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A Study for the State-of-the-Art on Arctic Issues for Floating Ices and Subsea Operations

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ABSTRACT

While there are huge energy potentials in the Arctic, latent risks for the recovering of hydrocarbons still remain, as well. One of the main causes of the risks is harsh environmental conditions, for instance, geographic remoteness, ice-covered areas, icing and ices. In particular, various types of floating ices, such as icebergs, can directly and immediately damage offshore and subsea facilities, and this can lead to serious consequences to the environment. Thus, this paper aims to review literatures and define research agenda on arctic issues for floating ices and subsea operation.

KEY WORDS : Arctic; Floating Ice; Subsea; Safety System; Structural Interaction.

INTRODUCTION

There are huge potential and opportunity of the Arctic in present. As one of underlying strengths, the length of shipping route and the shipping period from Asia to Europe through the Arctic are approximately forty percent and twenty five percent shorter, respectively, than those of existing routes through the Suez Canal (Baek, et al., 2016). Meanwhile, in terms of energy resources, it is expected that twenty five percent of undiscovered deposit of worldwide remaining petroleum resources is placed in the Arctic (Norway's technology strategy for the petroleum sector (OG21, 2006). According to the United States Geological Survey, moreover, it is assessed that almost thirty percent of the world's undiscovered natural gases are in the Arctic (King, N.D.).

In the exploitation of petroleum resource, development history of offshore industry will be looked over to find which part will receive attention in the future, and it will be analyzed whether the part is well-matched with the characteristics of the Arctic development.

Table 1. Futurity based on history of offshore industry

	1platform / 1well	Subsea production	Multi-well production	Subsea processing	Minimized platform and all subsea
Onshore	1887				
Shallow water	1947	1961	1973	2007	
Deep water				2010	Future
The Arctic and The Subarctic		1963			Future

In 1887, the first onshore well connected to sea was developed by H.L. Williams. The Christmas tree system was invented in 1922 and the first offshore well from a fixed platform was drilled in 1947, which is the start of the modern offshore system (NOIA, N.D.). The world's first subsea well production began in 1961 (UTF, N.D.). Meanwhile, the initial offshore development in ice-covered areas is recorded in 1963 and the regions have been expanded (SAMCoT, 2012; Shell, N.D.). The first multi well subsea template was applied in 1973. The first practical subsea processing system called Tordis, including a separator, a booster, and an injector, was installed in 2007. (Gundersen, et al., 2014) The deepest subsea field was exploited in 2010, which is located in the Gulf of Mexico and of which depth is 2934 m (DNV GL, 2014). Recently, management plan in two shifts, four weeks unmanned and two weeks manned, is being applied to the Valemon gas and condensate field in Norway. Besides, oil majors have started to introduce the concept that all functions of an offshore are intensively focused on subsea system, for instance, Subsea Factories of STATOIL, Subsea to Market of ABB and All Subsea of DNV GL. Based on this development history of offshore industry, it sounds clarified that the futurity would direct unmanned and minimized platforms and further all subsea system.

