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PROTECTING OFFSHORE PIPELINES AGAINST DRIFTING ICE: A DISCUSSION ON STANDARDS AND GUIDELINES

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Abstract

In freezing waters, seabed gouging ice features (icebergs, pressure ridges) are a threat to offshore pipelines, which must be buried to a safe depth. Several standards and guidelines addressing this issue are examined and compared. The type of information that each code deems significant varies considerably – factors that are important to some code writers are not to others. API RP 2N, CSA-ISO 19906, CSA Z662 and DNV OS F101 direct the users to specific factors that either must or could be considered for design, but do not indicate what is to be done with them. In contrast, the RMRS rules are highly prescriptive. From a code user's perspective, a comprehensive listing of all factors involved in ice-seabed-pipe interaction might provide better guidance in assessing what needs to be considered. This assessment could also be divided into three distinct operations: determination of design gouge depth, determination of clearance below the design gouge depth, and determination of pipeline response.

INTRODUCTION

Offshore pipelines (also referred to as 'subsea', 'marine' or 'submarine') in freezing waters are exposed to a number of environmental threats that do not exist in warmer waters [1-6]. Of particular concern is the damage they can sustain from ice features such as icebergs or pressure ridges that drift into shallow areas, typically as they approach the shoreline. Doing so, the ice keel comes in contact with the seabed and as the ice keeps drifting, it may gouge the seabed for considerable distances [7-10](Fig. 1). Trenching and burial is seen by the offshore engineering community as the best means of protecting these structures. The challenge is to determine what a safe and cost effective depth should be along the planned pipeline route.

During the gouging event, a complex interplay of forces takes place within the soil, which gets displaced laterally to form side berms, and ahead of it to form a front mound. The soil below the gouge base is dragged forward, resulting in sub-gouge soil displacements down to a significant depth below the gouge (Fig. 1). This means that even if the buried pipeline does not sustain a direct impact, it can undergo lateral displacement, thereby incurring an unacceptably large amount of bending strain. A design burial depth should provide sufficient clearance below the gouge so as to allow the pipeline to withstand some bending but only up to a level the design engineer deems acceptable.

The authors were interested in finding out what industry standards and guidelines existed that could assist the pipeline engineer in planning against these events. Five of these codes were examined and compared with that purpose in mind, and from a user perspective. This paper presents the outcome of that study.

PROTECTION AGAINST DRIFTING ICE FEATURES

Design codes, standards, rules, recommended practices provide information about important features of product, service or system [11]. In most cases, compliance is voluntary; in others, it is mandatory and monitored by regulatory bodies. Some are objective-based, others are prescriptive. The former, which have been adopted in many countries, set specific objectives of a qualitative nature to be used as guidance toward the desired performance level [12]. These documents are continuously being improved upon, with new editions appearing from time to time; others may be withdrawn. They are overseen by various national or international committees, and can be quite different even though they address similar issues. Even if a design meets a standard, it may still not be

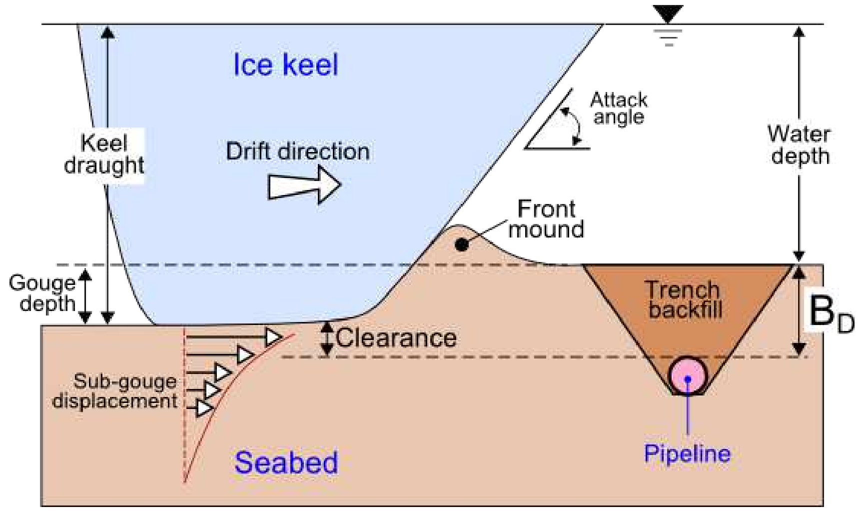

Figure 1: Pipeline burial against ice keel action (simplified scheme) – B_D is the design burial depth.

safe. Some standards specifically state that experience and sound engineering judgment are required.

