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The effect of ice floe on the strength, stability, and fatigue of hybrid flexible risers in the Artic sea. [Dataset]

KOROTYGIN, D., NAMMI, S.K. and PANCHOLI, K.

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Effect of Ice Floe on the Strength, Stability and Fatigue of Hybrid Flexible Risers in Arctic Sea

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Supplementary Data

Vessel data

FPU hull dimensional parameters were used from reference[16]

Pipeline end termination (PLET)

The pipeline end termination is located 580 m from the FPU' turret.

Vessel RAO

The FPU will be subjected to the loads generated by wind, current and waves (high and low frequency). The RAO only describes motions caused by high frequency waves. The low frequency waves, current and wind-induced loads are accounted for by the maximum floater offsets. The RAO characteristics are taken from a typical motion characteristics of an Orcaflex's Vessel for a given size and weight.

Riser system

Different riser configurations are evaluated in this research in order to determine the best suitable one according to the field environmental conditions. There are several assumptions are made for OrcaFlex software. First, no connectors can be modelled in OrcaFlex to simulate the flex joint, so the riser is modelled as pinned (free to rotate) pipe at both ends[18]

Turret

The turret is modeled as a 6 degree of freedom (6D) buoy and links that are used to connect the buoy to the floater. 6D allows the buoy to rotate to the motion of the floater it is connected to. The connection licks have disconnectable properties that make it possible to disconnect in case of severe loadings. **Error! Reference source not found.**S1 shows the parameters of the turret for OrcaFlex model.

Table S1: Turret model parameters [18]

Description	Value
Turret	
Turret length (m)	30
Outer Diameter (m)	10
Mass (kg)	3000
Turret Casing	
Turret casing shape length (m)	30
Stiffness (kN/m^2)	100
Links	
Unstretched length (m)	0.5
Stiffness ($N/m/m^2$)	200 $x10^6$

The use of turret casing in the modeling is necessary for simulation the forces exerted by the floating ice. In OrcaFlex 6D buoy do not have contact properties, so the casing with the same shape as the turret is used to cover the buoy in order to simulate the contact forces [3].

Bend stiffener

Bend stiffener data used for the simulation were used from[4]

Mooring lines

The mooring line model consists of nine catenary mooring lines that are connected to the turret in a single point mooring arrangement. Each mooring line consists of two 12 inch chain sections with wire rope in the mid-section. The wire rope is 6x19 wires and is introduced in the line in order to reduce the total weight of the line in water. The parameters of the catenary mooring line model are shown in Table S2.

Table S2: Mooring lines parameters [3]

Parameter	Value
Firs chain length (m)	100
Mid water length (m)	500
Second chain length (m)	100
Total riser length (m)	700
Chain bar (studlink) diameter (m)	0.305
Chain outer diameter (m)	0.576
Wire outer diameter (m)	0.48
Minimum breaking load (N)	228 $x10^6$

Buoyancy modules

Buoyancy modules in this study are modeled using clumps with various sizes and weight to form riser shape.

Ice floe

In OrcaFlex the ice floes are modeled as 6D buoy with shape. Because the ice floes are driven by wind, wave and current there is no initial velocity is assigned to the floes. As the buoys do not exert forces on the structures in OrcaFlex the shape function is used to cover the buoys hence their contact forces on riser or turret can be measured. The stiffness of the first-year ice and multiyear ice is different with multiyear ice being stiffer, so the stiffness of multiyear ice is used in the simulation to make more realistic. The overall parameters of the ice floes used in the simulation are listed in Table S31: Ice floes parameters [3]

S3.

Table S31: Ice floes parameters [3]

Parameter	Value
Mass (kg)	25.4
Volume (m^3)	27
Dimentions (m)	3x3x3
Drag are (m^2)	9
Drag coefficient	1.2
Added mass coefficient	1
Stiffness N/m/m^2	$1x10^9$

Seawater

The water depth at field location is 340 m. The seawater density is 1025 km/m^3.

Waves

The extreme sea-state is modeled by irregular waves using either Pierson-Moskowitz or JONSWAP energy spectrum taken from the met ocean data. In this study JONSWAP energy spectrum is used because Barents Sea is not fully developed sea [33]

Current

Table S4: Shtokman field current speeds [33]

S4 describes the most extreme current speed for all directions. The duration of extreme current event is 10 minutes with annular probability of 10^{-2} for 100 years return period and 10^{-1} for 10 years.

