FORUM ON RISK ASSESSMENT FOR SUBMARINE SLOPE STABILITY

Prepared by
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Report of a Forum held in Houston, Texas - May 10 and 11, 2002

Conducted by
Offshore Technology Research Center and The University of Texas at Austin
in Cooperation with
C-CORE, St. Johns, Newfoundland, Canada

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Introduction

Important decisions must often be made regarding the location of offshore oil production and handling facilities and the type and extent of site investigations required. These decisions highlight the need for understanding and quantifying the risks involved and the need for comprehensive, probabilistic-based methodologies for risk and reliability assessment of submarine slopes. This need is increased as slopes in deeper and deeper water become of interest. In order to advance the methodologies for risk assessment it is necessary to identify the various processes and mechanisms that can lead to submarine slope instabilities, define and quantify the various uncertainties associated with each process and mechanism, and, finally to develop, implement and test procedures for evaluating the risk and reliability associated with submarine slopes.

To better define and understand the elements of risk assessment for submarine slope stability in deep water a one and one-half day Forum was organized and held in Houston, Texas on May 10 and 11, 2002. The Forum was sponsored by the Minerals Management Service of the United States Department of Interior. It was planned and organized by the Offshore Technology Research Center in cooperation with C-CORE. The project supervisor for the Forum was Dr. Stephen G. Wright of The University of Texas at Austin. Attendance and participation was by invitation only. Approximately 55 people from industry, government and academia attended the Forum. The format and results of the Forum are presented in this report. In summarizing and reporting these results every effort has been made to reflect the input from the participants as it occurred and was presented at the Forum.

Format and Organization

In organizing and planning the Forum emphasis was placed on achieving open discussion and participation among all participants. Particular emphasis was placed on the industry's perspective on risk assessment of slope stability. Prepared presentations were intentionally kept to a minimum. The original agenda for the Forum is included in Appendix A. The general format for the Forum is presented below.

Opening Session (Day 1)

The opening session of the Forum began with brief introductory remarks by the organizers (University of Texas, Minerals Management Service, OTRC and C-CORE). Next Dr. Philippe Jeanjean of BP presented the keynote talk, which gave an industry perspective on submarine slope stability. This was followed by a short presentation on risk assessment by Dr. Robert Gilbert of The University of Texas at Austin.

"Mini-Panels" (Day 1)

A series of four "mini-panels" constituted the balance of the morning session of the Forum. Each panel was designed to address a particular aspect of risk assessment and to encourage audience participation and discussion. A total of thirty minutes was available for each panel. The objective of these mini-panels was to generate ideas and issues for follow-up discussion in the afternoon breakout sessions. The four mini-panels and participants were as follows:

Mini-Panel 1 - Topic: Facilities & Design Issues (impact of a slide):

- Ed Clukey, BP Amoco Corp
- Jason Newlin, Shell International E&P, Inc.
- Dick Raines, ExxonMobil URC

Mini-Panel 2 - Topic: Geologic Environment (processes, triggering mechanisms, stratigraphy):

- Bill Bryant, Texas A&M University
- Andy Hill, British Petroleum
- David Piper, Geological Survey of Canada (Atlantic)

Mini-Panel 3 - Topic: Geotechnical Properties

- Kevin Hampson, BP Exploration
- Jim Hooper, Fugro-McClelland Marine Geosciences
- Alan Young, Geoscience Earth & Marine Services

Mini-Panel 4 - Topic: Modeling (response given trigger)

- Jeremy Dean, Shell Global Solutions (US) Inc.
- Forrokh Nadim, Norwegian Geotechnical Institute (NGI)
- Ryan Phillips, C-CORE

No formal reporting was done of the individual presentations and discussion; however, much of what was discussed is reflected in the reports from the breakout sessions.

Breakout Sessions (Day 1)

The afternoon of the first day of the Forum was devoted to four simultaneous breakout sessions. Each breakout session was assigned a facilitator, who was also requested to appoint a scribe to document the session's deliberations. The facilitators were:

Session	Facilitator
1	Craig Shipp, Shell International E&P, Inc.
2	Jean Audibert, Fugro-McClelland Marine Geosciences, Inc.
3	Dick Raines, ExxonMobil URC
4	Philippe Jeanjean, BP

Breakout sessions were instructed to address any issues that they felt were important; they were not restricted to the same topics as covered by the morning's mini-panels. Each breakout session was asked to produce the following at the conclusion of the first day's deliberations:

1. One or more flip charts listing up to six prioritized "Contributing Elements" to Risk Assessment of Slope Stability in Deep Water. These were to be used to generate topics for voting on priorities on Saturday morning.