A look at how standards and guidelines address pipeline protection against gouging ice features appears justified. According to Mørk [2], "the growing focus on arctic oil and gas exploration has raised the need for new standards and industry practices… Material selection, qualification of materials for arctic pipelines, and *design for pipelines* against ice gouges are examples of areas that require more consideration." An adequate understanding of what the pipeline will be exposed to would also be desirable. According to Konuk [13, p. 155], "Current North American standards and regulations provide no explicit guidance on how to incorporate the ice gouge load conditions in the design of offshore pipelines or offer any explicit design criteria or design acceptance limit." This is vindicated by Lanan and Ennis [14], reporting on the Northstar development, who point out to a lack of a single industry standard in this regard. Duplenskiy and Gudmestad [15] also note that no strong recommendations seem to exist at this time.

STANDARDS AND GUIDELINES

Following is a condensed version of five of the better known standards and guidelines published in English that address, at least to some extent, offshore pipeline protection against loading by drifting ice keels. The editions that were examined are thought to be the most recent as of this writing.

API RP 2N: *Recommended Practice for Planning, Designing, and Constructing Structures and Pipelines for Arctic Conditions*

The API RP 2N version (2nd edition) reviewed in this article [16], published in 1995 and reaffirmed in 2007, is a recommended practice. Its purpose is to provide the latest knowledge for planning, designing and constructing arctic systems: offshore concrete and steel structures, gravel islands, ice islands, near shore causeways, subsea pipelines and shore crossing for pipelines. Hence, it mostly deals with the offshore environment. For subsea pipelines not located in the Arctic, it refers to API RP 1111.

API RP 2N points to trenching and burial as a means of protecting the pipeline in zones where ice gouging is known to occur, and includes sources of information (all pre-dating 1995) on seabed gouge data. Known methods of pipeline protection include trenching, through jetting, plowing, mechanical excavation and dredging, with the objective of minimizing environmental disturbances. It provides suggestions for types of data to be collected at a specific site: bathymetry, local topography, gouge depth, width, direction, and gouging frequency, either measured in number of gouges per km or per km^2. It acknowledges the difficulty in being able to date gouges – age estimates may vary by one or more orders of magnitude – and advocates repetitive seafloor surveys. Reference is made to methodologies by previous investigators to estimate rare gouging events, whose probability distribution is assumed to be exponential. Examples of deterministic methods are also provided. Further, the 'sharpness' of a gouge may be indicative of its age. The code warns of the influence of deep, but very old gouges, which may cause statistical distributions to appear overly conservative. Gouge infill through wave actions, currents and river sedimentation may have the opposite effect, because it will decrease gouge depth.

API RP 2N indicates that sub-gouge soil deformation around the pipeline may induce excessive strains in that structure as a result of bending. It points to a few theoretical analyses and an experimental program addressing this issue.

In more general terms, this code recommends environmental conditions, such as ice conditions and extent of seabed gouging, to be identified and described by means of probability distributions. A site investigation and soil testing program may be in order.

CSA Z662: ***Oil and Gas Pipeline Systems***

CSA Z662 [17] is the standard's 6th edition, first published in 2011 and revised in 2013 (including updates 1, 2 and 3). The standard has an informative section in annexes and is also accompanied by commentaries of a prescriptive nature and referring to other codes (*e.g.* CSA S471, DNV OS F101). This code deals with the design, construction, operation, and maintenance of oil and gas pipeline systems meant to transport liquid hydrocarbons, oilfield water or steam, carbon dioxide or gas. It has a clause for lines between facilities and for long or deep-water shore-to-shore pipeline crossings, in seawater and freshwater.

In cold oceans, ice loads on pipelines during installation and operation are to be considered, as well as the ice regime and keel characteristics. A commentary raises the importance of proper interpretation of statistical data. Well recognized probabilistic and reliability-based designs should also be used. Environmental data to be collected at a given location include season, ice type, dimensions, mechanical properties, and drift speed and direction. Loads and load effects are to be evaluated, and numerical and physical models and full scale data may be used for that purpose. They should factor in the nature of the interaction, ice mechanics, ice failure processes and scale effects.

On-site bathymetric surveys are preferred as a means of getting information on gouge width, depth, length, orientation, recurrence rate, as well as seabed properties. Gouging frequency, gouge residency (due to seabed erosion), gouge infilling, instrumentation accuracy, bias and data reliability should also be considered. If field data are lacking, mathematical models are to be used to get information on gouge parameters. In that case, adequate environmental data should be obtained (driving forces, ice regime, seabed properties).