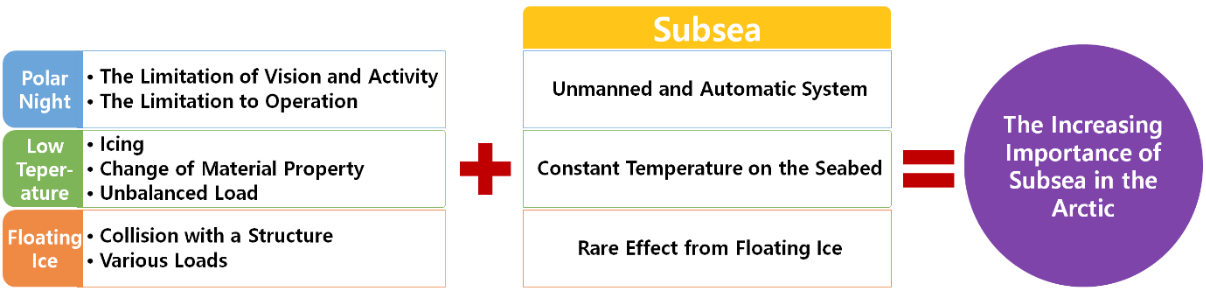

Figure 1. Subsea in the Arctic

Such tendency is expected to ultimately reach up to arctic region because the importance of subsea in the Arctic would increase. The reason for this is that it would be a key to solve three major obstacles in the area, which are polar nights, extremely low temperature, and floating ices (Figure 1). Firstly, it is clear that the polar night blocks vision and activity of workers, thereby interfering with the operation. Secondly, the extremely low temperature makes troubles, such as icing shown in Figure 2, triggering operation problems, the change of material property and unbalanced weight which contributes to capsizing a structure. For instance, icing is considered as one of causes of capsized Koskaya jack-up (Efimov & Kornishin, 2012). Thirdly, the collision with floating ices could damages a structure, but it is still hard to evaluate the exact impact because the physical characteristics of the ices is obscured by reason of the various kinds of the ices depending on development process, shape, and so on. For these matters, the unmanned and automatic system of subsea operations, constant water temperature on seabed, and depth of seabed would respectively help to overcome.

Figure 2. Examples of an icing matter (L: Davies, 2012; R: Efimov & Kornishin, 2012)

Nevertheless, several unsolved challenges still remain. One of them is a matter of interaction between a large floating ice and subsea operations. To explain, a floating ice can cause serious damage to subsea structure. The extent of damage varies depending on a variety of factors such as properties of ice, ice drift, strength of structure, structural protection, and so on. The structural damage can lead to various consequences of subsea operation (e.g., major oil spill, minor oil spill, no oil spill, etc.). This depends on the magnitude of the impact, the overall configuration of subsea facilities, and subsea safety systems. To prevent this difficulty, on the other hand, lots of efforts would be made, for instance, observation, forecast, towing, and destruction, and design criteria would be overestimated, as well. All of these will give rise to huge financial burdens. Hence, it is important to analyze in order to get over the threat and to reduce the financial burden.

Therefore, the main objective of this paper is to identify future direction of research on the interaction between floating ices and subsea operations through literature review. In details, it will be conducted to review literature on structural interaction between floating ice and subsea facility and against floating ice. Lastly, an appropriate research agenda for the future will be proposed.

OVERVIEW OF SUBSEA RISK CAUSED DUE TO FLOATING ICES

For systematic literature review on Arctic issues for floating ices and subsea operation, an overview of subsea risk caused by floating ices is provided in this section, using a bow-tie diagram.

A bow-tie diagram is an illustration that shows the relationship between a hazardous event, its causes and consequences, and the barriers that can reduce the probability of the hazardous event and/or mitigate the consequences (Rausand, 2011). A bow-tie diagram connects the hazards, the hazardous event and the consequences through a series of event lines and depicts the routes to accidents (Rausand, 2011).

A floating ice is one of the various hazards that may lead to the damage of subsea facilities due to external impacts, which is the hazardous event. The protection structure against floating ices is the barrier to reduce the probability of the hazardous event. The other hazards associated with external impact, which are not the scope of this study, are trawling, dropped object, subsea landslide, earthquake, etc. (Brand, 2004; ISO 13628-1, 2006; Gundersen, et al., 2014).

Once the subsea facilities are damaged by an external impact (in other words, after the occurrence of the hazardous event), subsea safety systems prevent or mitigate the consequences. If these barriers fail to respond to the hazardous event, then the worst consequence, large amount of hydrocarbon release, may occur.

The relationship between the hazards, hazardous event, consequences and barriers for subsea risk associated with floating ices is illustrated as a bow-tie diagram in Figure 3.

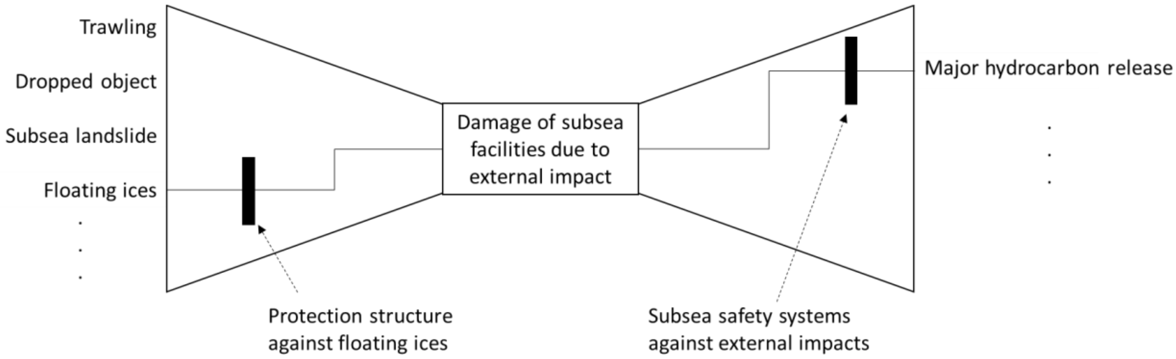

Figure 3. A bow-tie diagram for subsea risks caused due to floating ices

The barrier on the left side of the bow-tie diagram is a proactive barrier that prevents or reduces the probability of the hazardous event, while the barrier on the right side is a reactive barrier that is installed to avoid or reduce the consequences of the hazardous event (Rausand, 2011).

