TODAYS MOWII WEBINAR:

Why Good Mooring Systems Go Bad

Fatigue Factors in Mooring Systems for Floating Offshore Wind Turbines

Richard H. Akers, PE
Chief Technology Officer
Maine Marine Composites, LLC

July 16th, 10:00 AM ET

The presentation will begin at 10:03
to allow all attendees time to login

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Why Good Mooring Systems Go Bad

Fatigue Factors in Mooring Systems for Floating Offshore Wind Turbines

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Agenda

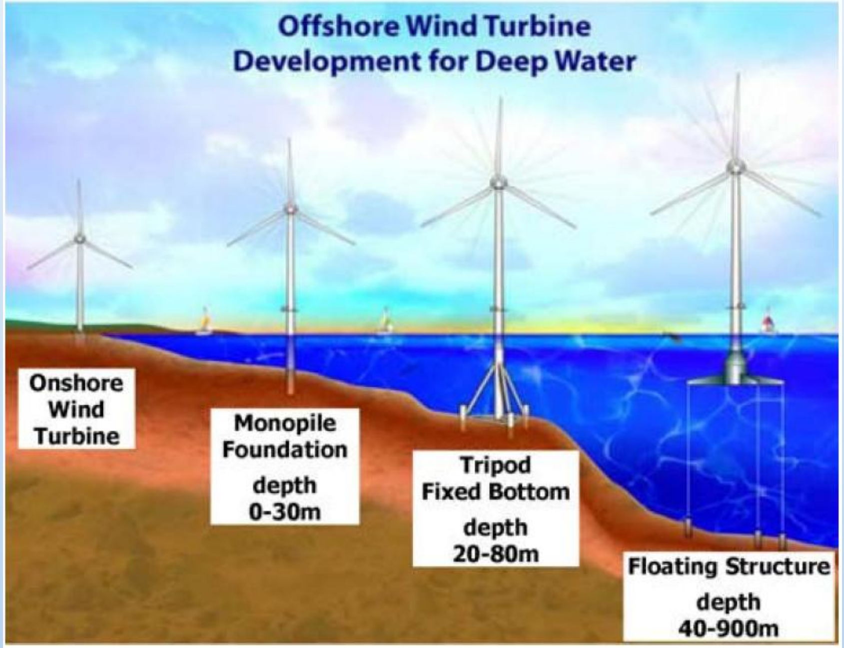
- Floating Offshore Wind Turbines: Background
- Mooring Components: Background
- Anchor Failures
- Mooring Failures
- Fatigue Mechanisms
- Rules & Regulations
- Modeling, Simulation, and Prediction
- Inspections