Soil failure processes, gouge clearing mechanism (to generate side berms and front mound) and sub-gouge deformation should be evaluated with recognized engineering practices that include field investigations, physical modeling (reduced scale 1g and centrifuge), analytical solutions and numerical methods. Data significance, technical uncertainty, and limitations of the selected approach should be appraised. The significance of decoupling the interaction between the keel and the seabed from that between the seabed and the pipeline should be evaluated. Load- and displacement-controlled and dynamic loading effect should be considered at the freely-floating, grounding and shoreline ice ride up stages.

DNV OS F101: ***On-Bottom Stability Design of Submarine Pipelines*****, and ICE PIPE JIP**

DNV GL (formerly known as Det Norske Veritas or DNV) has published a standard called DNV OS F101[18], which is intended to comply with ISO 13623 [19], which applies to on land and offshore pipeline systems and associated installations (*e.g.* connecting wells, production/process plants, refineries). DNV OS F101 addresses the following topics, in sequence: development, design, construction, operation and abandonment of offshore pipelines. Each, and divisions thereof, is the subject of a section. The final two sections are of an informative nature. As it stands, this standard is not written to take into account challenges facing offshore pipelines in Arctic waters. There is, therefore, very little on ice loads from drifting ice keels. It does state, however, that these events must be considered, and that the forces generated must be accounted for. Model testing of the ice-structure interaction may be required.

Unlike ISO and CSA standards, which are developed through consensus via committees, DNV OS F101 is based on Joint Industry Projects (JIPs). One such JIP (referred to as ICE PIPE), intended to supplement DNV OS F101, was dedicated to cold climate applications: ice gouging, permafrost instability, strudel scour, shore approaches. Some of the key findings of this JIP, addressing threats of gouging ice features to the main pipeline sections, are provided in Davies, et al. [20]. The ICE PIPE guideline "takes the user through the stages of environmental data collection and analysis, determination of characteristic values for ice gouge parameters, and assessment of the pipeline load effect" [20]. The proposed calculation methodology was divided into three steps:

1. Determination of the 100- and 10,000-year return gouging depth, for the ultimate limit state (ULS) and accidental limit state (ALS), respectively.
2. Assessment of the variability of additional governing parameters (gouge width, keel angle, soil properties).
3. With a 'suitable' model and appropriate sensitivity and statistical analyses, determination of how these gouging events translate into a load on the buried pipeline.

Davies, et al. [20] focus on uncertainties in measurement and interpretation of the bathymetry data, and what this entails for the validation of numerical models.

RMRS 2-020301-003: ***Rules for the Classification and Construction of Subsea Pipelines***

The Russian Maritime Register of Shipping's (RMRS) 2-020301-003 'Rules' [21] incorporate a pipeline classification scheme that takes into account the level of operational liability, the corrosiveness of the substance that circulates in the pipeline, and if it is meant to operate in a seismically active area or requires ice-resistant standpipes (vertical structures used for pressure control). The RMRS rules are considerably more prescriptive than the other codes.

To avoid the action of gouging ice keels, the RMRS code recommends laying the pipeline at maximum water depth and parallel to the prevailing drift direction. In waters where there is evidence of ice gouging, the pipeline is to be buried. Minimum burial depth must be set at a distance of one meter below the gouge depth. That distance is multiplied by a safety factor (from 1.0 to 1.3), based on a pipeline classification scheme provided in the rules. If the burial depth is to be less, proper justification must be given. Further, it is recommended that the route be divided into sections, and each section assessed separately. The value for the design gouge depth should be based on the three sets of procedures, which are here summarized.

1) From seabed gouge data

This procedure relies on the availability of seabed gouging data for each pipeline route section, as obtained via seabed surveys, for at least five consecutive years. The pipeline route is subdivided into sections on the basis of these data, in the following order of priority: gouge depth, gouging frequency across the route, gouge areal density. The design gouge depth G_D is determined as follows:

$$G_D = G_M \ln(N_T T) \qquad (1)$$

where

G_M : Mean gouge depth (m) for a given route's segment during the observation period

N_T : Average gouge crossing per year (year^{-1}), as determined by the seabed survey

T : Observation period (years) (100 years, unless stated otherwise)