In the bow-tie diagram in Figure 3, protection structure against floating ices is the proactive barrier, and subsea safety systems are the reactive barrier. In other words, the occurrence of the external damage of subsea facilities is relevant to the structural interaction between floating ices and subsea facility, while the mitigation of the consequence is closely related with response of subsea safety systems against external impacts. Based on this result, following literature review will be conducted in two parts: 1) structural interaction between floating ice and subsea facility, and 2) subsea safety systems against external impacts.

LITERATURE ON STRUCTURAL INTERACTION BETWEEN FLOATING ICE AND SUBSEA FACILITY

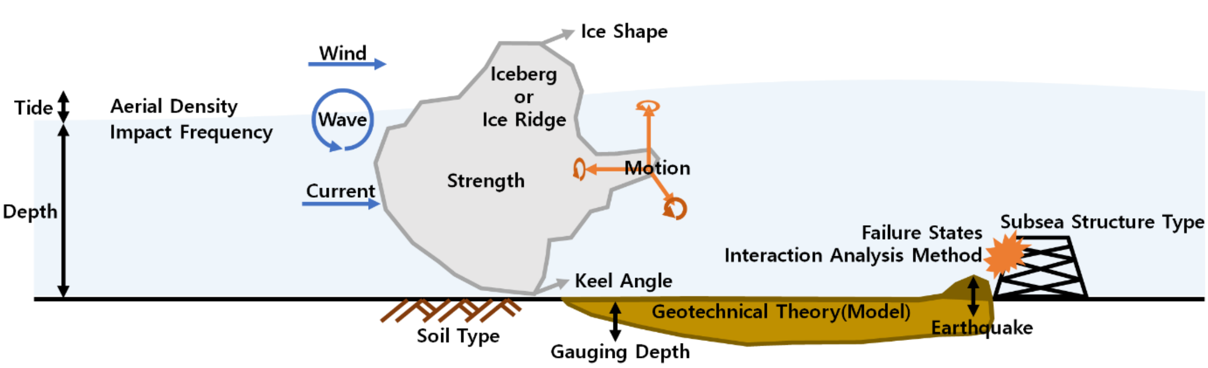

Figure 4. Considerations for interaction between a floating ice and a subsea facility

In the Arctic area, there are three kinds of big floating ice, which are ice ridges, icebergs, and ice islands. While ice ridges originate from accumulated sea ices, others come from glaciers, so they are likely to be harder than ice ridge. Plus, draughts of icebergs are deeper, in general, than keel depths of ice ridges and thicknesses of ice islands. These means that the effect and possibility of iceberg interaction with subsea operations would be prior to those of others. This is the reason why the focus will be on icebergs.

Studies about iceberg collision with GBS (Ground Based Structure) and Floating Structure like FPSO have considerably accumulated. In the case of subsea system, however, some of the knowledge would not be applicable on account of dissimilarities of the systems. Figure 4 introduces expected factors associated with interaction of a floating ice and a subsea structure based on the established research results. These factors would be categorized into two groups relying on whether methodology or tendency are resemble to the accumulated research or not. As an example, it is presumed that areal density, iceberg drift arising from wind, wave, and current, and uncertainty of iceberg shapes would be dealt with by the same way whereas subsea structure types, possible sites relevant with water depth, and interaction mechanism would be differently addressed.

Subsea Structures

A subsea system has been complicatedly developed for recent decades. In the beginning, production system including wellhead, X-mas tree, manifold, pipeline, and riser was necessarily applied. And then, processing system, such as subsea separator, injector and booster (SSIB) and gas compressor, has been added so as to improve effectiveness. All these facilities might be classified into three types regarding iceberg problem; subsea structures on seabed, pipelines on/under seabed, and risers. In spite of a cylindrical shape similar with a GBS, first of all, a riser has totally different structural characteristics owing to its slenderness. Further, differently from other two subsea structure types, its collision is nothing to do with water depth because it reaches from sea surface to seabed. Secondly, it is surmised that pipeline may be involved in the effect of interaction with soils and an iceberg called scouring, as well as direct contact with an iceberg. Lastly, other subsea operations on seabed have to be considered depending on their types, size and functions. This paper will mainly concentrate on this. The Figure 5 describes overall outline of a subsea system.