Table S4: Shtokman field current speeds [33]

	Return period			Prevailing Direction
	100 years	10 years	1 year	
U surface (m/h)	88	76	64	North-East direction
U bed (m/h)	39	36	32	

The riser extreme design analysis the 100 years return period current speed is used with annular probability of 10^{-2} [30]

Wind

The wind used for modeling is represented by the 10-minutes mean wind speed and height 10 m refer to 100 years return period. The overall wind parameters for Shtokman field are used from reference[33]

Hydrodynamic Coefficients of Riser

Drag Coefficient

The roughness of the flexible pipe is equal to

$K = 5 \times 10^{-5}$. As the riser outside diameter is 0.4 m K/D ration then can be calculated as $K/D = (5 \times 10^{-5})/0.4 = 1.2 \times 10^{-4}$.

Then based on the 100 year current (88 m/s) and kinetic viscosity of the seawater (1.15 cp) the Reynolds number is approximately equal to $R_e = UD/v = (88 \times 0.4)/1.15 \times 10^{-6} = 3 \times 10^5$. The drag coefficients for $K/D = 1.2 \times 10^{-4}$ for smooth pipe is $C_D = 0.55$ and for pipe with marine growth is $C_G = 1.2$.

Added Mass Coefficient

The added Mass coefficient is a function of Keulegan-Carpenter number that for a wave zone is equal to $KC= \pi H_{max}/D$. If the maximum wave height is equal to 23.3 m the KC = (3.14 x 23.3)/0.4 = 183. Using the graph illustrated on Figure 3.15 and KC = 183 the added mass coefficients for smooth pipe is 0.6 and for the rough pipe with marine growth is 0.2.

Soil – riser interaction

The soil-riser interaction is modeled as sliding resistance by specified soil stiffness and friction. The following soil-riser parameters are used in this study:

- Lateral friction coefficient - 0.5
- Horizontal lateral/axial stiffness – $100kN/m/m^2$
- Vertical soil stiffness – $100kN/m/m^2$
- Axial friction coefficient - 0.3

Sea state scattered diagram

The sea scatter[34]diagram for Eastern Barents Sea was used for analysis.

Table S5: Static analysis results for catenary riser configuration

Load case	Riser minimum Bending Radius (m)	Riser effective tension at turret (kN)	Riser effective tension at PLET (kN)	Riser bending moment at turret (kN.m)	Riser bending moment at PLET (kN.m)	Riser effective tension at TDP (kN)
1	79	283	2	1	0	26.5
2	24	293	2.8	5.1	0	36
3	31	274	1.2	4	0	17.5
4	23	286	2.3	5.5	0	29
5	95	437	3	1	0	41
6	28	447	4	4.3	0	52
7	45	426	2.2	2,73	0	30.5
8	29	440	3.5	4.3	0	43.8
9	59	462	3.2	1.1	0	43.5
10	29	474	4.2	4.2	0	54
11	48	452	2.3	2.5	0	32
12	31	465	3.6	4	0	46
13	56	277	1.4	2.2	0	20
14	19	286	2.2	6.7	0	22
15	43	268	0.7	2.8	0	11
16	21	279	1.7	5.9	0	22
17	45	427	2.3	2.7	0	31
18	20	437	3.2	6.2	0	41
19	49	417	1.5	1.15	0	21
20	25	430	2.6	4.8	0	34
21	44	452	2.4	2.8	0	32
22	20	462	3.3	6.1	0	43
23	46	442	1.6	0.9	0	22
24	26	455	2.8	4.7	0	36

