator if it does not follow One Call guidelines/standards, has little employee training and some quality assurance?

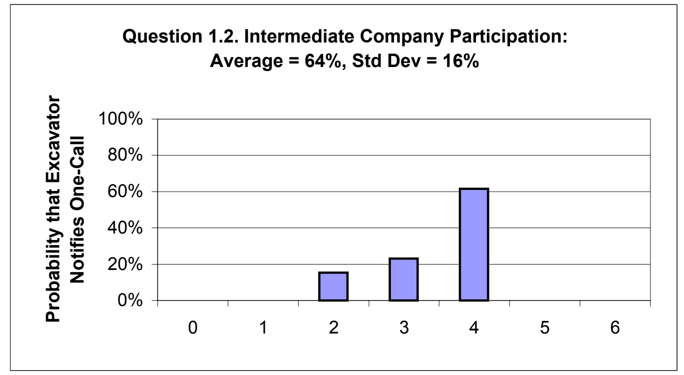
☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7 ☐ 8 ☐ 9 ☐ 10

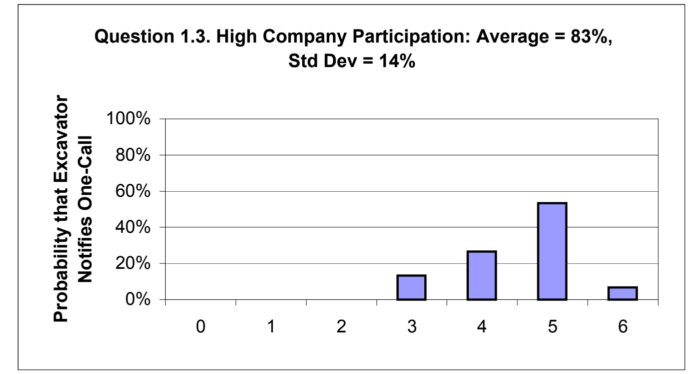
5.3 What is the probability that a One Call centre notifies the operator if it follows One Call guidelines/standards, has extensive employee training and high quality assurance?

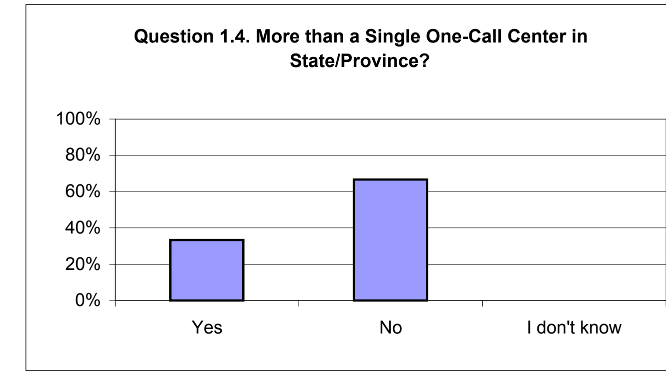
☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7 ☐ 8 ☐ 9 ☐ 10

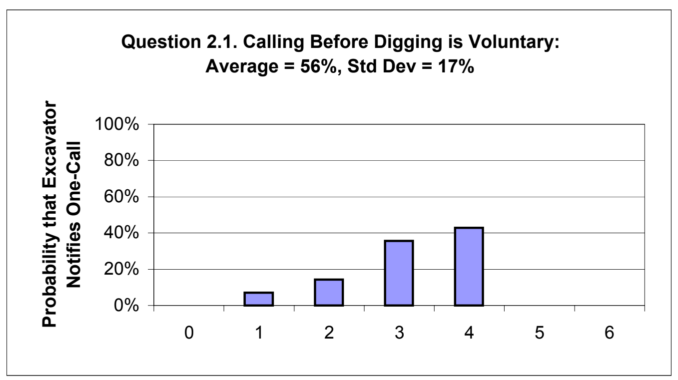
5.4 Does your One Call centre follow guidelines/standards set for One Call centres?	◯ Yes	◯ No	◯ I don't know
If yes, specify which guidelines/standards (e.g. Common Ground Alliance Best Practices, American Public Works Association Guidelines):			
Comments:			

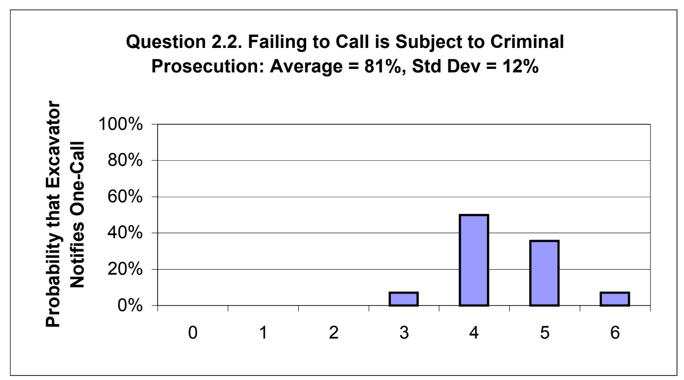

Question 1.1. Exempted Area and Low Company Participation: Average = 46%, Std Dev = 28%
Probability that Excavator Notifies One-Call
100%
80%
60%
40%
20%
0%
0 1 2 3 4 5 6