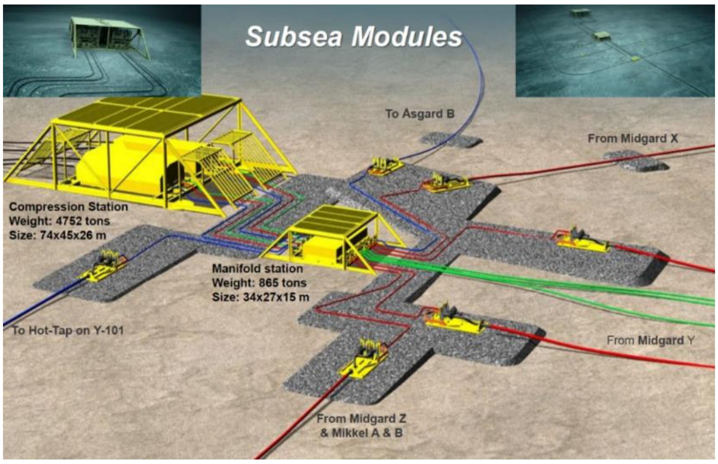

Figure 5. Outline of subsea modules (Vinterstø, N.D.)

As shown in Figure 5, lots of equipment ranging from a small power unit to a huge station template are applied to a subsea system in these days. When it comes to collision with an iceberg and a subsea module, it is plausible that bigger and taller structures would be more risky. The table 2 indicates specification of several subsea installations relatively larger than others.

Table 2. Size and weight of several subsea operations (Aguilera, 2013; Vinterstø, N.D.; Jahanshahi, 2013)

Project	Åsgard	Ormen Lange	Gulfaks	Pazflor
Country	Norway	Norway	Norway	Angola
Type	Compression Station	Compression Station	Compression Station	Separation
Dimension	75×45×26 m^3	60×38×12 m^3	34×20×12 m^3	21×21×19 m^3
Weight	4800 tons	3300 tons	950 tons	900 tons

The biggest type of operations is a compression station mainly targeted at a natural gas field. The dimensions of a compressor station relies on the pipe diameter, the volume of gas, and the differences of gas elevation. (Rover Pipeline, 2016) Hence, it seems convincing that the priority of considerations for structure type would be given to the compression station due to its size and role.

Sites and Areal Density

Several conditions are fundamentally required for sites of this collision scenario. To start with, submarine reservoirs have to be located in the sites. In particular, natural gas fields are more to do with this scenario because of the compression station as mentioned previously. The Figure 6 shows main resource regions in the Arctic circle. (EIA, 2012)

Figure 6. Arctic resource province map

In addition, icebergs ought to appear at least intermittently in the above marked sites, Beaufort Sea, Kara Sea, Barents Sea, Baffin Bay(West Greenland, East Canada), and East Greenland in Figure 6. Concerning these seas, Table 3 presents average annual values of icebergs. (ISO 19906, 2010; Diemand, 2001) In accordance with the Table 3, the frequency of iceberg appearance is comparatively higher for Baffin Bay, Greenland, Western and North-eastern Barents Sea than Beaufort and Pechora sea in Barents. Considering the maximum size of subsea facility (compression station : 26 m) and the maximum iceberg draft (130 m) in Table 3, the most possible sites in the four locations would be inferred as a place with natural gas reservoirs not deeper than the sum of the height and the iceberg draft.

Table 3. Average annual value of icebergs (ISO 19906, 2010)

		Beaufort	Western Barents	North-eastern Barents	Pechora Sea in Barents	Greenland	Baffin Bay
Size	Mass [10^6 ton]	10	~ 6	~ 4	ND	0.5 ~ 1 (Max. 8)	5 ~ 10
	Mean draught [m]	-	-	-	-	60 ~ 80	100
	Maximum draught [m]	-	-	-	-	120 ~ 130	-
Frequency	Months present	Poorly known	1 ~ 6	All year	Infrequent occurrence	All year	12
	Number / year	Poorly known	10 ~ 40	ND	ND		1000
	Maximum number / month	Rare	30	ND	ND		Numerous