2. A completed Table ("matrix") listing Contributing Elements, Importance, Current State of Knowledge and Knowledge Needs summarizing Friday afternoon's discussion. This information was used after the Forum in preparing this final Forum report.

Plenary Session (Day 2)

All participants reconvened for the second day of the Forum in a plenary session. For the first portion of this morning's session each of the four breakout sessions reported on their discussion and presented what they decided represented the top six (in one case, top seven) contributing elements for submarine slope stability risk assessment. All reports were made by the session facilitators except for breakout session 3, where Jim Hooper (Fugro) substituted for Dick Raines (Exxon Mobil).

Presentations by individual breakout session facilitators were followed by open discussion among participants of the importance of contributing elements. Initially the organizers anticipated that participants would vote on priorities and importance of the contributing elements that had been defined earlier. However, after considerable discussion it was decided that the earlier reports sufficiently represented results of the participants' deliberations and no attempt was made to prioritize them. However, it was decided to vote on a list of the top six factors that were identified as important causes/reasons for uncertainty in risk assessment of slope stability. Following this vote the Forum was adjourned.

Summary of Reported Findings

The majority of the findings and conclusions are presented in the reports of each of the breakout sessions. Detailed summaries of each breakout session's identification and rankings of Contributing Elements, Importance to Design Decisions, Current State of Knowledge and Knowledge Needs are presented in Appendix D. The complete, sometimes annotated, listing of the top six "Contributing Elements" submitted by each breakout session are presented in Appendix E.

Summaries of each breakout session's prioritized listing of the important Contributing Elements of risk assessment for submarine slope stability are presented below. The final listing and ranking of the sources of uncertainty are summarized at the end of this section.

Breakout Session 1:

The top six items identified by Breakout Session 1 are:

1. Magnitude and frequency (spatial and temporal) of slope failure mechanisms
2. State-of-the-art geological/geophysical data supported by appropriate geotechnical data for integrated analysis.
3. Identification of key factors responsible for cause of failures.

4. Consistent standards for slope instability risk assessment - criteria and procedures
5. Relationships between slope conditions, instability mechanisms, and resulting geometries.
6. Integration of all data types to develop a site-performance model in terms of slope stability.

Breakout Session 2:

Breakout Session 2 identified and prioritized seven items as follows:

1. Pore pressures - existing field and how it might change spatially and temporally.
2. Soil shear strength.
3. Earthquake loading.
4. Active sediment deposition (and dating).
5. Geotechnical stratigraphy.
6. Fault properties
7. Modeling

Breakout Session 3:

The top six items identified and prioritized by Breakout Session 3 are as follows:

1. Pore pressures
2. Weak or brittle layers.
3. Geologic scale issues.
4. Triggering mechanisms.
5. Slide dynamics.
6. Operation impacts

Breakout Session 4:

Six items were identified and ranked by Breakout Session 4:

1a. Lack of understanding of trigger mechanisms.
1b. Lack of definition of shallow stratigraphy.
3. Lack of case studies.
4a. Lack of understanding of pore pressures.
4b. Better geotechnical characterization.
6. Laboratory and numerical modeling

Sources of Uncertainty

Under the guidance of Dr. Robert Gilbert during the final day's plenary session, participants identified and discussed a list of six sources of important uncertainties pertaining to assessment of risk for submarine slope stability. Following that discussion the participants were all allowed to vote. Each participant was given two votes to select their choice from the list of six uncertainties. Participants were allowed to either vote for two items or place both of their votes on one item. The list of uncertainties and number of votes received are summarized below beginning with the highest ranked items and continuing to successively lower ranked items:

1. Don't Understand Relationship between Slope Conditions, Instability Mechanisms and Resulting Geometries - 23 votes.
2. Trouble Identifying Key Factors that Cause Failures - 17 votes.
3. Lack of Information on Magnitude and Frequency (Spatial and Temporal) of Slope Failures - 13 votes.
4. Imbalance in Geotechnical/Geological vs. Geophysical Data - 12 votes.
5. Lack of Case Studies - 7 votes.
6. Lack of Integration of Data - 4 votes.