If the exact location of the pipeline route is not known, but its orientation is, and there is adequate information on the orientation of the gouges and the gouge density, N_T is determined as follows:

$$N_T = N_f M[L\,|\sin(\Phi)|\,] \qquad (2)$$

where

N_f: Gouge density (km^{-2})

M : 'Expectation factor' (not explained in the Rules but presumably in km/year)

L : Not explained in the Rules, but presumably the length of the route segment (km)

Φ : Angle between the pipeline route and the orientation of the gouges

If gouging direction is evenly distributed (or there is no information on this parameter), N_T is determined as follows:

$$N_T = 2\pi G_L N_A \qquad (3)$$

where

G_L : Average gouge length (km)

N_A : Gouging frequency per unit length (year^{-1}km^{-1})

The pipeline burial depth B_D is determined from the above information, as per the following:

$$B_D \geq G_D + Dk_0 \qquad (4)$$

where

D : A given 'margin' (=1 meter), which can be decreased upon adequate justification

k_0 : A safety factor (from 1.0 to 1.3) based on the aforementioned pipeline classification

2) From statistical analyses

For this procedure, the criteria for pipeline route subdivision are soil properties and ice keel draught. The pipeline burial depth B_D is determined using Eqn. (4). The design gouge depth G_D is obtained via statistics-based mathematical modeling, that has to factor in wind conditions, tides, bathymetry, soil properties and ice keel characteristics. No additional information is provided on the modeling, except that it has to be approved by RMRS.

3) From bathymetry and ice regime

For this third procedure, the target burial depth is also determined from Eqn. (4). But the design gouge depth is derived from information recorded on the bathymetry and the ice conditions along the pipeline route, during a minimum of five consecutive years. The route subdivision is made on that basis. This is a 3-step procedure.

Firstly, a value for the parameter a is obtained with the following equation:

$$a = 0.99^{\frac{1.6}{P_0 I_F V T_R T_P}} \qquad (5)$$

where

P_0 : Probability that the keel draught exceeds water depth

I_F : Average number of drifting ice formations per unit area (km^{-2})

V : Average drift velocity (km/day)

T_R : Ice residency (days)

T_P : Pipeline's operational lifespan (years)

Secondly, a burial factor K is determined from the following:

$$K = Zd^2 H_k \qquad (6)$$

where

d : Keel draught variability

Z : Parameter derived from parameter a above and d – this is done via a table for which no explanation is provided

H_k : Mean draught ratio (mean keel draught/water depth)

If K ≤ 1, pipeline burial is not required.

Thirdly, the design gouge depth is determined from the following:

$$G_D = H_S(K-1)k_g \qquad (7)$$

where

H_S : Water depth (taking into account tidal activity)

k_g : Correction factor to take into account the nature of the seabed (0.95, 0.60 and 0.20, for sands, sandy clays and clays, respectively).

CSA-ISO 19906: *Petroleum and Natural Gas Industries — Arctic Offshore Structures*

CSA-ISO 19906 [22] does not specifically address offshore pipelines, but it does include a section on subsea production systems. It is discussed herein for the purpose of this analysis. This is the standard's first edition, and an adoption without modification of the document produced by the International Standards Organisation known as ISO 19906. The standard provides recommendations and guidance for the design, construction, transportation, installation and removal of offshore structures related to the activities of the petroleum and natural gas industries in the Arctic and other cold regions (see also [23]). It deals with ice actions for in-field components referenced in ISO 13628, including flowlines, umbilicals, manifolds, wellheads, subsea storage tanks and processing equipment. ISO standards are divided into a normative and an informative section with references to previous studies; the latter is quite extensive and offers the code user some background knowledge.

Burial is required in water depths less than the deepest ice keels. In the assessment of ice actions on flowlines, the following parameters must be considered: location, frequency and orientation of ice gouge events, whether it is a furrow (linear gouge) or pit (a single point), gouge geometry (length, width and depth), direction and the relative orientation of the line and the gouges. The mechanical properties of soil and keel, as well as soil pressures and displacements, must also be included in the assessment. In doing so, information on expected loading frequency, and the magnitude of direct (through contact) and indirect (through the soil) forces must be taken into account. The potential variation of soil properties as a result of gouging must also be addressed, as well as the effects of environmental factors (wind, wave, current, seismic activity).

Both direct and indirect ice actions must be considered in the assessment, by factoring in the required parameters. For instance, the maximum gouge depth is what matters for direct ice-to-pipe contact. Proper knowledge of keel morphology and mechanical properties is recommended. The relative orientation of the gouges with respect to the flowline must be considered where this affects ice action. The pipeline's mechanical response (extension, ovalization, bending) should also be considered. In cases where the pipeline is covered with infill or backfill material, the shape and the state of that material should be duly considered, along with how it evolves with time.