Concerning West Greenland waters, according to a research article (Chumakov, 2011), it has been known that there was no major discovery for petroleum resource. On the other hand, a twenty-year plan for offshore development around Svalbard was declared in 2011 (Gibbs & Koranyi, 2011), and seven test drillings near Svalbard were arranged and financial approval was also decided by Norwegian Parliament. (Leiendecker, 2015) Although economical reservoir has not been found yet, it seemed highly positive for the potential to be revealed soon. The rationale behind this is that, as shown in Figure 7 (Fadeyev, 2012), it is obvious that gas condensate, oil and even natural gas are widely exist in the Barents and Kara region.

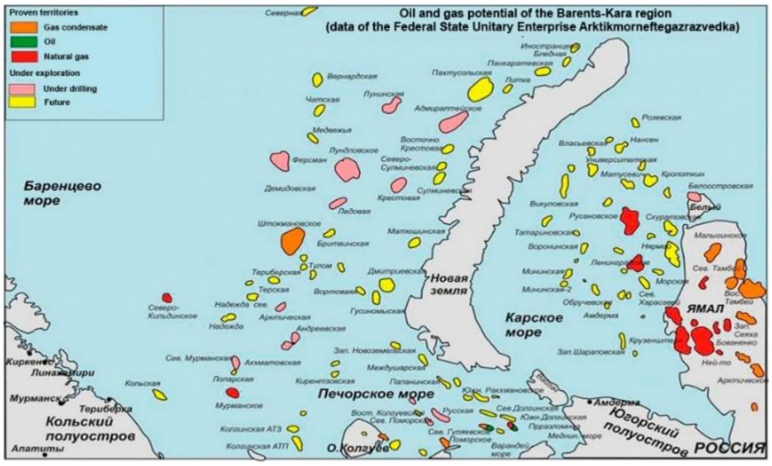

Figure 7. Oil and gas potential of the Barents-Kara region

For these reasons, the sites are selected by combining Arctic resource province map (Figure 6) and Bathymetry of the Barents and Kara (Foraminiferal Research at Byrd Polar Research Center, N.D.) based on boundaries and regions of the Barents sea seen in the Table 3 (ISO19906, 2010). To explain, the circled spots in Figure 8 are shallower than 100 m. Concurrently, they are included not only in the shadow areas in Figure 6 but also in the region that icebergs quite frequently appear shown in Table 3.

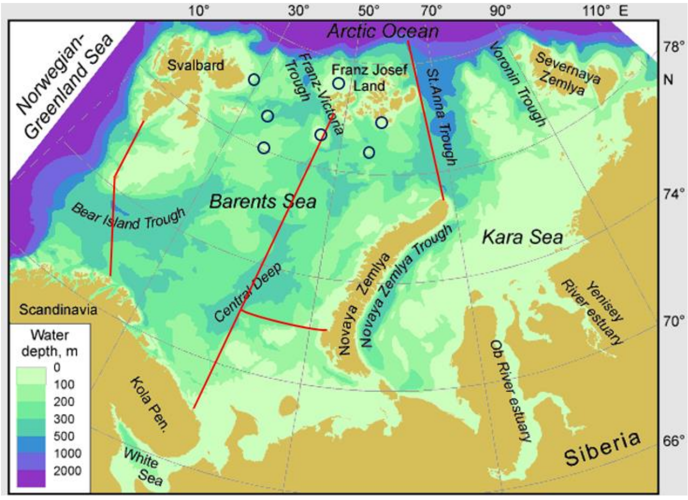

Figure 8. Expected sites for interaction between an iceberg and a subsea operation