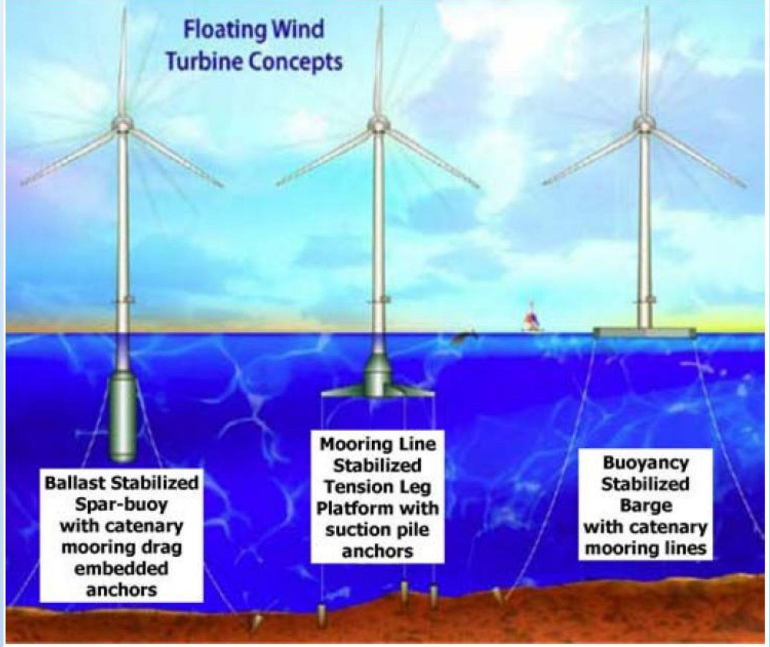
Floating Offshore Wind Turbines

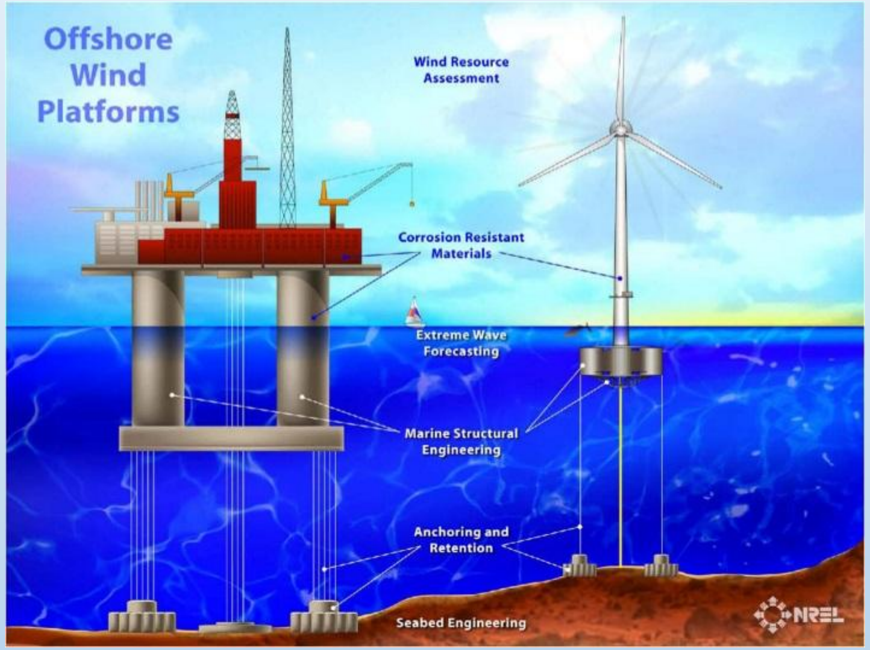
- Performance of oil & gas platforms well understood
- Key differences between oil & gas platforms and FOWTs
  - Additional uncertainties
    - Any accidents will receive significant publicity
    - Interaction between turbine, control system, floating platform, mooring system not well understood (yet)
  - Performance & dynamics
    - FOWT likely to be located in shallower water
    - Have lower mass
    - Wind loads have greater influence on global performance & loads
    - Turbine control systems, angle of attack, nacelle yaw
      - Introduce additional complexity
      - Can complicate relative severity of “operational” and “survival” conditions
    - Unmanned
  - Economics:
    - StatoilHydro Hywind Spar: $62.5 million
    - Perdido Spar (world’s deepest oil & gas spar): $3 billion
  - Design margins
    - Current practice is for less redundancy on mooring systems of FOWTs
    - Less risk of environmental pollution

The New York Times, “Offshore Wind Farm Approved in New Jersey,” http://green.blogs.nytimes.com/2008/10/03/offshore-wind-farm-approved-in-new-jersey/?_php=true&_type=blogs&_r=0, July 15, 2014

Floating Offshore Wind Turbines







Pao, Lucy Y., and Kathryn E. Johnson. "A tutorial on the dynamics and control of wind turbines and wind farms." *American Control Conference, 2009. ACC'09.*. IEEE, 2009.

Hurst, T., “Plans for Floating Offshore Wind Making Waves in Mass,” Crisp Green, October 10 2009, http://crispgreen.com/2009/10/plans-for-floating-offshore-wind-farm-making-waves-in-mass/.