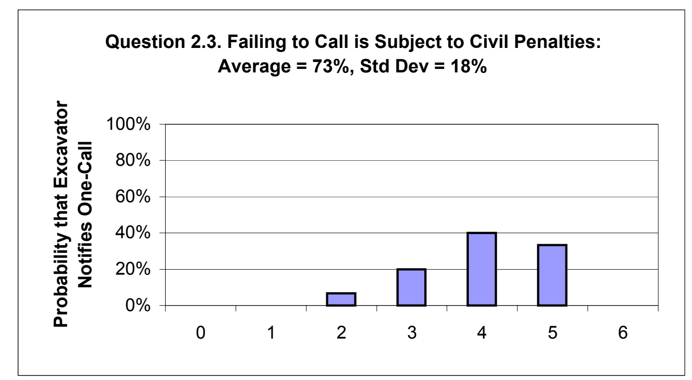

Question 1.2. Intermediate Company Participation: Average = 64%, Std Dev = 16%
Probability that Excavator Notifies One-Call
100%
80%
60%
40%
20%
0%
0 1 2 3 4 5 6

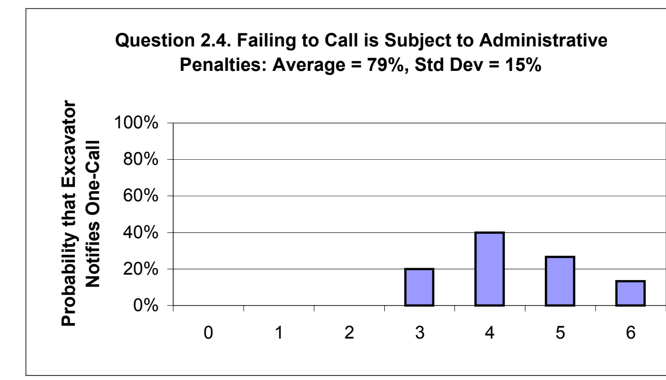

Question 1.3. High Company Participation: Average = 83%, Std Dev = 14%
Probability that Excavator Notifies One-Call
100%
80%
60%
40%
20%
0%
0 1 2 3 4 5 6

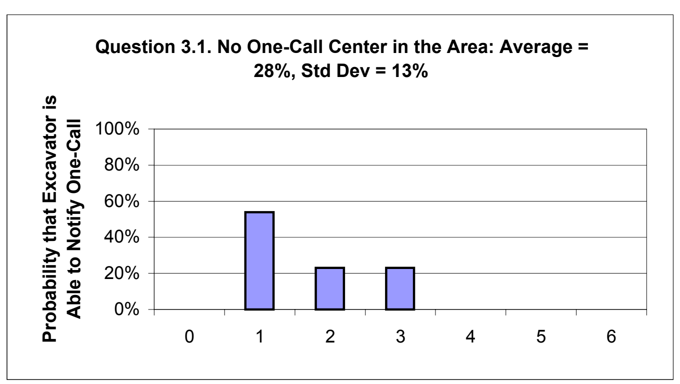

Question 1.4. More than a Single One-Call Center in State/Province?
100%
80%
60%
40%
20%
0%
Yes
No
I don't know

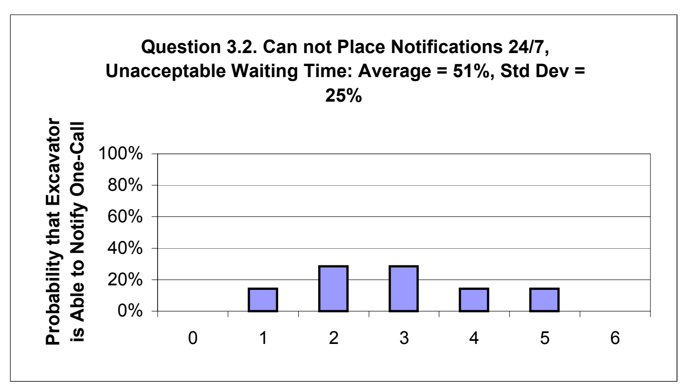

Question 2.1. Calling Before Digging is Voluntary: Average = 56%, Std Dev = 17%
Probability that Excavator Notifies One-Call
100%
80%
60%
40%
20%
0%
0 1 2 3 4 5 6

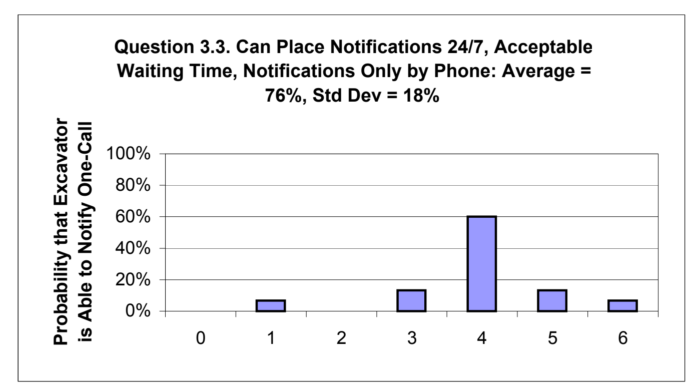

Question 2.2. Failing to Call is Subject to Criminal Prosecution: Average = 81%, Std Dev = 12%
Probability that Excavator Notifies One-Call
100%
80%
60%
40%
20%
0%
0 1 2 3 4 5 6

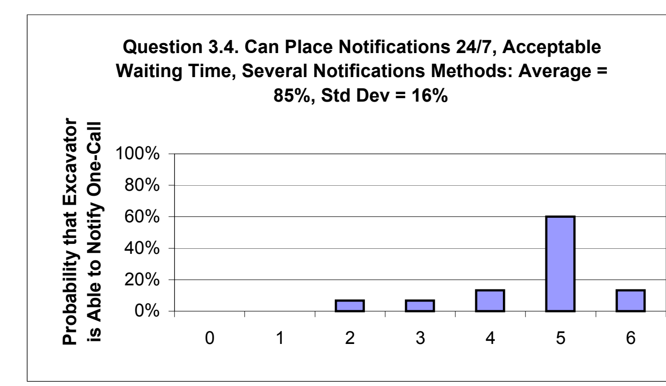

Question 2.3. Failing to Call is Subject to Civil Penalties: Average = 73%, Std Dev = 18%
Probability that Excavator Notifies One-Call
100%
80%
60%
40%
20%
0%
0 1 2 3 4 5 6