It is evident that all environmental factors shown in Figure 4 would be actually involved in sites and have their own uncertainties. Moreover, the iceberg collision is not thought to be prevalent. Hence, it would be more rational that the factors are treated as probabilistic parameters, if possible. The representative stochastic parameter depending on the site is encounter frequency, save for impetuses of iceberg movement, for example wave. It is the rate of interactions per unit time and calculated from areal density which is the average annual number of features per unit area. (ISO 19906, 2010) The history of major research tendency on this topic is well-summarized on the whole in the most recent study. (Habib, et al., 2016) According to the summary, since IIP(International Ice Patrol) started to observe icebergs, the IIP data has been a basis for estimation of areal density. Deterioration and drift models were employed to anticipate more exact areal density. (Anderson, 1971) The observation of the areal density has been improved by using more various ways for iceberg detection to collect more data. Extensive dataset since 1960 by 1992 were added to the IIP data in order to study the characteristics of iceberg frequency in the degree square (Fuglem, et al. 1996, 1996a). Comprehensive database for icebergs has been provided by the PERD(Program on Energy Research and Development) since 1998. The database consists of the data mostly from the IIP and Province Airlines, and additionally from ships and satellites. (Trott & Comfort, 2007) In order to utilize data from the IIP and the Envisat ASAR satellite at the same time, a formula to mutually compensate for upside and downside of the each was proposed. (Habib, et al., 2015) To be specific, the IIP data could be more trustful in certain fields but the coverage would be restricted owing to the limited number of observing flights whereas the satellite data could cover a target range completely, but not thoroughly due to the limitation of imagery resolution. Lastly, Habib et al. also compared the results of areal densities calculated from aerial reconnaissance data and from bi-weekly iceberg charts. The study represented that the areal densities from different data sources in the same regions could be unmatched for each other, therefore ultimately leading to exaggerate or belittle the iceberg impact load.

Iceberg Drift

Iceberg drift is one of the most important things for this issue. This is because it plays vital roles in evaluation for iceberg design load as well as in risk assessment of iceberg and iceberg management which, in turn, could become probabilistic factors of the design load evaluation. Iceberg drift model includes trajectories of iceberg movements and drift speeds. Hence, the iceberg drift model fairly depends on weather forecasts such as winds, currents, and waves, and the simulation of the iceberg drift normally regards an iceberg as a point mass (SAMCoT, 2012).

In order to calculate iceberg impact, speed of an iceberg is essential because the kinematic energy, deemed as the governing factor of the limit energy mechanism which is usually applied to analysis of a huge floating ice, originates from the velocity of the iceberg. Basically, the iceberg speed would arise from the interaction between the iceberg and fluids like air and water. Such a fluid-structure interaction is fundamentally affected by a projection area and speed of the flows like current, wind, and wave. On this point, the drift speed model accepted in general nowadays has been developed as a function of significant wave height and waterline length of the iceberg. (Fuglem, 1997; Stuckey, 2008)

First of all, waterline length is the representative parameter of the projection area, which is the longest width of the projection area of an iceberg and easiest to be measured. In detail, iceberg draft could be deduced from a waterline length with a power law relation (Stuckey et al., 2016(a)), and the projection area, in turn, could be calculated. When it comes to the velocity of flows, on the other hand, the significant wave height plays a key role because of the well-known relationships between wind speed and significant wave height and between wind speed and current speed from Ekman theory. The relationships are based on the fact that wave and current are triggered by wind in nature.

So as to infer the iceberg velocity, a basic assumption is that the iceberg is supposed to show relatively steady movement, so considerations involved in acceleration and inertia would be ignored. This means that all external environment forces would be kept in equivalence one another. Therefore, consequent velocity of iceberg drift would be decided by the total environment load.

Based on this, probabilistic drift model was proposed (Stucky, 2008). Sensitivity analysis was, firstly, performed for iceberg interaction with FPSO and GBS. Then, lots of data containing waterline lengths and locations of icebergs with significant wave heights were analyzed on the Grand Bank in Canada. Finally, the result was compared with the deterministic result.

Prevention

Generally, the definition of ice management is all actions to diminish or avoid any types of ice features (SAMCoT, 2012). Because of immovable subsea structures including pipelines and risers, the only way for avoidance would be to get rid of an approaching iceberg before impact. The conventional method starts from forecasting approaches of the potentially risky icebergs based on the information about traveling icebergs detected by IIP stated previously. If an iceberg comes in the immediate vicinity of an offshore, a tug vessel lets it towed away. There are several towing methods in history; predominantly single vessel rope, prop washing, net, water cannon, two vessel tow, ramming, and others arranged in order of the number of towing operations (Young & Rudkin, 2006). The maximum speed of an iceberg is nearly 2.7 kilometer per an hour (SAMCoT, 2012). Additionally, it may take ten hours for the towing vessel to reach a speed of just one knot during towing owing to the massive weight of the iceberg, so the towing can need up to three days (Kaushik, 2014). For these reasons, the task would have to complete within a time not so long.