Mooring Components

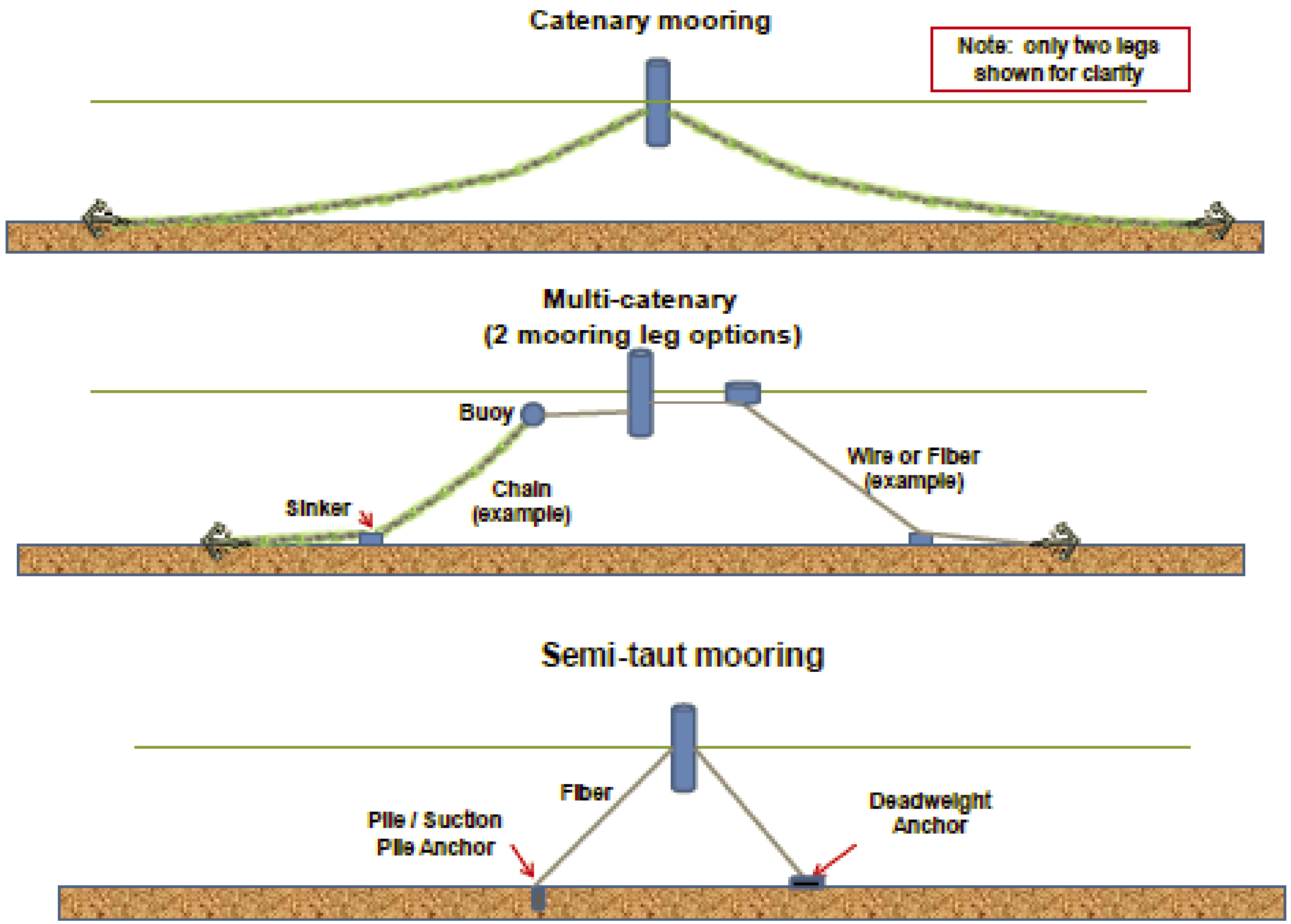


Figure 35 Spread Mooring Configuration Options

Sound & Sea Technology, "Advanced Anchoring and Mooring Study," November 30, 2009