Table S6: Static analysis results for lazy wave configuration

Load case	Riser minimum Bending Radius (m)	Riser effective tension at turret (kN)	Riser effective tension at PLET (kN)	Riser bending moment at turret (kN.m)	Riser bending moment at PLET (kN.m)	Riser effective tension at TDP (kN)
1	8	170	73	14.9	0	75
2	20	174	96	6	0	99
3	5	171	47	25.6	0	48
4	6	180	93	23	0	96
5	148	323	32	0.8	0	61
6	24	327	40	5.1	0	75
7	21	318	24	5.8	0	47
8	16	325	41	7.4	0	69
9	80	349	29	1.5	0	60
10	19	353	35	6.4	0	74
11	30	345	22	4	0	47
12	18	351	36	7	0	67
13	9	168	69	14	0	71
14	25	171	94	4.8	0	96
15	6	169	41	25	0	42
16	6	176	86	22	0	89
17	139	321	30	0.8	0	57.3
18	20	325	37	6	0	71
19	24	316	22	5	0	42
20	16	323	38	7.5	0	65
21	55	348	27	2.2	0	56.3
22	17	352	33.5	7.2	0	70
23	37	343	20	3.3	0	41
24	17	350	34	7.2	0	63

Table S7: Static analysis results for pliant wave configuration

Load case	Riser minimum Bending Radius (m)	Riser effective tension at turret (kN)	Riser effective tension at PLET (kN)	Riser bending moment at turret (kN.m)	Riser bending moment at PLET (kN.m)	Riser effective tension at TDP (kN)
1	19	220	48	6.57	0	60
2	98	223	62	1.2	0	75
3	13	217	35	11	0	46
4	16	222	52	11	0	63
5	88	368	60	1.41	0	77
6	21	371	73	5.8	0	93
7	30	364	47	4.1	0	61
8	18	371	69	6.8	0	83
9	45	397	56	2.7	0	77
10	17	401	67	7.3	0	91
11	46	393	46	2.6	0	62
12	18	399	68	6.7	0	84
13	22	218	45	5.4	0	57
14	45	220	59	0.7	0	73
15	14	215	32	11	0	43
16	14	220	49	10.7	0	60
17	61	366	56	2	0	72
18	18	369	69	6.7	0	88
19	38	362	42	3.2	0	57
20	17	369	65	7	0	79
21	38	390	53	3.2	0	71
22	15	392	64	7.9	0	86
23	60	385	42	2	0	58
24	17	392	65	7.2	0	80

Table S8: Static analysis results for steep wave riser configuration.

Load case	Riser minimum Bending Radius (m)	Riser effective tension at turret (kN)	Riser effective tension at PLET (kN)	Riser bending moment at turret (kN.m)	Riser bending moment at PLET (kN.m)	Riser effective tension at TDP (kN)
1	7	311	650	7.2	16.6	-
2	10	312	652	3.7	11.5	-
3	6	310	644	10	21	-
4	7	318	654	11.3	17.8	-
5	21	470	477	5.7	2.3	-
6	13	473	488	9.2	7.14	-
7	42	467	468	2.8	2.9	-
8	13	476	483	6.2	9.4	-
9	17	492	450	7.2	5	-
10	11	496	466	10.7	9.8	-
11	31	490	446	3.9	0.2	-
12	11	499	462	7.2	10.8	-
13	6	304	645	5.3	18	-
14	9	306	652	2.1	12.7	-
15	6	303	638	9	23.8	-
16	7	311	649	10.2	19.2	-
17	17	436	471	7	0.5	-
18	11	467	482	10.6	5.6	-
19	24	460	461	3.5	5	-
20	13	470	477	7.5	9	-
21	14	486	449	8.6	3.2	-
22	10	490	460	12.2	8.4	-
23	24	483	439	5	2.2	-
24	12	493	456	8.6	10	-

Table S92: Static analysis results for lazy S riser configuration.

Load case	Riser minimum Bending Radius (m)	Riser effective tension at turret (kN)	Riser effective tension at PLET (kN)	Riser bending moment at turret (kN.m)	Riser bending moment at PLET (kN.m)	Riser effective tension at TDP (kN)
1	15	273	29	1.9	0	41
2	14	280	34	3.8	0	48
3	14	267	35	2.6	0	35
4	14	279	30	4.6	0	42
5	15	417	51	3.2	0	72
6	15	425	58	4.6	0	81
7	15	411	44	2.1	0	64
8	15	425	54	2.8	0	74
9	15	437	55	3.4	0	77
10	15	445	63	4.8	0	86
11	15	428	48	2.2	0	68
12	15	445	57	2.7	0	79
13	14	267	28	3.3	0	40
14	14	273	33	5.8	0	46
15	15	261	23	1.2	0	34
16	14	273	29	4.9	0	41
17	15	409	49	5	0	69
18	15	416	57	6.9	0	78
19	16	402	42	3	0	60
20	15	417	51	4	0	72
21	15	428	52	5.3	0	73
22	15	436	60	7	0	83
23	15	421	45	3.3	0	64
24	12	436	55	9	0	61

Table S10: Static analysis results for steep S riser configuration.