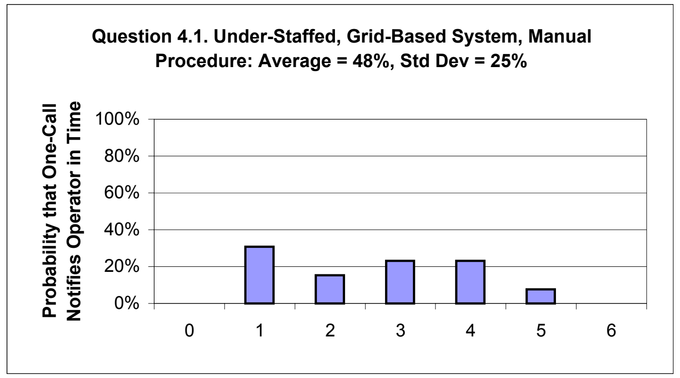

Question 2.4. Failing to Call is Subject to Administrative Penalties: Average = 79%, Std Dev = 15%
Probability that Excavator Notifies One-Call
100%
80%
60%
40%
20%
0%
0 1 2 3 4 5 6

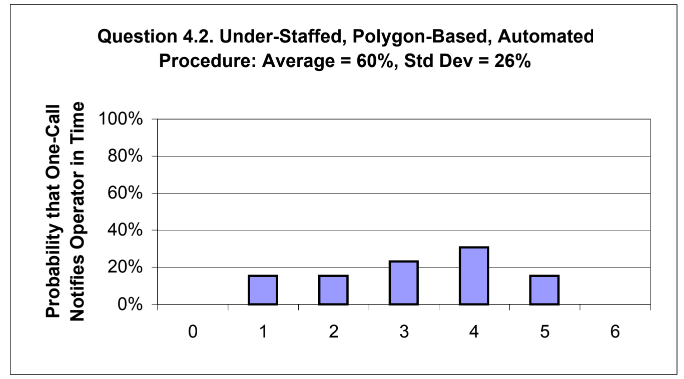

Question 3.1. No One-Call Center in the Area: Average = 28%, Std Dev = 13%
Probability that Excavator is Able to Notify One-Call
100%
80%
60%
40%
20%
0%
0 1 2 3 4 5 6

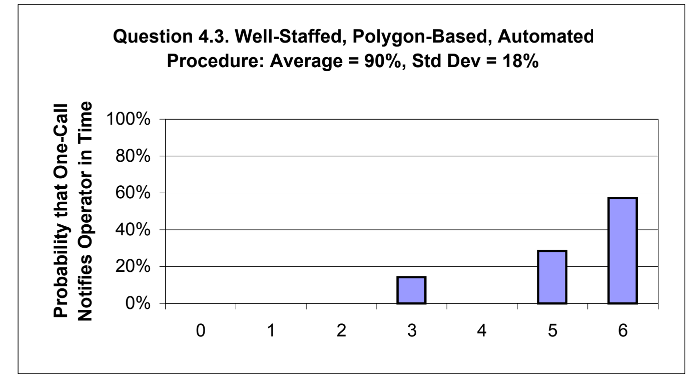

Question 3.2. Can not Place Notifications 24/7, Unacceptable Waiting Time: Average = 51%, Std Dev = 25%
Probability that Excavator is Able to Notify One-Call
100%
80%
60%
40%
20%
0%
0 1 2 3 4 5 6

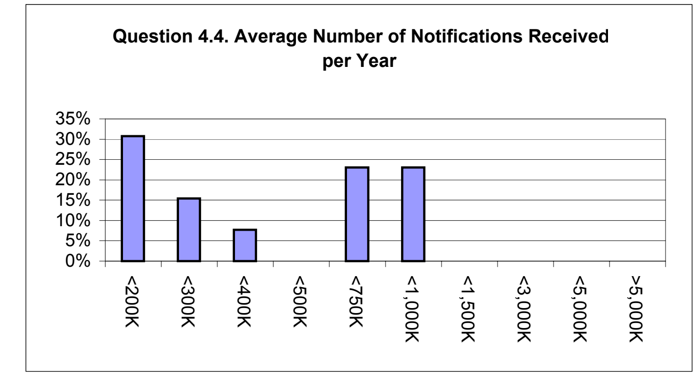

Question 3.3. Can Place Notifications 24/7, Acceptable Waiting Time, Notifications Only by Phone: Average = 76%, Std Dev = 18%
Probability that Excavator is Able to Notify One-Call
100%
80%
60%
40%
20%
0%
0 1 2 3 4 5 6

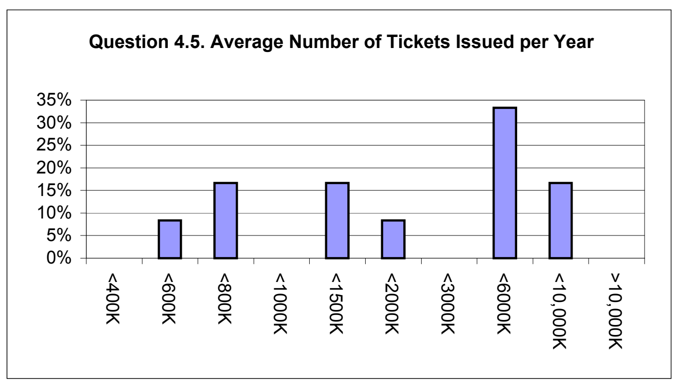

Question 3.4. Can Place Notifications 24/7, Acceptable Waiting Time, Several Notifications Methods: Average = 85%, Std Dev = 16%
Probability that Excavator is Able to Notify One-Call
100%
80%
60%
40%
20%
0%
0 1 2 3 4 5 6