Existing Floating Offshore Wind Turbin

Statoil Hydro Hywind Spar, 2.3 MW
3 catenary mooring chains in 200-220m water depth with single clump weight

“Floating Wind Turbine,” Wikipedia, July 9 2014, http://en.wikipedia.org/wiki/Floating_wind_turbine

Principle Power WindFloat, 2 MW
Semi-taut moorings, drag anchors

Principle Power, “WindFloat The Offshore Wind Solution,” IBC Deep Water Wind Farms Seminar, London, 2013.

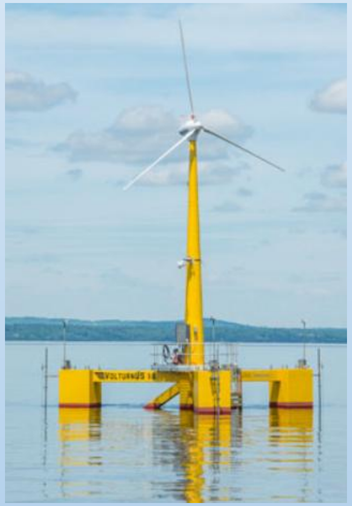
Fukushima Wind Farm, 2 MW

The Japan Times, “Floating wind farm debuts off Fukushima,” November 11, 2013.

Kabashima Island Spar, 100 kW (2 MW full scale)
3 catenary 56mm anchor chains
Survived typhoon

Utsunomiya et al. 2014. Dynamic response of a spar-type floating wind turbine at power generation. OMAE.

VolturnUS, 12 kW
3 catenary moorings
Experienced scaled 50-year and 500-year events