Summary and Concluding Remarks

This Forum brought together a number of participants with broad views and backgrounds related to issues of risk assessment for slope stability in deep water. In reality the field is even much broader than represented by the participants. Views ranged from relatively narrow, well-focused views of technological needs in specific areas to broader views of issues such as integration and planning. Based on the discussion over the course of the Forum at least several observations can be made:

- There is a need for better integration of geological, geotechnical, and geophysical data gathering and interpretation. The high cost of obtaining these data limits how much can be obtained and requires that the information be integrated to optimize its usefulness.
- There is a need for more advanced planning and investigation. "Paper" or "desktop" studies and studies in the very early stages of planning should improve the understanding and maximize what can be learned. Often there is neither time nor money to do as thorough an investigation as might otherwise be possible.
- The understanding of properties and processes at a single, site-specific point is very good compared to the understanding of properties and processes both spatially and temporarily. While additional resources might improve on this, better integration of data and earlier starts to investigations could also help.
- There is still need for improved technology and more data collection. Pore water pressures and how soils behave as failure progresses and the soil changes in state, e. g. from a solid to a fluid, are examples of where further investigation is warranted. There is also need for fundamental understanding of triggering mechanisms and how slope failures progress.
- Standards comparable to those that have been developed for foundations and for risk assessment for earthquakes would be beneficial and could probably be developed even with the present state of knowledge.
- There is a lack of well documented case histories. Often the triggering mechanisms are unknown and there is usually a paucity of good geological, geotechnical or geophysical data. In some instances well-documented cases may exist, but are not in the public domain and thus not available to many.

- Economics represent a real and practical element in most assessments of slope stability. Because resources are often tied to the proven feasibility of oil reserves, the resources are not available in the early stages.

It seems likely that some objectives and advances could be achieved much more quickly than others. For example, steps could soon be taken toward developing standards for risk assessment of slope stability in deep water. Progress could also be made in integration of the geotechnical, geological and geophysical investigations. In contrast, advances in measuring and understanding pore water pressures, including variations both spatially and temporally have been sought for many years and will probably require many more years to reach the desired level of understanding

Many of the obstacles to evaluation of risk of slope failure in deep water still rest in the lack of a robust framework for assessing all risks and communicating these effectively to managers who make the most important decisions. While it may seem most appropriate to the engineer, geologist or geophysicist that the objective of additional investigation is to improve one's understanding, the more important issue is probably how this will influence the risk to health, safety and the environment in terms of economics, public perception and industry reputation. Better ties between what is needed technically and how it impacts these larger issues of risk and the necessary communication of this to all parties involved will probably produce the greatest impact. Although the Forum did not address these broader issues in depth, it is hoped that the discussions at this Forum will initiate activities that will ultimately address and impact these broader issues of risk and communication.

Appendix A - Forum Agenda

The formal agenda for the Forum is included on the following two pages.

Slope Stability Forum

Dates: May 10-11, 2002, Houston, Texas

Location: Institute of Biosciences and Technology Bldg - 2nd Floor Auditorium
Texas A&M University System Health Science Center
2121 West Holcombe Blvd. (at Shamrock & Holcombe)

Agenda

FRIDAY MORNING - May 10

8:00 - 8:30 AM	Hot Continental breakfast
8:30 - 8:40	Welcome - Purpose of Workshop (to assess technology and needs for risk assessment of slope stability in deep water); in partnership with MMS/C-CORE/OTRC [Steve Wright, UT/OTRC]
8:40 - 8:45	Opening remarks - MMS [Charles Smith, MMS]
8:45 - 8:55	Opening remarks - C-CORE [Judith Whittick, C-CORE]
8:55 - 9:15	Industry Perspective [Philippe Jeanjean, BP]
9:15 - 9:25	Risk and Probabilistic Perspective [Bob Gilbert, UT/OTRC]
9:30 - 10:00	Mini-Panel 1 - Facilities & Design Issues (impact of a slide) [Ed Clukey, BP; Jason Newlin, Shell; Dick Raines, ExxonMobil]
10:00 - 10:20	Morning break
10:20 - 10:50	Mini-Panel 2 - Geologic Environment (processes, triggering mechanisms, stratigraphy) [Bill Bryant, TAMU/OTRC; Andy Hill, BP; David Piper, NRC-Canada]
10:50 - 11:20	Mini-Panel 3 - Geotechnical Properties [Jim Collins, Marathon Oil; Jim Hooper, Fugro; Alan Young, GEMS]
11:20 - 11:50	Mini-Panel 4 - Modeling (response given trigger) [Jeremy Dean, Shell ; Forrokh Nadim, NGI; Ryan Phillips, C-CORE]
11:50 - 1:00	Lunch