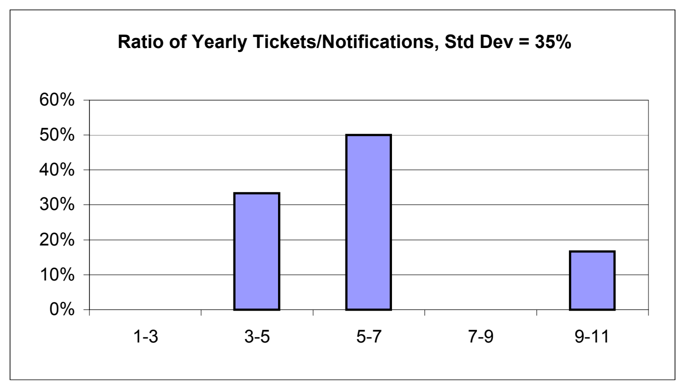

Question 4.1. Under-Staffed, Grid-Based System, Manual Procedure: Average = 48%, Std Dev = 25%
Probability that One-Call Notifies Operator in Time
100%
80%
60%
40%
20%
0%
0
1
2
3
4
5
6

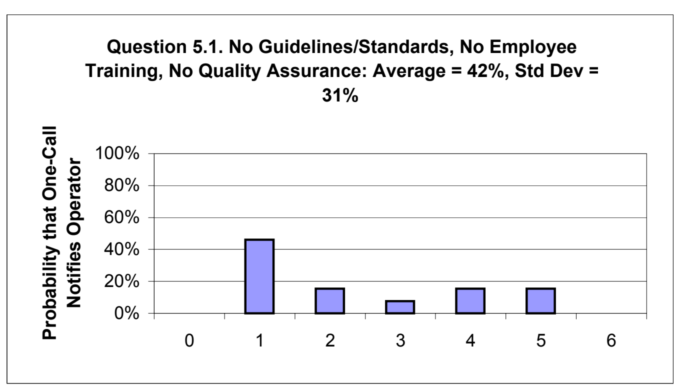

Question 4.2. Under-Staffed, Polygon-Based, Automated Procedure: Average = 60%, Std Dev = 26%
Probability that One-Call Notifies Operator in Time
100%
80%
60%
40%
20%
0%
0
1
2
3
4
5
6

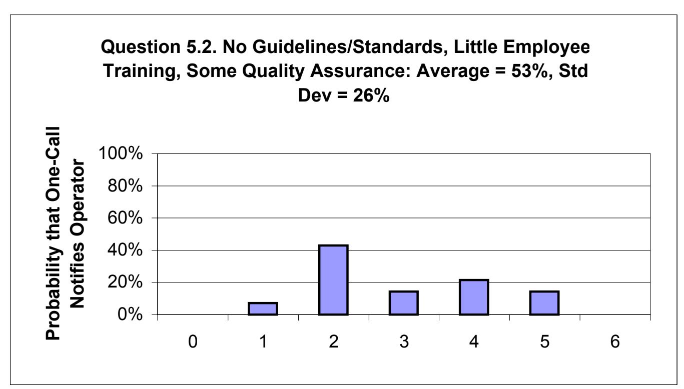

Question 4.3. Well-Staffed, Polygon-Based, Automated Procedure: Average = 90%, Std Dev = 18%
Probability that One-Call Notifies Operator in Time
100%
80%
60%
40%
20%
0%
0
1
2
3
4
5
6

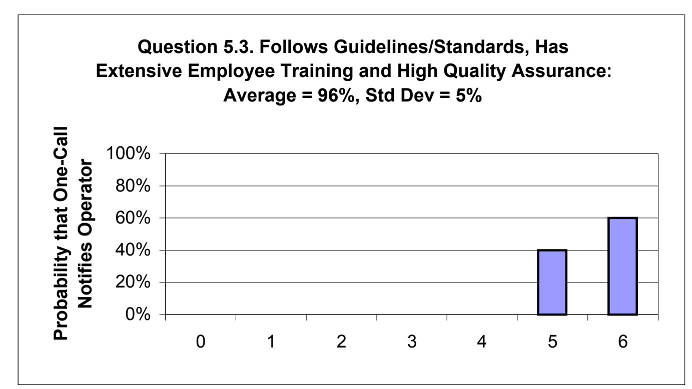

Question 4.4. Average Number of Notifications Received per Year
35%
30%
25%
20%
15%
10%
5%
0%
<200K
<300K
<400K
<500K
<750K
<1,000K
<1,500K
<3,000K
<5,000K
>5,000K

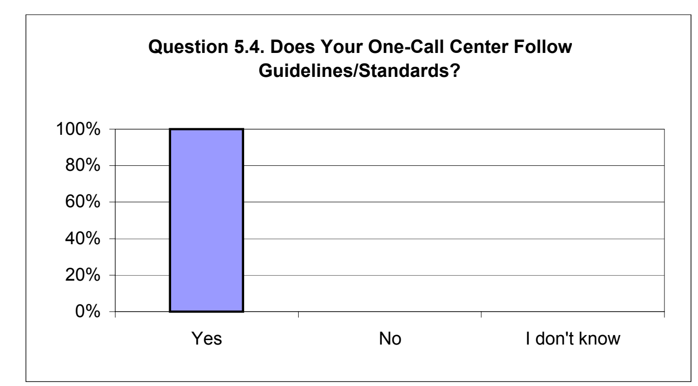

Question 4.5. Average Number of Tickets Issued per Year
35%
30%
25%
20%
15%
10%
5%
0%
<400K
<600K
<800K
<1000K
<1500K
<2000K
<3000K
<6000K
<10,000K
>10,000K