Load case	Riser minimum Bending Radius (m)	Riser effective tension at turret (kN)	Riser effective tension at PLET (kN)	Riser bending moment at turret (kN.m)	Riser bending moment at PLET (kN.m)	Riser effective tension at TDP (kN)
1	7	318	176	2.1	16	-
2	8	325	201	3.8	15	-
3	7	312	153	2.5	16.8	-
4	7	324	185	4.7	16	-
5	5	491	248	2.6	21.5	-
6	6	499	277	3.5	20.6	-
7	5	483	221	2.3	22.4	-
8	6	499	262	2.9	21	-
9	6	514	257	2.6	22.2	-
10	5	523	287	3.5	21.3	-
11	5	506	230	2.3	23	-
12	5	523	272	2.7	21.7	-
13	7	312	167	3.3	16.6	-
14	7	319	191	5.6	15.9	-
15	7	307	144	1.3	17.3	-
16	7	318	176	5.1	16.3	-
17	6	482	232	4.1	22.3	-
18	5	490	261	5.5	21.3	-
19	5	474	206	2.5	23.2	-
20	5	490	247	3.6	21.7	-
21	5	505	241	4.2	22.9	-
22	5	513	270	5.5	22	-
23	5	497	214	2.7	22.9	-
24	5	514	256	3.5	23.3	-

Table S11: Dynamic analysis results for MBR.

Load case	Limit state	Internal Fluid	FPU Offset	MBR (m)	Location
1	ULS	Empty	Far	16	Turret
2	ULS	Empty	Near	6	Turret
3	ULS	Empty	Cross	6	Turret
4	ULS	Operation	Far	7	Turret
5	ULS	Operation	Near	7	Turret
6	ULS	Operation	Cross	7	Turret
7	ULS	Flooded	Far	6	Turret
8	ULS	Flooded	Near	8	Turret
9	ULS	Flooded	Cross	6	Tether
10	ALS	Empty	Far	14	Turret
11	ALS	Empty	Near	6	Turret
12	ALS	Empty	Cross	6	Turret
13	ALS	Operation	Far	7	Turret
14	ALS	Operation	Near	8	Turret
15	ALS	Operation	Cross	6	Turret
16	ALS	Flooded	Far	6	Turret
17	ALS	Flooded	Near	8	Turret
18	ALS	Flooded	Cross	5	Turret

Table S12: Dynamic analysis results for turret tension.

Load case	Limit state	Internal Fluid	FPU Offset	Min tension (kN)	Max tension (kN)	Static tension (kN)	DAF
1	ULS	Empty	Far	177	262	223	1.17
2	ULS	Empty	Near	132	275	217	1.27
3	ULS	Empty	Cross	168	269	222	1.21
4	ULS	Operation	Far	311	432	371	1.16
5	ULS	Operation	Near	273	427	364	1.17
6	ULS	Operation	Cross	273	427	371	1.15
7	ULS	Flooded	Far	333	259	401	0.65
8	ULS	Flooded	Near	294	451	393	1.15
9	ULS	Flooded	Cross	320	456	399	1.14
10	ALS	Empty	Far	176	260	220	1.18
11	ALS	Empty	Near	140	271	215	1.26
12	ALS	Empty	Cross	166	265	220	1.20
13	ALS	Operation	Far	308	427	369	1.16
14	ALS	Operation	Near	273	433	362	1.20
15	ALS	Operation	Cross	300	428	369	1.16
16	ALS	Flooded	Far	330	454	392	1.16
17	ALS	Flooded	Near	249	447	385	1.16
18	ALS	Flooded	Cross	320	467	392	1.15

Table S13: Dynamic analysis results for tension at PLET.