FRIDAY AFTERNOON - MAY 10

1:00 - 3:00	Four Breakout Sessions (first portion of Fri. PM) - Development of list of "Contributing Elements" (for risk assessment); Their importance and the current state of knowledge; Research needs [Jean Audibert, Fugro; Philippe Jeanjean, BP; Dick Raines, ExxonMobil; Craig Shipp, Shell]
3:00 - 3:20	Afternoon break
3:20 - 4:30	Four Breakout Sessions (last hour of Fri. PM) - Each group prioritize top six "Contributing Elements"

SATURDAY MORNING - MAY 11

8:00 - 8:30 AM	Hot Continental breakfast
8:30 - 8:50	Breakout Group 1 report & discussion
8:50 - 9:20	Breakout Group 2 report & discussion
9:20 - 9:50	Breakout Group 3 report & discussion
9:50 - 10:10	Morning break
10:10 - 10:30	Breakout Group 4 report & discussion
10:30 - 11:15	Final discussion and listing of items for ranging/prioritization
11:15 - 11:45	Voting on priorities by each participant
11:45 - 12:00	Closing remarks and summary
12:00	Adjourn

Appendix B

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A listing of Forum participants, including contact information, is presented in the following pages of this section:

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Appendix C

Breakout Session Participants

This appendix contains a listing of the participants in the four breakout sessions. In some case participants may have chosen to participate in more than one breakout session and may be listed accordingly.

Breakout Session 1:

- Hans Abramson
- Joe Bracci
- Bill Bryant
- Jack Clark
- Ed Clukey
- Peijun Guo
- Phillip Hogan
- Lionel Lemoine
- Brian McAdoo
- Tom McGee
- David Piper
- David Prior
- Craig Shipp - Facilitator
- Alan Young

Breakout Session 2:

- Mike Angell
- Jean Audibert - Facilitator
- Laura Brown
- Jack Clark
- Jim Collins
- Jeremy Dean
- Peijun Guo
- Kevin Hampson
- Jim Hance
- Harry Kolk
- Dejan Krunic
- Armand Silva
- Judith Whittick

Breakout Session 3:

- Ken Been
- Kerry Campbell
- Kevin Day
- John Egan
- Andrew Hill
- Jim Hooper
- Mary Beth Hueste
- Vernon Kasch
- Eric Liedtke
- Vincent Morgan
- Farrokh Nadim
- Dick Raines - Facilitator
- Tor-Inge Tjelta
- Charles Winker

Breakout Session 4:

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- Clarence Ehlers
- Trevor Evans
- Yoann Hispa
- Andrew Hume
- Philippe Jeanjean - Facilitator
- Homa Lee
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- Jason Newlin
- Dan Orange
- Ryan Phillips
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Appendix D

Breakout Session Listings of the Contributing Elements to Risk Assessment, Their Importance, Current State of Knowledge, and Knowledge Needs

Each breakout session was asked to identify important contributing elements to risk assessment of slope stability in deep water, list their importance, and define the current state of knowledge and knowledge needs. This information was summarized in tables, which are presented in the following pages of this appendix.