Ratio of Yearly Tickets/Notifications, Std Dev = 35%
60%
50%
40%
30%
20%
10%
0%
1-3
3-5
5-7
7-9
9-11


Question 5.1. No Guidelines/Standards, No Employee Training, No Quality Assurance: Average = 42%, Std Dev = 31%
Probability that One-Call Notifies Operator
100%
80%
60%
40%
20%
0%
0
1
2
3
4
5
6


Question 5.2. No Guidelines/Standards, Little Employee Training, Some Quality Assurance: Average = 53%, Std Dev = 26%
Probability that One-Call Notifies Operator
100%
80%
60%
40%
20%
0%
0
1
2
3
4
5
6


Question 5.3. Follows Guidelines/Standards, Has Extensive Employee Training and High Quality Assurance: Average = 96%, Std Dev = 5%
Probability that One-Call Notifies Operator
100%
80%
60%
40%
20%
0%
0
1
2
3
4
5
6


Question 5.4. Does Your One-Call Center Follow Guidelines/Standards?
100%
80%
60%
40%
20%
0%
Yes
No
I don't know

APPENDIX B – SURVEY OF EXCAVATING CONTRACTORS

C-FER Technologies

Survey

This survey is part of a study conducted by C-FER Technologies (Edmonton, Alberta) for the Pipeline Research Council International Inc. (PRCI) and the Office of Pipeline Safety (OPS). PRCI is a non-profit corporation consisting of energy pipeline companies (including: Chevron Pipe Line Company, Duke Energy Gas Transmission, ConocoPhillips, Enbridge Pipelines, ExxonMobil Pipeline Company, BP, Rosen, Shell Pipeline Company LP, Texas Gas Transmission, TransCanada Pipelines Limited, and TransGas Limited).

The main purpose of this survey is to quantify different probabilities defined below. The collected data will be processed and presented in summary format to ensure that parties participating in the survey remain anonymous. This information, along with the final results of the study, will be incorporated in a technical report that will be submitted to PRCI and OPS.

Please define probabilities as a percentage value representing the likelihood of occurrence of the event. **To answer the questions, you can rely on your experience and judgment or on statistical data that you may possess.** If you are unfamiliar with some of these cases or if the question does not apply to your area of operation, please provide answers only for the cases that you are familiar with.

Thank you for your participation in this survey.

Company name and location:

Name and contact of participant (Optional):

For the scenarios described below, please enter the corresponding probabilities for excavation equipment to accidentally interfere with a marked pipeline alignment (without necessarily hitting the pipeline):

Indicator	0	1	2	3	4	5	6
Probability	0%	1-20%	21-40%	41-60%	61-80%	81-99%	100%
	Will **NOT** interfere	**Very unlikely** to interfere	**Unlikely** to interfere	**Equal chance** of interfering or not	**Likely** to interfere	**Very likely** to interfere	**Will** interfere

1- Inadequate Excavation Procedure
1.1 What is the probability for excavation equipment to accidentally interfere with a marked pipeline alignment if no documented excavation procedure was provided by the pipeline company? ☐ 0 ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6
1.2 What is the probability for excavation equipment to accidentally interfere with a marked pipeline alignment if the pipeline company provided the excavator with a documented excavation procedure consisting of general guidelines (e.g. digging with caution) without any specific requirements? ☐ 0 ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6
1.3 What is the probability for excavation equipment to accidentally interfere with a marked pipeline alignment if the excavation procedure includes an appropriately defined buffer zone (e.g. 5 ft on each side from the pipeline) and requires site supervision for digging within this zone? ☐ 0 ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6
1.4 What is the probability for excavation equipment to accidentally interfere with a marked pipeline alignment if the excavation procedure requires hand or hydraulic digging (or other non-invasive methods) within a tolerance zone (e.g. 1-1.5 ft on each side from the pipeline)? ☐ 0 ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6
1.5 What is the probability for excavation equipment to accidentally interfere with a marked pipeline alignment if both conditions (1.3) and (1.4) are satisfied? ☐ 0 ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6
1.6 What is the probability for excavation equipment to accidentally interfere with a marked pipeline alignment if the pipeline company exposes the pipe at selected locations (e.g. turns and ends of the excavation zone)? ☐ 0 ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6

For the scenarios described below, please enter the corresponding probabilities for excavation equipment to accidentally interfere with a marked pipeline alignment (without necessarily hitting the pipeline):

Indicator	0	1	2	3	4	5	6
Probability	0%	1-20%	21-40%	41-60%	61-80%	81-99%	100%
	Will **NOT** interfere	**Very unlikely** to interfere	**Unlikely** to interfere	**Equal chance** of interfering or not	**Likely** to interfere	**Very likely** to interfere	**Will** interfere

2- Failure of Site Supervision

2.1 What is the probability that excavation equipment will accidentally interfere with a marked pipeline alignment if site supervision is not provided at all?

☐ 0 ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6

2.2 What is the probability that excavation equipment will accidentally interfere with a marked pipeline alignment if site supervision is not provided, but staff of pipeline company will visit the excavation site from time to time?

☐ 0 ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6

2.3 What is the probability that excavation equipment will accidentally interfere with a marked pipeline alignment if site supervision is provided during part of the excavation?