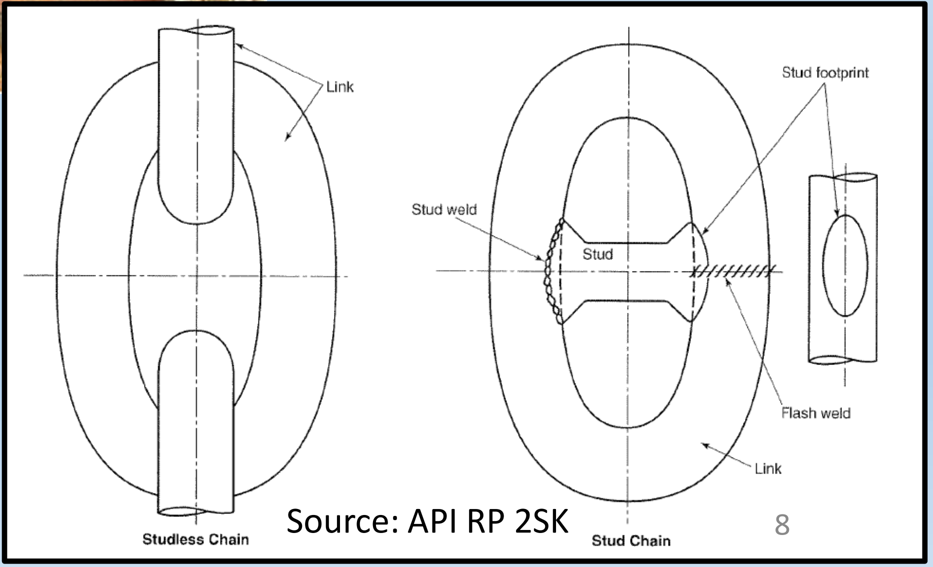


Cianbro, http://www.cianbro.com/

Mooring Materials: Chain

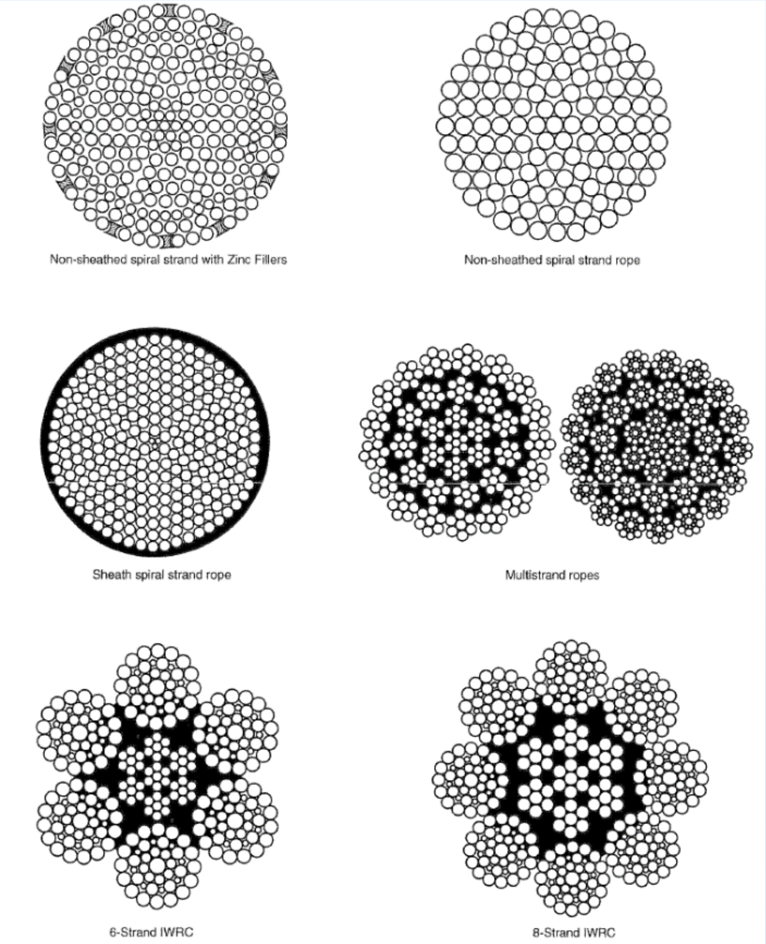
Duggal, A.S and Fontenot, W.L. 2010. Anchor Leg System Integrity – From Design through Service Life, Offshore Technology Conf., Houston, TX, pp. 1-5.

Chain Wire Size		Break	Proof	Weight	
		R3	R3		
			Stud	Stud	Average EA
inches	mm	KN	KN	Kgs/m	N
1.50	38	1.32E+03	8.75E+02	3.20E+01	1.379E+08
1.97	50	2.23E+03	1.48E+03	5.50E+01	2.388E+08
2.52	64	3.55E+03	2.36E+03	9.00E+01	3.912E+08
2.99	76	4.88E+03	3.24E+03	1.26E+02	5.516E+08
3.54	90	6.65E+03	4.41E+03	1.77E+02	7.736E+08
4.02	102	8.32E+03	5.52E+03	2.28E+02	9.936E+08
4.49	114	1.01E+04	6.71E+03	2.85E+02	1.241E+09
5.00	127	1.22E+04	8.08E+03	3.53E+02	1.540E+09