Risk Assessment for Submarine Slope Failures - Group 1

Contributing Elements	Importance to Design Decisions*	Current State of Knowledge*	Knowledge Needs
Magnitude and Frequency (spatial and temporal) of slope failure mechanisms • how big? • how many? • how old? • where? • what type?	High	Variable by geographic area	Quantify the recurrence intervals by regional studies. Definition of active vs. relict.
State-of-the-Art Geologic/Geophysical Data Supported by Appropriate Geotechnical Data for Integrated Analysis		An imbalance exists between geophysical and geotechnical data; volume and quality. Limitation due to cost of acquiring geological and geotechnical data.	Innovative and inexpensive ways to develop geotechnical parameters and integration with seismic data.
Characterization of Triggers: Identification of key factors responsible for cause of failures.	High	Varies from location to location depending on mechanism. We don't know how to define regional and local, and there is an imbalance between the understanding of the two.	Quantify factors on local and regional scales. Apply the earthquake risk methodology as a "go by".
Consistent Standards for Slope Instability Risk Assessment Criteria and Procedures	High	Non-existent	Guidelines: Some kind of recommended practice the industry can generally approve.

Characterization of Mechanisms of Failure: Relationship between slope conditions, instability mechanisms, and resulting geometries.		Imperfect - many of our models are based on land, which is inappropriate. Concerns are limited by land experience.	More laboratory experimentation of flow mechanics and resultant morphologies. Field case studies. Monitoring of active slides.
Improve Assessment Practice		Questions exist regarding factors of safety.	Define acceptable levels of safety. Communicate and understand the implications of factors of safety.
Integrating all types of data to develop a site performance model in terms of slope stability.		Desktop studies at the beginning of a project are not sufficiently used. Economics of decision process.	Get data organized in the right order.

***Rank importance as "High", "Medium", "Low"**

Risk Assessment for Submarine Slope Failures - Group 2

Contributing Elements	Importance to Design Decisions*	Current State of Knowledge*	Knowledge Needs
Pore pressure	High	Low	Data acquisition; development of non-invasive technology
Soil shear strength selection	High	Good	Spatial variability and resolution; geophysical non-invasive technologies; calibrated extrapolation model (e.g. shear wave velocity and porosity)
Earthquake loading	High	Good	Scaling up to design magnitude earthquake; collection of lower magnitude data for local calibration; better attenuation models; improve understanding of deepwater soil dynamic behavior
Active sediment deposition (and dating)	High	Good for less than 40,000 years, poor for older layers	Better understanding of spatial distribution of sediment deposition; higher resolution and more accurate dating techniques
Geotechnical stratigraphy	High	Good	Improved ability to pick up small scale changes; reduce gas blanking (4D4C); better understanding of spatial variation
Fault properties (for slope stability analysis)	High	Poor-Fair	
Modeling	High	Fair	
Sediment erosion	High		

Soil-structure/soil-pipeline interaction		Low	Need to include a "hydrodynamic" approach; characterization of forces and parameters needed to quantify such forces; better understanding of sensitivity of design
Drilling related activities		Medium	Learn from available case histories and calibrate our tools and models
Mud volcanoes (e.g. Caspian, high rate of deposition, gas overpressure)	High	Medium	Study existing databases and learn from them; understand eruptive nature
Gas hydrates		Good and increasing	Improved testing; detection and confirmation of existence of hydrates
Bathymetry		Good	
Salt dynamics (salt uplifiting and intrusion; slope steepening; pressure halo; increased horizontal stresses; high salinity; extreme underconsolidation)	High	Low	Research on high salinity effects on soil parameters
Oversteepening of slopes			
Shallow gas and gas seeps			
Seafloor currents	High	Good and rapidly improving	Existence of solutions; characterizing and quantifying their effects; application of that knowledge and implication to design; current survey campaigns and share knowledge among operators

***Rank importance as "High", "Medium", "Low"**

Risk Assessment for Submarine Slope Failures - Group 3

Contributing Elements	Importance to Design Decisions*	Current State of Knowledge*	Knowledge Needs
#1 - Pore Pressure	High	Poor - can measure at a point, but 3D and temporal knowledge is poor.	(1) Better, faster measurement tools. (2) Pore pressure 3D models, including time
#2 - Weak Layers	High	Poor: Difficult to detect and characterize	Geological understanding of their origin and characteristics.
#3 - Geologic Scale Issues - Temporal and Spatial	High	Locally good, but regionally can be poor	Required for integrated studies Need C14 dates, long cores, regional mapping.
# 4 - Triggering mechanisms	High	Can be good for earthquakes, poor for slow failures.	Slow (geological scale) mechanisms most difficult. Need mathematical models.
#5 - Slide Dynamics	Medium-to-High	Better models are available Sediment properties poor at large energy failures.	Calibrate models by project/testing. Testing of remolding effects on S_u/viscosity.
#6 - Operation Impacts	Medium-to-High	e.g.: Trigger by well blowout. Underreported, but can impact slope failures.	Better documentation. Better modeling of failure processes.
#7 - 3D Material Stratigraphy	High	3D High resolution is not used enough to characterize sediments.	Use high res. 3D. Borehole logging. Seismic inversion.
#8a - Large Strain Strength	High	Poor for high-energy remolding process during failure.	Required for slide runout. Testing of different sediments.