☐ 0 ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6

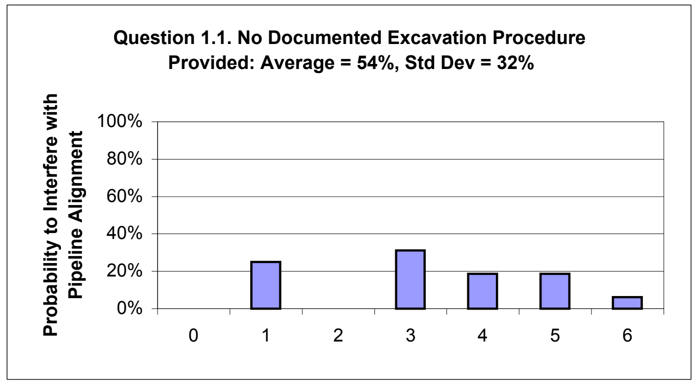
2.4 What is the probability that excavation equipment will accidentally interfere with a marked pipeline alignment if site supervision is provided throughout the excavation?

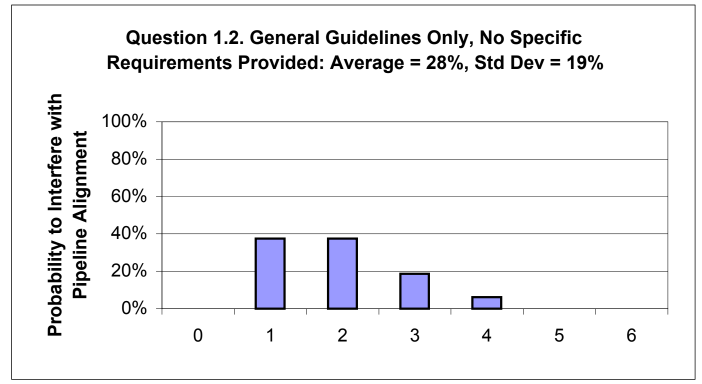
☐ 0 ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6

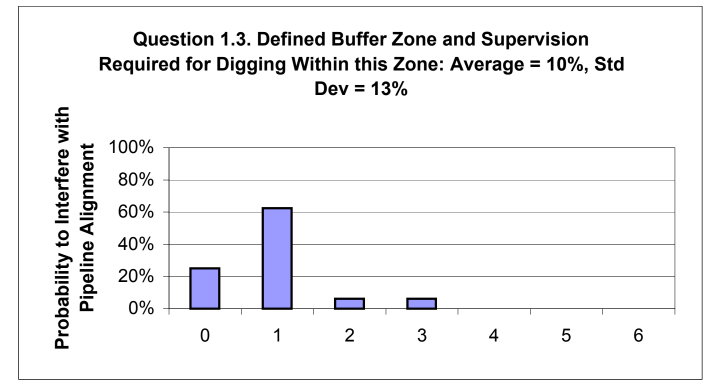
For the scenarios described below, assuming that the public awareness communication messages are frequent, please enter the corresponding probabilities that an excavator notifies the One Call centre before digging:

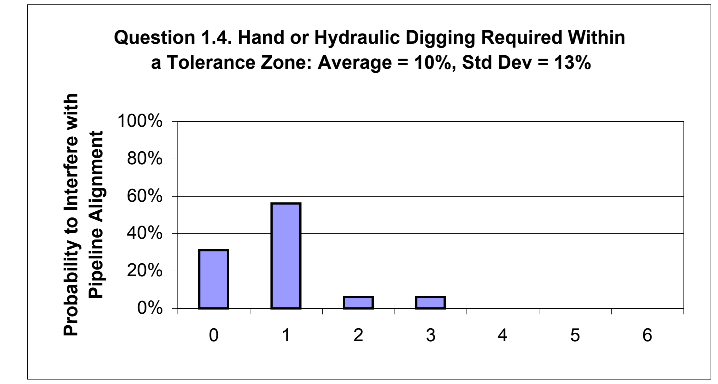
Indicator	0	1	2	3	4	5	6
Probability	0%	1-20%	21-40%	41-60%	61-80%	81-99%	100%
	Will **NOT** notify	**Very unlikely** to notify	**Unlikely** to notify	**Equal chance** of notifying or not	**Likely** to notify	**Very likely** to notify	**Will** notify

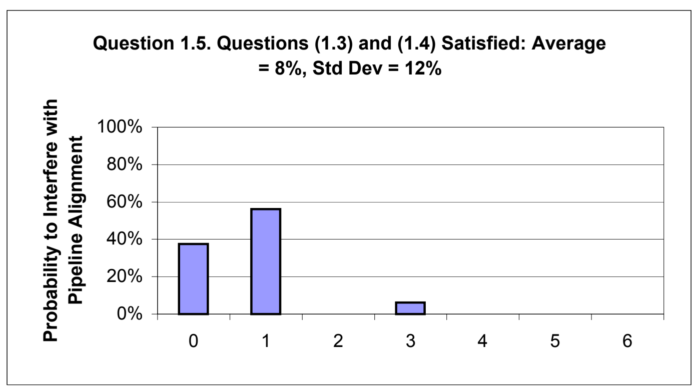
3- Public Awareness Message Efficiency
3.1 What is the probability that an excavator notifies the One Call centre if the public awareness message does not clearly mention calling a One Call centre before digging? ☐ 0 ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6
3.2 What is the probability that an excavator notifies the One Call centre if the public awareness message mentions the necessity of contacting a One Call centre before digging without providing further details? ☐ 0 ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6
3.3 What is the probability that an excavator notifies the One Call centre if the public awareness message mentions the necessity of calling a One Call centre before digging, provides a toll free number and an overview of how One Call centres operate? ☐ 0 ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6
3.4 <u>In addition to scenario 3.3</u>: the message explicitly states that the One Call service is free and that calling before digging is required by law (when applicable)? ☐ 0 ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6