DISCUSSION

Overview of the design codes

API RP 2N, CSA-ISO 19906, CSA Z662 and DNV OS F101 either instruct or suggest that the information be addressed, but not how that should be done (*i.e.* what to do with the information). These are essentially reminders, as noted by Palmer [24]. They direct the users to specific factors that either must or could be considered for design, but do not indicate what is to be done with them. Examples are as follows:

"If ice gouging is present at a site, the ice gouge distributions, depths, widths, orientation, rates, and properties of infill and surrounding materials should be investigated.*"* API RP 2N [16]

"Ice gouge data acquired through in-situ ice gouge field surveys represent the preferred option *to obtain site-specific data. The parameters to be determined include gouge width, depth and length, gouge orientation, recurrence rate, and seabed geotechnical conditions."* CSA Z662 [17]

"Forces from floating ice shall be calculated according to recognised theory. Due attention *shall be paid to the mechanical properties of the ice, contact area, shape of structure, direction of ice movements, etc."* DNV OS F101 [18]

"For interactions with subsea installations or components below the sea floor, the following parameters should be included in the assessment of ice actions*: […] ice gouge geometry, including length, width and depth, and corresponding variations along and across the impressions in the seabed;"* CSA-ISO 19906 [22]

As for the RMRS code, it is uncompromisingly straightforward, and indicates precisely how this information should be processed. The emphasis is placed on specific parameters and how they should be used to determine gouge depth. Noteworthy is how it deals with sub-gouge deformation: by default, pipeline burial depth is set at 1 m or more below the gouge depth. Vershinin, et al. [25, p. 22] indicate other Russian standards (PD 412-81 and BCH 51-9-86) that had the same approach. One drawback with this code may be its oversimplification.

The first five columns of Table 1 contain information extracted from each of the five codes, as it specifically applies to the issue at hand: offshore pipeline protection against ice keel action. An attempt was made to include the main topics explicitly brought up in each code: data to be collected, the gouging-related processes to be aware of, and the procedures and data processing methodologies, suggested or mentioned.

Table 1: Listing of some factors raised in each standard/guideline. The three columns on the right are for the three operations proposed in this paper, to address design gouge depth, sub-gouge clearance depth and pipeline response (G_D, S_D and P_S).

	Information extracted from the documents					Proposed approach		
	API RP 2N	**CSA Z662**	**DNV OS F101, Davies et al. (2011)**	**RMRS 2-020301-003**	**CSA-ISO 19906 (norm. section)**	G_D	S_D	P_S
Pipeline burial	X		X	X	X			
Data to be collected								
Distinction between furrow and pits					XX	XX	XX	
Ice type and seasonal regime	X	XXX		X		XX	XX	
Ice mechanical properties		XXX	X	X	XXX	XXX	XXX	
Keel draught				X	XXX	X		
Keel attack angle			X		XXX	XX	XXX	
Drift speed		XXX		X	XXX	X	X	
Drift direction		XXX	X	X	XXX	X		
Gouge depth	X	X	X	X	XXX	XXX	X	
Gouge width	X	X	X		XXX	XXX	XXX	
Gouge length	X	X		X	XXX	XX		
Gouge orientation	X	X		X	XXX	XX		
Gouging density/distribution	X			X	X	XX		
Gouging frequency	X	X	X	X	XXX	XXX		
Soil properties	X	X	X	X	XX	XXX	XXX	XXX
Gouge infill and trench backfill properties	X		X		XXX	XXX	XXX	
Pipeline operational lifespan				X				X
Pipeline specifications			X					X
Gouging-related processes/factors to consider								
Shoreline ride-up/slope in seabed		XXX	X			X	X	X
Ice failure and changes in ice properties		XXX			XX	XXX	X	
Rare/Extreme gouge depth, stamukha action	X	XXX	X	X		XXX	X	
Gouge infilling (i.e. seabed mobility)	X	XXX	X		XXX	XXX		
Seabed erosion (i.e. gouge residency)		XXX				XXX		
Change in backfill properties with time					XXX	XXX		
Effects of backfill on keel action					XXX	XXX		
Soil stresses/failure mechanism		XXX	X		XX	XXX	XXX	
Sub-gouge deformation	X	XXX	X		XX		XXX	
Changes in soil properties due to gouging					X	XX	X	
Pipeline loading		XXX	X		XXX			XXX
Pipeline response			X		XXX			XXX
Procedures and methodologies								
For planning pipeline route			X	X		X	X	X
For retrieving bathymetry data	X					X		
For determining rare gouge depth	X					X		
For gouge dating	X		X			X		
For determining gouge density/distribution			X			X		
For performing repetitive seafloor surveys	X			X		X		