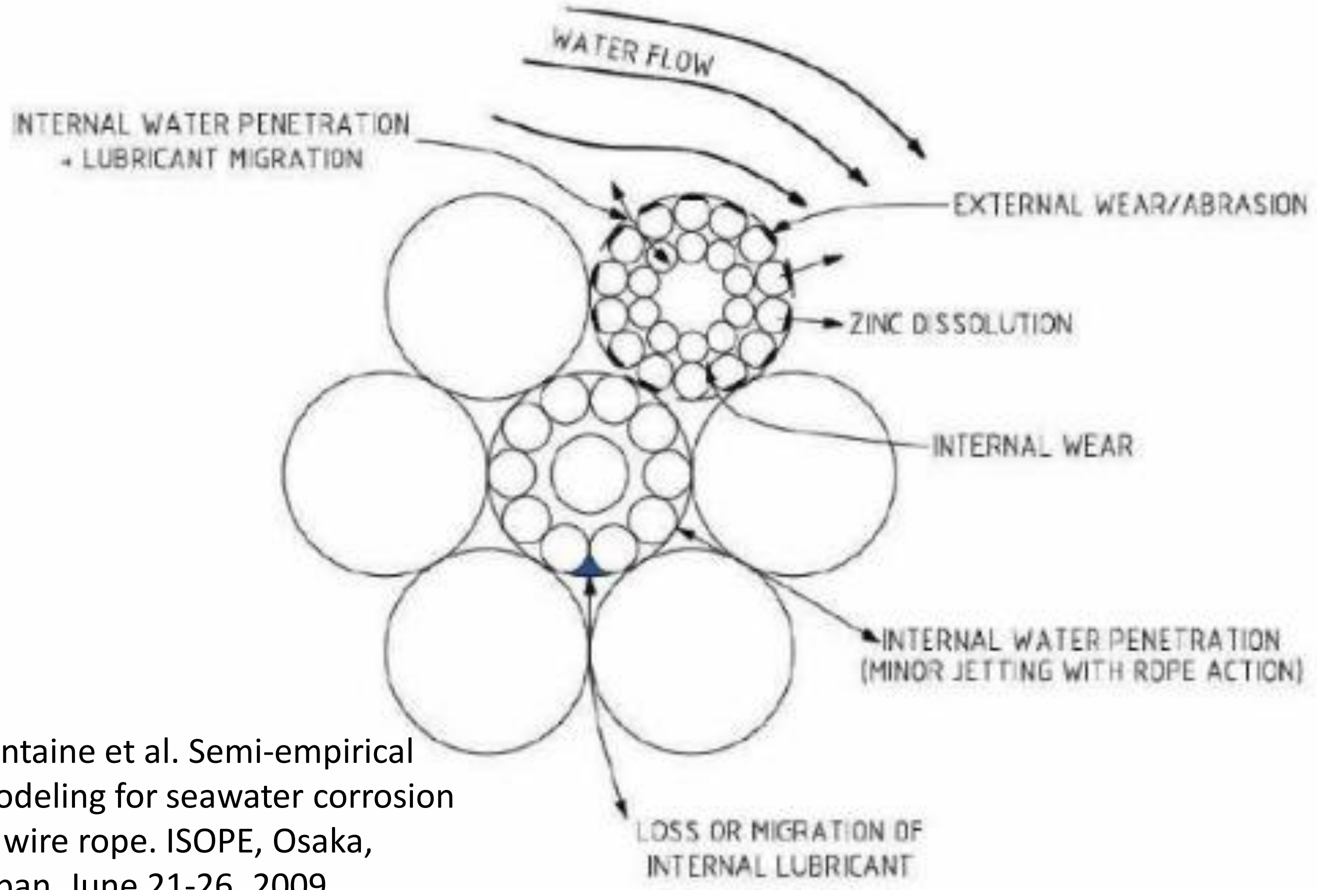


Source: API RP 2SK

Mooring Materials: Wire Rope



Source: API RP 2SK



Fontaine et al. Semi-empirical modeling for seawater corrosion of wire rope. ISOPE, Osaka, Japan, June 21-26, 2009.