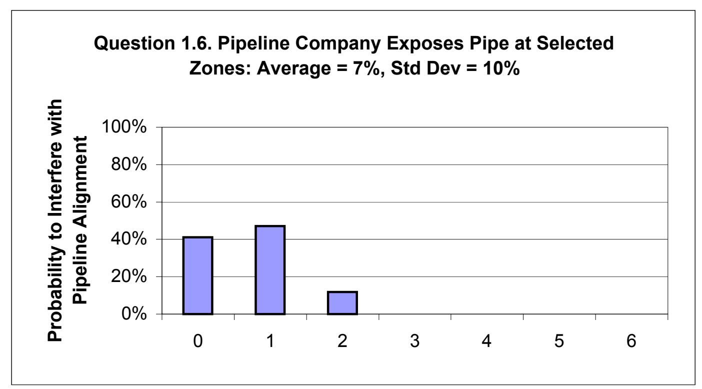

Question 1.1. No Documented Excavation Procedure Provided: Average = 54%, Std Dev = 32%
Probability to Interfere with Pipeline Alignment
100%
80%
60%
40%
20%
0%
0 1 2 3 4 5 6

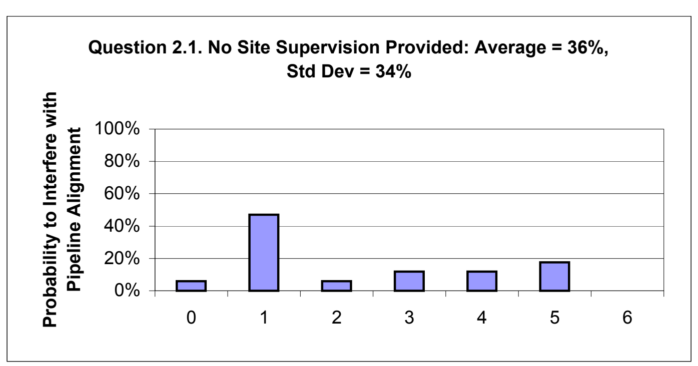

Question 1.2. General Guidelines Only, No Specific Requirements Provided: Average = 28%, Std Dev = 19%
Probability to Interfere with Pipeline Alignment
100%
80%
60%
40%
20%
0%
0 1 2 3 4 5 6

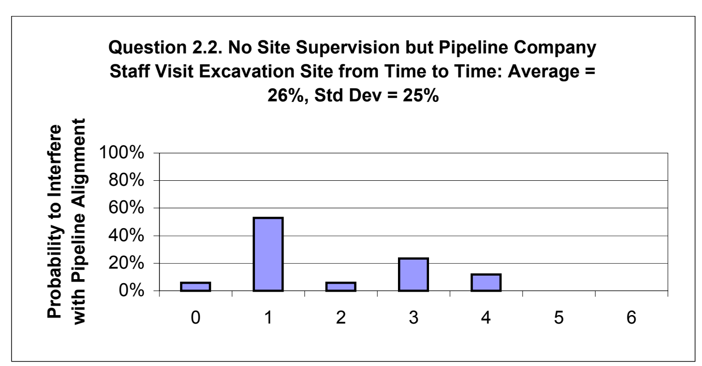

Question 1.3. Defined Buffer Zone and Supervision Required for Digging Within this Zone: Average = 10%, Std Dev = 13%
Probability to Interfere with Pipeline Alignment
100%
80%
60%
40%
20%
0%
0 1 2 3 4 5 6

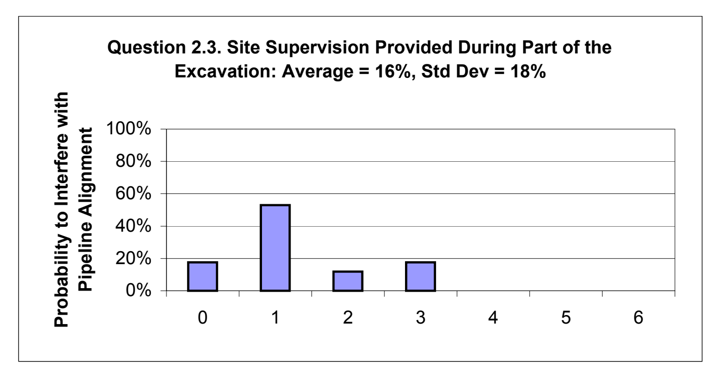

Question 1.4. Hand or Hydraulic Digging Required Within a Tolerance Zone: Average = 10%, Std Dev = 13%
Probability to Interfere with Pipeline Alignment
100%
80%
60%
40%
20%
0%
0 1 2 3 4 5 6

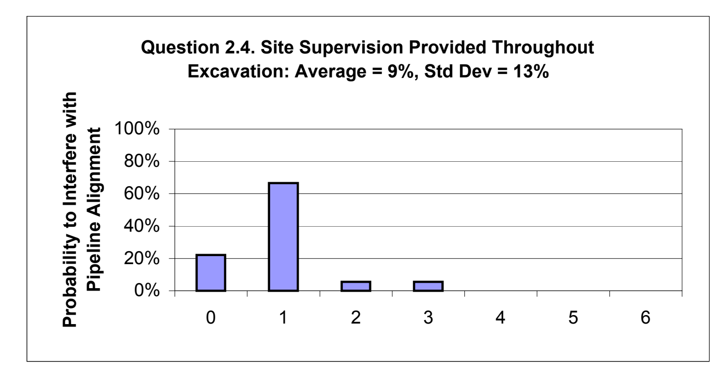

Question 1.5. Questions (1.3) and (1.4) Satisfied: Average = 8%, Std Dev = 12%
Probability to Interfere with Pipeline Alignment
100%
80%
60%
40%
20%
0%
0 1 2 3 4 5 6