#8b - Gassy Sediments	High	Can measure at a point, but poor regional capability.	Faster sampling tools Correlations with geophysics Models S_u (strength) testing

***Rank importance as "High", "Medium", "Low"**

Risk Assessment for Submarine Slope Failures - Group 4

Contributing Elements	Importance to Design Decisions*	Current State of Knowledge*	Knowledge Needs
Pore pressure evolution with time (yesterday, today, tomorrow): • in-situ measurements • magnitude • distribution • fluid flow regime • relationship to geological model • 2 phase (gas vs. water pressure) • resolution at depths of interest	High	Low-to-medium	More in-situ More long-term Use of basin modeling
Lack of early desktop studies: • if we don't do it … might miss something • utilize existing (public domain <u>and</u> proprietary) data	High in early stages	Low-to-medium (have the means)	Systematic documentation of what's been done. Need to publish & share Encouragement from regulators to share.
Lack of understanding of trigger mechanisms: • possible reactivation of existing failures • earthquakes • any evidence of pre-existing instability • how do they interact? • too quick to jump to <u>one</u> trigger mechanism	High	Low for a given slide Low for combined mechanisms Low for future	

Shallow stratigraphy: • incl. presence/absence of gas hydrate • weak layers? • weak layers? • high salinity • clay structure / sensitivity • strain softening behavior (drained, undrained, limitation of SHANSEP) • mechanical properties • relationship to sea level • spatial/lateral (3D) variability (observation, interpretation, modeling) • integrated detailed geology, geotechnical & modeling • how to deal with faulting (as resolution gets better, see more & more).	High; project dependent		More continuous information, logging More use of geophysics data to assess soil mechanical properties.
Lack of use of laboratory models & numerical models to understand pore pressure response during failure, failure and fate of failed material; threshold values	High	Medium	Use of real marine soils in laboratory Better modeling of multi-layered, anisotropic strata.
Lack of definition of threshold values, e. g. strains, pore pressure, creep, earthquake activity.			
Lack of understanding of timing - including case studies.			
Lack of case studies integrating observed features and quantitative analysis. • in those that have been published ill-defined problem • lack of information sharing	High	Low in public domain	Publish well-documented case studies.

How to deal with active processes such as erosion, channeling, scouring	Project dependent.	Low-to-medium	Modeling of facility seabed interaction More current measurements on seabed. More local measurements near slides.
Lack of understanding of mechanisms to generate oversteepening (fault, salt, sediment accumulation, failure on adjacent slopes)	See triggering mechanisms		
We have 3D view of geometry (seismic), but don't have comparable 3D geotechnical properties			In-situ techniques. New tools: • shear wave velocity measurements • burial assessment tools
Measured geotechnical properties / samples may not reproduce/reflect what actually happens in nature: • in-situ • extrapolation • can only measure discrete	High	Medium	New techniques: In-situ, large strain, stress-strain, brittleness behavior. More samples through existing failure surfaces.
Lack of ability to do back analysis to explain past failures. • regional geology, what were soil parameters, pore pressures triggers, state of stress, at time of failure (sensitivity analyses) • back analysis may not capture failure mechanisms • might have to run multiple models (earthquake, hydrate melting) • requires integrated team.	Med (High?)	Poor	Need to define parameters.