Anchor Types

Sound & Sea Technology, "Advanced Anchoring and Mooring Study," November 30, 2009

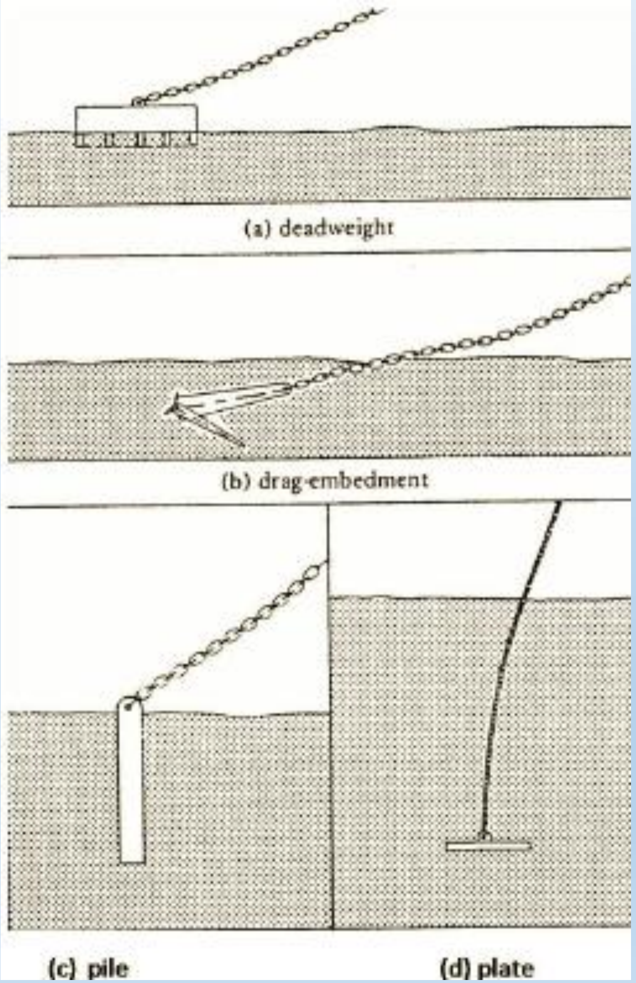


Figure 13 Enhanced Deadweight Anchor

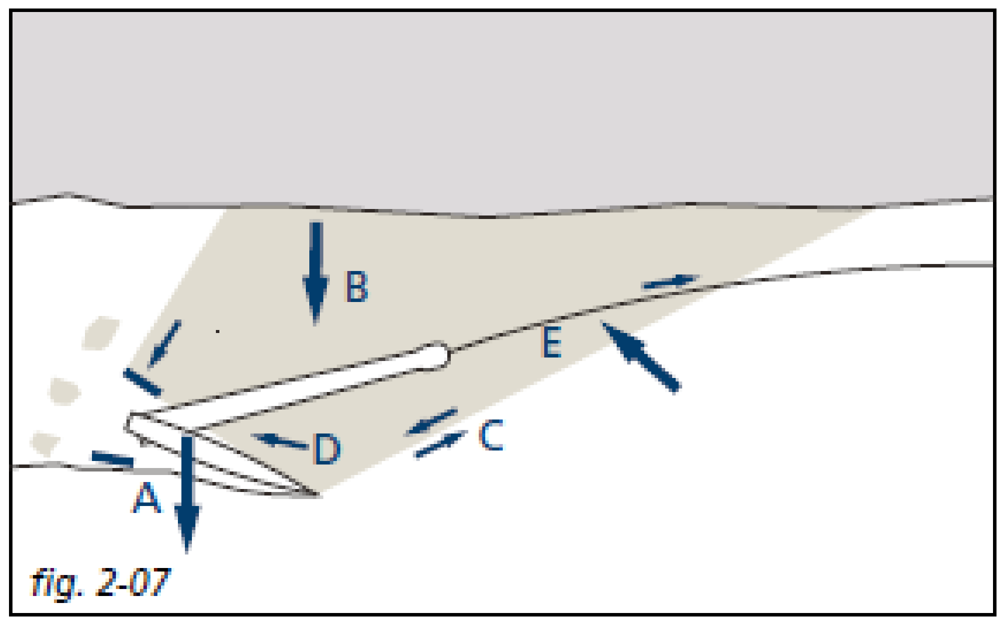
Figure 19 Coral Plate Driven Anchor

Toal et al. Gryphon Alpha FPSO – Experience gained during moorings replacement and hook-up. OTC-25322, Houston, Texas, May 5-8, 2014.