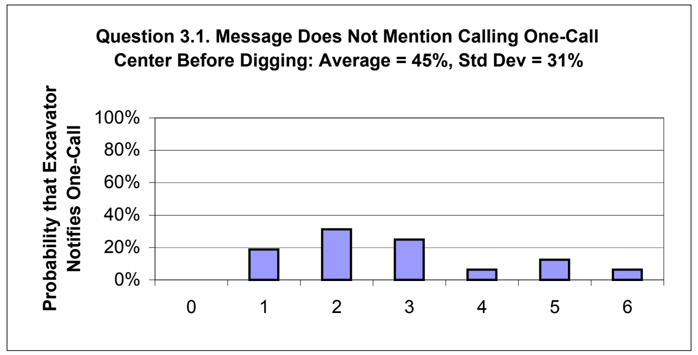

Question 1.6. Pipeline Company Exposes Pipe at Selected Zones: Average = 7%, Std Dev = 10%
Probability to Interfere with Pipeline Alignment
100%
80%
60%
40%
20%
0%
0 1 2 3 4 5 6

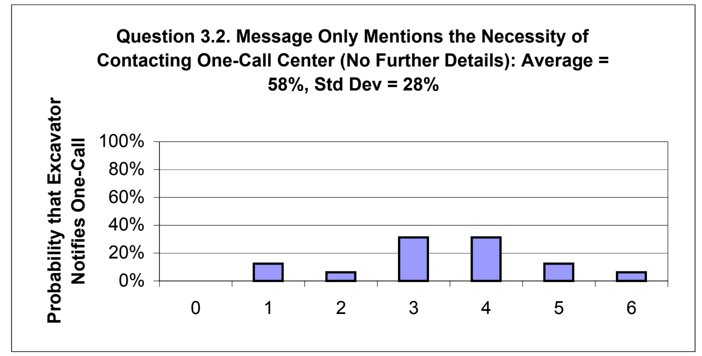

Question 2.1. No Site Supervision Provided: Average = 36%, Std Dev = 34%
Probability to Interfere with Pipeline Alignment
100%
80%
60%
40%
20%
0%
0 1 2 3 4 5 6

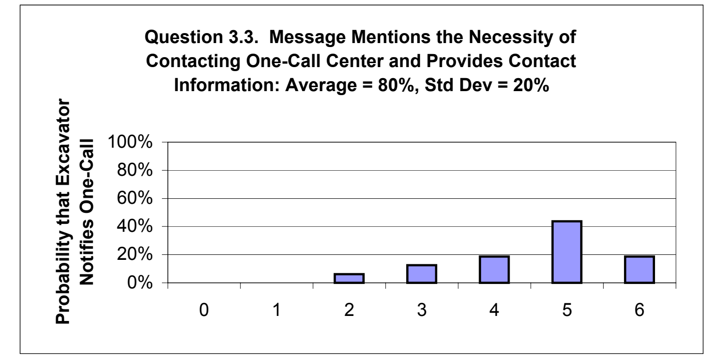

Question 2.2. No Site Supervision but Pipeline Company Staff Visit Excavation Site from Time to Time: Average = 26%, Std Dev = 25%
Probability to Interfere with Pipeline Alignment
100%
80%
60%
40%
20%
0%
0 1 2 3 4 5 6

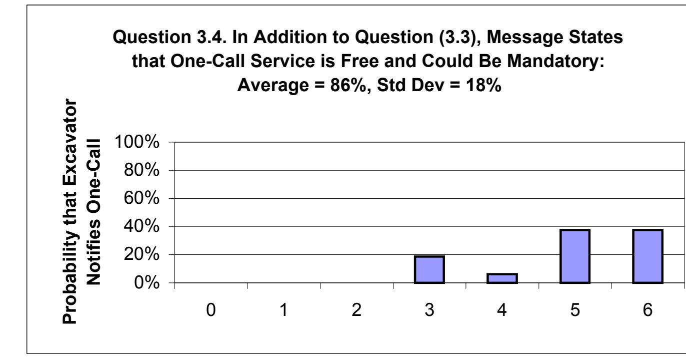

Question 2.3. Site Supervision Provided During Part of the Excavation: Average = 16%, Std Dev = 18%
Probability to Interfere with Pipeline Alignment
100%
80%
60%
40%
20%
0%
0 1 2 3 4 5 6


Question 2.4. Site Supervision Provided Throughout Excavation: Average = 9%, Std Dev = 13%
Probability to Interfere with Pipeline Alignment
100%
80%
60%
40%
20%
0%
0 1 2 3 4 5 6


Question 3.1. Message Does Not Mention Calling One-Call Center Before Digging: Average = 45%, Std Dev = 31%
Probability that Excavator Notifies One-Call
100%
80%
60%
40%
20%
0%
0
1
2
3
4
5
6


Question 3.2. Message Only Mentions the Necessity of Contacting One-Call Center (No Further Details): Average = 58%, Std Dev = 28%
Probability that Excavator Notifies One-Call
100%
80%
60%
40%
20%
0%
0
1
2
3
4
5
6


Question 3.3. Message Mentions the Necessity of Contacting One-Call Center and Provides Contact Information: Average = 80%, Std Dev = 20%
Probability that Excavator Notifies One-Call
100%
80%
60%
40%
20%
0%
0
1
2
3
4
5
6


Question 3.4. In Addition to Question (3.3), Message States that One-Call Service is Free and Could Be Mandatory: Average = 86%, Std Dev = 18%
Probability that Excavator Notifies One-Call
100%
80%
60%
40%
20%
0%
0
1
2
3
4
5
6