For CSA Z662 and CSA-ISO 19906, this information was taken from the standards' normative sections only (not from the informative part), since this is where the emphasis is placed on what factors are to be considered by the design engineer. In these two CSA codes, the 'should' and 'shall' (must) connotations are indicated by 'XX' and 'XXX', respectively; otherwise, a single 'X' (may) is used. The listing in that table is not comprehensive, but it provides a bird's eye view of what is involved and is here presented as an example, for the purpose of discussion. The last 3 columns of Table 1 (in blue) are discussed in the next section of this paper, on the proposed approach for guidelines.

Except for CSA Z662, pipeline burial is explicitly mentioned as a means of protecting the structure from seabed gouging ice features. The information that each code requires the users to address varies. Gouge characteristics, soil types and ice properties are amongst those that are brought up most frequently. Noteworthy are the factors whose relevance is raised by one or two codes only – for example: keel attack angle, effects of backfill, number of years during which seafloor surveys should be conducted prior to pipe lay.

Proposed approach to standards and guidelines

The development of explicit standards and guidelines for the determination of pipeline burial depth is hindered by limited knowledge of gouging phenomena, which are complex. Genuine gouging scenarios are difficult to observe [26]. Getting information on soil deformation below the gouge is also challenging – this has been documented, not from recent events, but from on-land relict gouges a few thousand years old [27]. There are few known cases of damage to pipelines [28, 29]. Physical testing and modeling offer a strong potential for gaining additional insight – nearly 500 simulations were done by various research groups over the past 40 years [30]. But most of these test programs focus on particular aspects of the events, the supplied datasets are incomplete and critical issues have yet to be addressed [31]. This research notwithstanding, there have been calls for additional testing [20, 32]. As for numerical modelling, it has been used extensively by different research groups to simulate gouging processes [33], but model validation is 'non-trivial' [20] and it cannot yet capture all aspects of the interaction.

In this context, and since a standard is not meant to be a complete guide to good design, a code's underlying philosophy is to make code users aware of what needs to be considered, and how much emphasis should or must be placed on any given factor. But as discussed above, recommendations vary. Factors that are important to some code writers are not to others. As pointed out by Palmer [24], lack of agreement reflects a lack of knowledge.

Presumably then, a discrepancy between codes is not exceptional, and for this reason, some designers may like to look at more than one code. If so, then one possibility is to help code users establish priorities by resorting to a listing of factors that is as comprehensive as possible. This may make it easier for the users, who already benefit from the code's informative sections, to make a judgment call on which factors needed to be attended to, and how.

Table 1 could have incorporated additional information regarding design philosophy. The selection of a safe, technically feasible and cost effective pipeline solution is generally based on limit state principles with a strain based approach [4]. Integrity assessment has to predict the pipeline strain demand (PSD) and deformation capacity (PDC) under operating conditions. The ultimate purpose is to optimize the steel wall thickness for the minimum burial depth. Also, that depth requirement has to factor in upheaval buckling propensity at high pressure and temperature, and effect of potential backfill liquefaction (due to storms, earthquake) on the pipeline's vertical position.

In parallel, another possibility is to bring to the users' attention three separate operations that need to be considered on the way to determining a pipeline burial depth (Fig. 2):

1. *Determination of design gouge depth (G_D)*:
   This can be done deterministically, based on seabed mapping data (geophysical, bathymetric), *i.e.* taking into account seabed properties, ice keel characteristics and hydro-metocean data (wind, wave, current, temperature, etc.). It can also be done probabilistically, with repetitive seabed mapping over a given number of years, so as to quantify the gouging regime.
2. *Determination of clearance below the design gouge depth (S_D)*:
   This can be done in the same deterministic manner as mentioned in the first operation. The amount of clearance required will depend on what constitutes an acceptable pipeline response for the structure the engineer has in mind.
3. *Determination of pipeline response (P_S)*:
   This operation takes into account pipeline specifications along with soil properties and its reaction to the gouging event.