Between the forecast and the removal action, a supplementary step may be needed to calculate accurate probability of iceberg collision with subsea modules. The precise prediction would help to improve cost-effectiveness and operation efficiency since it does not necessarily mean colliding each other just because an adjacent iceberg approaches to subsea operations or floats above them, due to the fact that the iceberg keel might not be reachable up to structures on seabed. However, it is not easy at all to make out the submerged part of icebergs by reason of the invisibility of the underwater and the randomness of iceberg shapes. The 2012 Iceberg Profiling Program can give a direction for this. Twenty nine icebergs were measured, using optical cameras, laser finder, and GPS for parts above water and multi-beam sonar installed in ROV for submerged parts, along the coastal line of Newfoundland and Labrador. (Younan, et al., 2016) This database contributed to upgrade various related research, such as iceberg impact modelling, iceberg towing, iceberg hydrodynamics, iceberg risk, iceberg design load. (Fuglem & Younan, 2016; Bruce, et al., 2016; Talimi, et al., 2016; King., et al., 2016; Stuckey, et al., 2016(b))

Compared to the surveyed field, however, the selected regions in the Barents sea are much closer to the origin of icebergs as seen in Figure 10. Thus, more immediate system, for example, on-the-spot iceberg observation and profiling sonar system on seabed, may be needed in the future to develop offshore and subsea system in the Arctic region to prevent the crash of icebergs.

Figure 10. The selected sites (yellow mark) and the surveyed field of the 2012 Iceberg Profiling Program (red mark)

LITERATURES ON SUBSEA SYSTEMS AGAINST EXTERNAL IMPACTS

The first and most important barrier that is installed to stop the unwanted hydrocarbon release is the downhole safety valve (DHSV) (Torbergsen, et al., 2012; Kim, et al. 2016). The DHSV closes automatically when the hydraulic pressure is lost due to a command from the topside emergency shut down (ESD) system, or due to an abnormal situation, like rupture of hydraulic supply lines (Bai & Bai, 2012; Kim, et al. 2016).

The second pressure barrier to control the flow of hydrocarbons is the production master valve (PMV) and production wing valve (PWV) installed in the subsea X-mas tree (Bai & Bai, 2012; Kim, et al. 2016). The PMV and PWV closes automatically when the hydraulic pressure is lost, and the loss of hydraulic pressure can be initiated by a command of the topside ESD, production shutdown (PSD) system and subsea PSD system.

A brief overview of subsea facilities and the locations of DHSV, PMV, and PWV are illustrated in Figure 9. If a large floating ice damages subsea facilities and/or pipelines, then DHSV, PMW, and PWV can shut down the hydrocarbon flow to prevent unwanted hydrocarbon release to the environment.