Lack of time/resources necessary to do acquisition, interpretation, modeling.	High	N/A	
Lack of awareness on the part of management re: importance of studies for risking facilities.			
Lack of integration of industry and academic expertise.			
Lack of multi-disciplinary integrated team approach.			
Lack of integration of individual disciplines.			Need communication!
Poor integration of available skills within a given company applied to geohazards. • basin modelers • exploration • drilling • research			
Lack of analysis of historical deep water slides through JIP, academic, industry. • develop a fully defined case history			GOM JIP after Norwegian model? Need more support for generic JIP decoupled from exploration Need to start big picture geohazard survey early.
Lack of understanding of human-induced affects (drilling, cuttings during riserless drilling, facilities placement). • effects on pore pressure regime • gas hydrate dissolution	High	Low	Need fundamental modeling, published case studies. Need fundamental studies of gas hydrate.
Lack of understanding of transition from intact to remolded material acquiring mobility.	High	Low-to-medium	Modeling Documented case studies Laboratory experiments, controlled environment.

Lack of understanding of erosion, non-depositional and depositional processes.		Low-to-medium	
Need for detailed, 100% seafloor image	High	Project dependent	Required
Succession planning (next generation expertise)			
Need to estimate dynamic loads on structures, including high currents.	Project dependent.	Medium	Input from other disciplines, fluid dynamics Tool development, software Guidance & standards.

***Rank importance as "High", "Medium", "Low"**

Appendix E

Breakout Session Rankings of the Top Six Contributing Elements to Risk Assessment

Each breakout session's summary of the top six (or seven) elements for risk assessment are included in this appendix. In some cases these were presented with annotation regarding the Importance to Design Decisions, Current State of Knowledge and Knowledge Needs. Also, in most case further information can be found in the breakout session's detailed tables that are included in Appendix D.

Priorities - Group 1

Priority #1

Contributing Element: Magnitude and frequency (spatial and temporal) of slope failure mechanisms - How big? How many? How old? Where? What type? Why?
Importance to Design Decisions: High
Current State of Knowledge: Highly variable by geographic area.
Knowledge Needs: Better definition of active vs. relict. Quantification of recurrence intervals by regional studies.

Priority #2

Contributing Element: State-of-the-art geological/geophysical data supported by appropriate geotechnical data for integrated analysis.
Importance to Design Decisions: High
Current State of Knowledge: Imbalance exists between geophysical and geotechnical data - volume and quality. Limitation due to cost of acquiring data, e. g. data collected from cores.
Knowledge Needs: Innovative and inexpensive ways to develop geotechnical parameters and integrate with seismic data.

Priority #3

Contributing Element: Identification of key factors responsible for cause of failures.
Importance to Design Decisions: High
Current State of Knowledge: Varies by location depending on primary mechanism Inability to define balance between regional and local understanding.
Knowledge Needs: Quantification of factors on local and regional scales. Apply earthquake risk methodology as a template.

Priority #4

Contributing Element: Consistent standards for slope instability risk assessment - criteria and procedures	
Importance to Design Decisions: Moderate	
Current State of Knowledge: Nonexistent	
Knowledge Needs: Guidelines - recommended best practices that industry can use.	

Priority #5

Contributing Element: Relationships between slope conditions, instability mechanisms, and resulting geometries.	
Importance to Design Decisions: Moderate.	
Current State of Knowledge: Concepts are limited by land experience. Some aspects of marine setting can be different.	
Knowledge Needs: More laboratory experimentation on flow mechanics and resultant morphologies. Actual field-based case studies. Monitoring of presently active systems.	

Priority #6

Contributing Element: Integration of all data types to develop a site-performance model in terms of slope stability.	
Importance to Design Decisions: Moderate	
Current State of Knowledge: Questions exist regarding factors of safety. Desktop studies at project initiation are not widespread. Economics of the decision process - "won't spend the money until you have the grease."	
Knowledge Needs: Define acceptable levels of safety. Communicate and understand the implications of safety factors. Acquire data and organize in the right sequence.	

Priorities - Group 2

Priority #1

Contributing Element: Pore pressures - existing field and how it might change spatially and temporally.
Importance to Design Decisions: High
Current State of Knowledge: Low
Knowledge Needs: Data acquisition - especially non-intrusive.

Priority #2

Contributing Element: Soil Shear strength
Importance to Design Decisions:
Current State of Knowledge: Good
Knowledge Needs: Spatial variability resolution Non-intrusive way to extrapolate over 3-D (V_s & n)

Priority #3

Contributing Element: Earthquake loading
Importance to Design Decisions:
Current State of Knowledge:
Knowledge Needs: Scaling from small earthquake to larger earthquake design event. Attenuation/soil dynamic properties.