The three columns at the right in Table 1 illustrate how information on the three operations could be presented, with the usual three-fold classification on the importance of each factor: 'X' (may), 'XX' (should), 'XXX' (shall). The entries shown in these three columns are for illustrative purposes only. For instance, information on ice type and keel mechanical properties may be relevant for G_D and S_P, but not to P_S if the code assumes decoupling of keel-seabed and seabed-pipeline interaction. Information on keel draft, gouge length and gouge orientation may be used to estimate G_D at a specific location on a probabilistic basis, in which case it would not be relevant for S_P and P_S. Pipeline specifications, loading and response would only be relevant for the P_S operation, following well established procedures, in which case reference may be made to an appropriate section of the code (or to another standard or guideline).

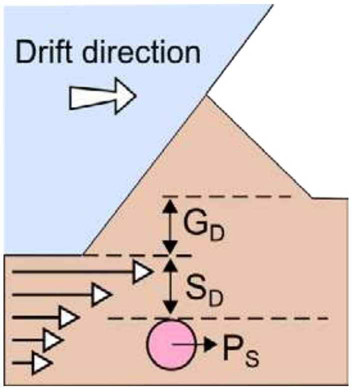

Figure 2: Components G_D, S_D and P_S resulting from the three operations mentioned in the text.

CONCLUSION

This paper compares how a few standards and guidelines address offshore pipeline protection against drifting ice features. A discrepancy in the information required by each code is noted, which is attributed to the current level of uncertainty and state of knowledge regarding the processes involved in gouging phenomena. We feel standards and guidelines would better assist the designer in determining pipeline burial depth if they provided a comprehensive listing of all factors potentially involved in the interaction.

Further, the design procedures could conceivably be divided into three distinct operations: (1) determination of design gouge depth, (2) determination of clearance below the design gouge depth, and (3) determination of pipeline response. In the research literature, these operations are usually the subject of separate investigations, conducted by different specialists, *i.e.* marine geophysicists and sedimentologists for the gouge data, geotechnical engineers and soil scientists for the soil behavior, structural/pipeline engineers for the pipeline response. A standard's end user, on the other hand, may be a field engineer with extensive offshore experience, but who is not always fully versed with all aspects of gouging scenarios. This three-fold design scheme, combined with good judgment, would allow the engineer to better appreciate what information should be given priority and what factors need to be taken into account.

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REFERENCES

[1] Kenny, S., Palmer, A. C., and Been, K., 2007, "Design challenges for offshore pipelines in Arctic environments," Exploration and Production Oil & Gas Review, 6(2).

[2] Mørk, K., 2007, "The challenges facing Arctic pipelines - Design principles for extreme conditions," Offshore, 67(9).

[3] DeGeer, D., and Nessim, M., 2008, "Arctic pipeline design considerations," Proceedings of the 27th International Conference on Offshore Mechanics and Arctic Engineering (OMAE), Estoril, Portugal.

[4] Bruschi, R., and Vitali, L., 2010, "Lessons learned from Sakhalin and Caspian Arctic offshore and onshore pipelines extreme load conditions and demanding strength requirements," Deep Offshore Technology International (DOT), Amsterdam.

[5] Palmer, A., and Croasdale, K., 2012, Arctic Offshore Engineering, World Scientific Publishing Company.

[6] Paulin, M., 2014, "Arctic offshore pipeline design and installation challenges," Proceedings of the Arctic Technology Conference (ATC), Houston.

[7] Barrette, P., 2011, "Offshore pipeline protection against seabed gouging by ice: An overview," Cold Regions Science and Technology, 69, pp. 3-20.

[8] King, T., 2011, "Protection of pipelines from ice gouging," Journal of Pipeline Engineering, 10(2), pp. 115-120.

[9] Been, K., Croasdale, K., Jordaan, I., and Verlaan, P., 2013, "Practice for pipeline design in ice scoured environments: Application to the Kashagan Project," Proceedings of the 22nd International Conference on Port and Ocean Engineering under Arctic Conditions (POAC), Espoo, Finland.

[10] Liferov, P., Nes, H., Asklund, J., Shkhinek, K., and Jilenkov, A., 2014, "Ice gouging and its effect on pipelines," Proceedings of the Arctic Technology Conference (ATC), Houston.

[11] SCC, 2014, "Website of the Standards Council of Canada," www.scc.ca/en.

[12] National Research Council of Canada, 2011, "Evaluation of NRC Construction Portfolio," http://www.nrc-cnrc.gc.ca/eng/about/planning_reporting/evaluation/2013_2014/ecp.html.