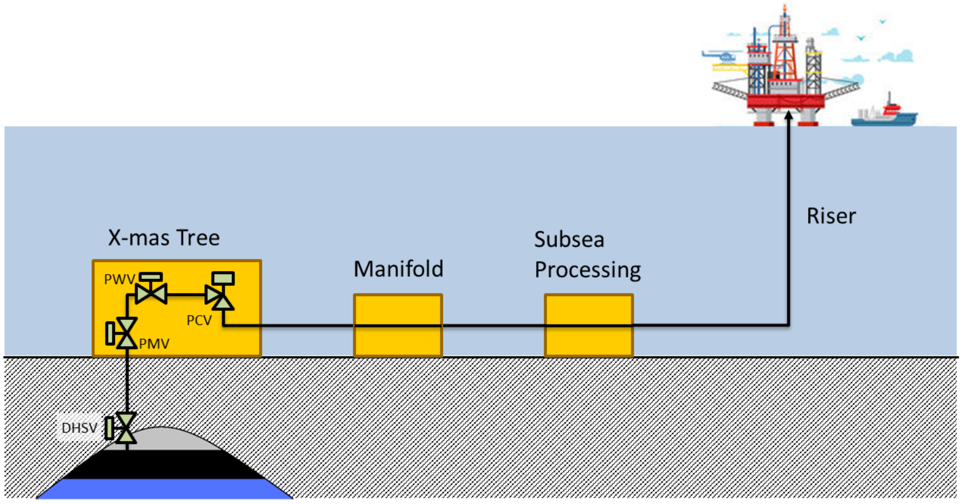

Figure 9. DHSV, PMW, and PWV

These subsea safety systems are installed not only for floating ices, but also for all the other kinds of subsea hazardous events, such as hydrocarbon release due to critical loads from trawling, dropped objects, material defect, erosion/corrosion, rupture of riser, etc. Therefore, there have been a high number of studies and efforts on theses subsea safety systems, including standards and regulations such as ISO 13628-6 (2006), NORSOK S-001 (2008), NOG GL 070 (2001), API RP 17A (2010), The Facilities Regulations (PSA, 2015), etc. For instance, NORSOK S-001 (2008) suggests ESD shut down principle hierarchy as shown in Figure 10, and the reliability analysis of ESD systems have been studied by Farwana (2014), Hauge, et al. (2010), Byrne (1994), Lundteigen and Rausand (2007), Hauge et al. (2015), and by various reliability researchers. In addition, NOG GL 070 (2001) provides guidelines for quantitative reliability analysis of subsea safety systems, based on IEC61508 (2010) and IEC61511 (2003).

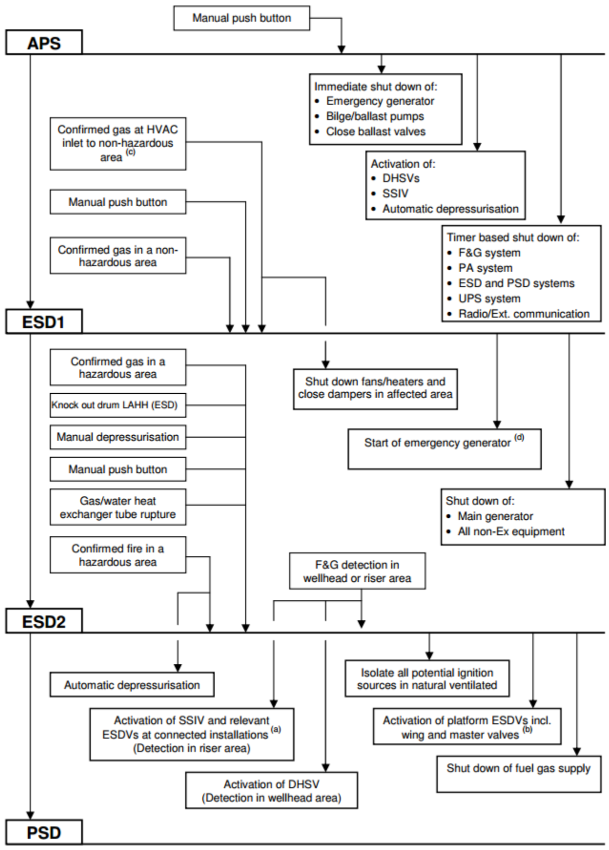

Figure 10. Emergency shut down (ESD) principle hierarchy (NORSOK S-001, 2008)

However, there are limited studies on specific consideration of subsea safety systems against floating ices. While several studies discuss the challenges and solutions of Arctic subsea operation (Lanan, et al., 2001; Aggarwal & D'Souza 2011, El-Wardani 2013), interaction between subsea safety systems and floating ices is still an unexplored field. In addition, the overall risk model associated with floating ices, including both subsea structure and safety systems, is not well investigated yet.

CONCLUSIONS

In this paper, a wide range of recent Arctic issues related to interaction between an iceberg and a subsea structure are briefly introduced. Firstly, it was demonstrated that a role of subsea system in the Arctic would increase more and more. Thus, subsea risks from floating ices were arranged by a Bow-tie diagram. Secondly, factors linked to the interaction between subsea and an iceberg are arrayed based on the existing research. Thirdly, a reasonable structure type on seabed in iceberg impact was clarified, and possible sites are specified based on the type. Finally, assessment methodology of areal density and of iceberg drift were simply summarized respectively, and safety systems applied to subsea operation against external impacts were summed up, as well. As a result, this paper would contribute to identify research agenda and develop future studies on interaction with a floating ice and subsea operations in that this contents could be a base of such relevant issues because there has seldom been research exactly fitted with this topic.

In the future, other possible sites could be searched broadly regarding similar problems, such as ice ridges in Sakhalin Sea and icebergs in Baffin Bay. Furthermore, effect of variation of keel angle attributed to rotation of a floating ice like rolling would be identified as a key point. Furthermore, geotechnical mechanism between soils and pipelines under iceberg impact, if possible including earthquake, could be an interesting problem. Also, it may be needed to research thoroughly if it is right or not to employ the existing design load estimation to a subsea structure due to the fact that the specification of the subsea facility is completely different from a huge GBS and/or FPSO. Lastly, all these further research would be connected with risk assessment and development of subsea protection and/or prevention system against iceberg impact

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