Priority #4

Contributing Element: Active sediment deposition (and dating)
Importance to Design Decisions:
Current State of Knowledge:
Knowledge Needs: Better understanding of spatial distribution of sediment deposition. Higher resolution on dating.

Priority #5

Contributing Element: Geotechnical stratigraphy.
Importance to Design Decisions:
Current State of Knowledge:
Knowledge Needs: Small scale variations (weak layers) Spatial variations Reduce gas blanking.

Priority #6

Contributing Element: Fault Properties
Importance to Design Decisions:
Current State of Knowledge:
Knowledge Needs: Pressure core samplers. V_s measurements.

Priority #7

Contributing Element: Modeling
Importance to Design Decisions:
Current State of Knowledge:
Knowledge Needs: Verify and calibrate existing models. Better tie between data and impact.

Priorities - Group 3

(1) Pore Pressures

- model/predict distribution of pore pressures spatially and temporally
- existing tools for measurements are too cumbersome and not used enough

(2) Weak or Brittle Layers

- common "suspected" cause of lots of observed failures
- difficult to identify, sample and test
- tools exist but not being used
- could be weak or brittle

(3) Geologic Scale Issues

- size of study region
- need regional views (geologic and geotechnical)
- "integrated studies"
- temporal - how fast do things happen? Earthquake, erosion, salt uplift

(4) Triggering Mechanisms

- slow loading more of a concern than rapid, e. g. earthquake, loading
- creep properties of soil
- soil response to slow stress changes
- long-term tests needed on a variety of soil types

(5) Slide Dynamics

- how far it goes
- how big is it
- transition/runout process
- need calibrated models
- "large-scale" high-energy remolding process

(6) Operation Impacts

- drilling issues (well failures)
- frequent occurrences

Priorities - Group 4

Priority #1a

Contributing Element:

Lack of understanding of trigger mechanisms

- Fault
- Salt
- Sediment Accumulation
- Failure on adjacent slopes
- Earthquakes
- Reactivation

How do they interact?

Importance to Design Decisions: High

Current State of Knowledge:

High for historical slides (slides in recorded history)
Low for geological (slides before recorded history)

Knowledge Needs:

Fundamental research
Monitoring

Priority #1b

Contributing Element:

Lack of definition of shallow stratigraphy

- Weak layers (where and why)
- High salinity
- Clay structure / Sensitivity
- Strain softening behavior
- Mechanical properties (drained, undrained, limitation of SHANSEP)
- Relationship with sea level
- Spatial variability (x, y, z, t)
- Fault plane properties.

Importance to Design Decisions: High

Current State of Knowledge:

Project dependent

Knowledge Needs:

Continuous information, logging
Use geophysical data to assess geotechnical properties

Priority #3

Contributing Element:

Lack of case studies

- Not enough
- Not well enough documented
- No integration of observed features with quantitative analyses
- Lack of information sharing.

Importance to Design Decisions: High

Current State of Knowledge:

Low in public domain

Knowledge Needs:

Publish well-documented case studies

Priority #4a

Contributing Element:

Lack of understanding of pore pressures

- In-situ measurements
- Magnitude / distribution
- Fluid flow regime
- Relationship to geological model
- Two phase: gas vs. water
- Resolution of measurements @ high water depths
- Evolution with time (past, present, future)

Importance to Design Decisions: High

Current State of Knowledge:

Low to medium

Knowledge Needs:

More in-situ measurements, long-term

Basin modeling

Priority #4b

Contributing Element:

Better geotechnical characterization

- Lab behavior ≠ in-situ behavior

Importance to Design Decisions: High

Current State of Knowledge:

Medium

Knowledge Needs:

New techniques:

- In-situ stress-strain curves for large displacements.
- Quantify brittleness behavior.

Priority #6

Contributing Element: Laboratory and Numerical Modeling • Lack of understanding of pore pressure response during failure (undrained vs. drained) • Threshold values (stress, strain, pore pressure) • Fate of failed material.
Importance to Design Decisions: High
Current State of Knowledge: Medium
Knowledge Needs: Use marine soils in the laboratory. Better modeling of multi-layered anisotropic strata.