[13] Konuk, I., 2009, "Arctic pipeline design challenges and current practices - Ice scour," Proceedings of the 28th International Conference on Ocean, Offshore and Arctic Engineering (OMAE), Honolulu, Hawaii.

[14] Lanan, G. A., and Ennis, J. O., 2001, "Northstar offshore Arctic pipeline design and construction," Proceedings of the 33rd Offshore Technology Conference (OTC), Houston.

[15] Duplenskiy, S., and Gudmestad, O. T., 2013, "Protection of subsea pipelines against ridge ice gouging in conditions of substantial surface ice," Proceedings of the 32nd International Conference on Ocean, Offshore and Arctic Engineering (OMAE), Nantes, France.

[16] API RP 2N, 2007, "Recommended Practice for Planning, Designing, and Constructing Structures and Pipelines for Arctic Conditions," American Petroleum Industry, Washington, D.C.
[17] CSA Z662, 2011, "Oil and Gas Pipeline Systems," Canadian Standards Association, Toronto, Canada.
[18] DNV OS F101, 2013, "Submarine Pipeline Systems," DNV-GL, Oslo, Norway.
[19] ISO 13623, 2009, "Petroleum and Natural Gas Industries — Pipeline Transportation Systems," International Standards Organization, Geneva.
[20] Davies, G., Marley, M., and Mørk, K., 2011, "Limit state design methodology for offshore pipelines against ice gouging - Industry guidelines from the ICEPIPE JIP," Arctic Technology Conference, Houston.
[21] RMRS 2-020301-003, 2012, "Rules for the Classification and Construction of Subsea Pipelines," Russian Maritime Register of Shipping, St. Petersburg.
[22] CSA-ISO 19906, 2011, "Petroleum and Natural Gas Industries — Arctic Offshore Structures," Canadian Standards Association, Toronto, Canada.
[23] McKenna, R., Spring, W., and Thomas, G., 2011, "Use of the ISO 19906 Arctic Structures Standard," Proceedings of the 43rd Offshore Technology Conference (OTC), Houston.
[24] Palmer, A., 2011, "Moving on from ISO 19906: What ought to follow?," Proceedings of the 21st International Conference on Port and Ocean Engineering under Arctic Conditions (POAC), Montreal, Canada.
[25] Vershinin, S. A., Truskov, P. A., and Liferov, P. A., 2008, Ice Action on Seabed and Subsea Structures, PPC Russkaya kniga, Moscow, Russia.
[26] Lever, J. H., Bass, D. W., Lewis, C. F. M., Klein, K., Diemand, D., and Dyke, M., 1991, "Iceberg/seabed interaction events observed during the DIGS experiment," Journal of Offshore Mechanics and Arctic Engineering, 113(1), pp. 74-87.
[27] Woodworth-Lynas, C. M. T., and Guigné, J. Y., 1990, "Iceberg scours in the geological record: examples from glacial Lake Agassiz," Geological Society Special Publication, 53, pp. 217-233.
[28] Noble, P. G., and Comfort, G., 1982, "Damage to an underwater pipeline by ice ridges," Proceedings of Workshop on Sea Ice Ridging and Pile-up, Snow and Ice Subcommittee, Associate Committee on Geotechnical Research, National Research Council Canada, Technical Memorandum No.134, R. M. W. Frederking, and G. R. Pilkington, eds., pp. 248-284.
[29] Grass, J., 1998, "Ice scours and ice ridges of Lake Erie, Ontario, Canada," Proceedings of the 1st Ice Scour and Arctic Marine Pipelines Workshop, 13th International Symposium on Okhotsk Sea and Sea Ice, Mombetsu, Hokkaido.
[30] Barrette, P., and Sudom, D., 2012, "Physical simulations of seabed scouring by ice: Review and Database," Proceedings of the 22nd International Offshore and Polar Engineering Conference (ISOPE), Rhodes, Greece.
[31] Barrette, P., and Sudom, D., 2014, "Ice-soil-pipeline interaction during seabed gouging in physical tests: Database analysis and outstanding issues," Proceedings of the Arctic Technology Conference (ATC), Houston.
[32] Eltaher, A., 2014, "Gaps in knowledge and analysis technology of ice-gouge – pipeline interaction," Proceedings of the Arctic Technology Conference (ATC), Houston.
[33] Babaei, H., and Sudom, D., 2014, "Ice-seabed gouging database: Review & analysis of available numerical models," Proceedings of the Arctic Technology Conference (ATC), Houston.