Load case	Limit state	Internal Fluid	FPU Offset	Min tension (kN)	Max tension (kN)	Static tension (kN)	DAF
1	ULS	Empty	Far	63	71	62	1.15
2	ULS	Empty	Near	27	38	35	1.09
3	ULS	Empty	Cross	52	59	52	1.13
4	ULS	Operation	Far	71	85	73	1.16
5	ULS	Operation	Near	36	53	47	1.13
6	ULS	Operation	Cross	36	53	69	0.77
7	ULS	Flooded	Far	67	79	67	1.18
8	ULS	Flooded	Near	35	53	46	1.15
9	ULS	Flooded	Cross	67	92	68	1.35
10	ALS	Empty	Far	60	67	59	1.14
11	ALS	Empty	Near	25	35	32	1.09
12	ALS	Empty	Cross	50	56	49	1.14
13	ALS	Operation	Far	67	83	69	1.20
14	ALS	Operation	Near	32	48	42	1.14
15	ALS	Operation	Cross	62	76	65	1.17
16	ALS	Flooded	Far	63	75	64	1.17
17	ALS	Flooded	Near	32	50	42	1.19
18	ALS	Flooded	Cross	72	96	65	1.42

Table 3: Dynamic analysis results for tension at TDP.

Load case	Limit state	Internal Fluid	FPU Offset	Min tension (kN)	Max tension (kN)	Static tension (kN)	DAF
1	ULS	Empty	Far	75	85	75	1.13
2	ULS	Empty	Near	33	46	46	1.00
3	ULS	Empty	Cross	60	68	63	1.08
4	ULS	Operation	Far	85	103	93	1.11
5	ULS	Operation	Near	43	63	61	1.03
6	ULS	Operation	Cross	43	63	83	0.76
7	ULS	Flooded	Far	80	96	91	1.05
8	ULS	Flooded	Near	34	63	62	1.02
9	ULS	Flooded	Cross	76	100	84	1.19
10	ALS	Empty	Far	72	82	73	1.12
11	ALS	Empty	Near	31	42	43	0.98
12	ALS	Empty	Cross	58	65	60	1.08
13	ALS	Operation	Far	81	100	88	1.14
14	ALS	Operation	Near	39	57	57	1.00
15	ALS	Operation	Cross	71	89	79	1.13
16	ALS	Flooded	Far	76	91	86	1.06
17	ALS	Flooded	Near	39	59	58	1.02
18	ALS	Flooded	Cross	72	103	80	1.29

Table S15: Dynamic analysis results for tether tension.

Load case	Limit state	Internal Fluid	FPU Offset	Max tension (kN)
1	ULS	Empty	Far	887
2	ULS	Empty	Near	201
3	ULS	Empty	Cross	192
4	ULS	Operation	Far	30
5	ULS	Operation	Near	30
6	ULS	Operation	Cross	0
7	ULS	Flooded	Far	0
8	ULS	Flooded	Near	0
9	ULS	Flooded	Cross	38
10	ALS	Empty	Far	172
11	ALS	Empty	Near	200
12	ALS	Empty	Cross	193
13	ALS	Operation	Far	9
14	ALS	Operation	Near	31
15	ALS	Operation	Cross	31
16	ALS	Flooded	Far	0
17	ALS	Flooded	Near	16
18	ALS	Flooded	Cross	60

Table S16: Dynamic analysis results for maximum bending moment.

Load case	Limit state	Internal Fluid	FPU Offset	Maximum bending moment (kN.m)	Location
1	ULS	Empty	Far	7.6	Turret
2	ULS	Empty	Near	23	Turret
3	ULS	Empty	Cross	19.9	Turret
4	ULS	Operation	Far	17.4	Turret
5	ULS	Operation	Near	16.2	Turret
6	ULS	Operation	Cross	16.2	Turret
7	ULS	Flooded	Far	19	Turret
8	ULS	Flooded	Near	15.1	Turret
9	ULS	Flooded	Cross	19.2	Turret
10	ALS	Empty	Far	8.9	Turret
11	ALS	Empty	Near	22.3	Turret
12	ALS	Empty	Cross	19.3	Turret
13	ALS	Operation	Far	18.6	Turret
14	ALS	Operation	Near	15.5	Turret
15	ALS	Operation	Cross	18.6	Turret
16	ALS	Flooded	Far	20.4	Turret
17	ALS	Flooded	Near	14.7	Turret
18	ALS	Flooded	Cross	24	Turret