Drag/Embedment Anchors

- Lots of drag anchor choices
  - Vryhof Stevpris, Stevmanta shown
- Uplift in anchor/mooring design?
  - Depends on how deep the anchor is imbedded
  - Inverse catenary of mooring line (E) allows for uplift up to 20 degrees before anchor loads change
- Proof load test required
  - 50% of breaking load of chain

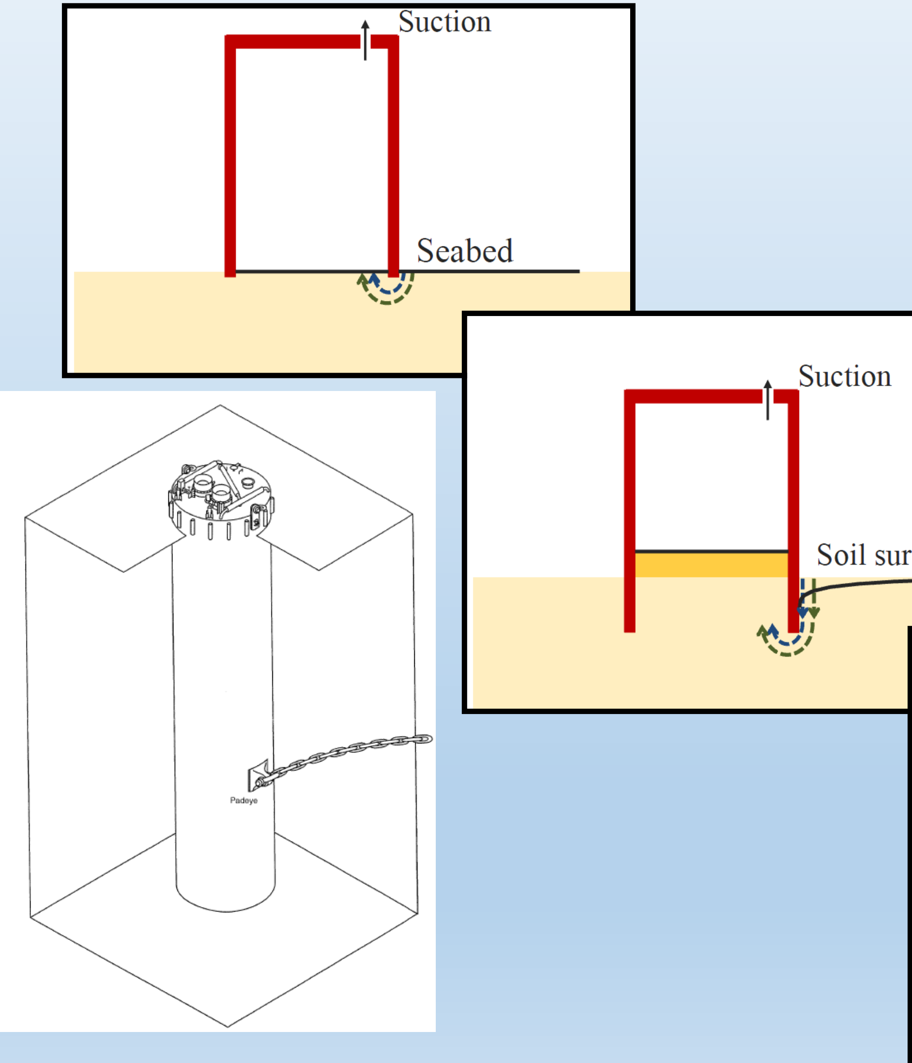
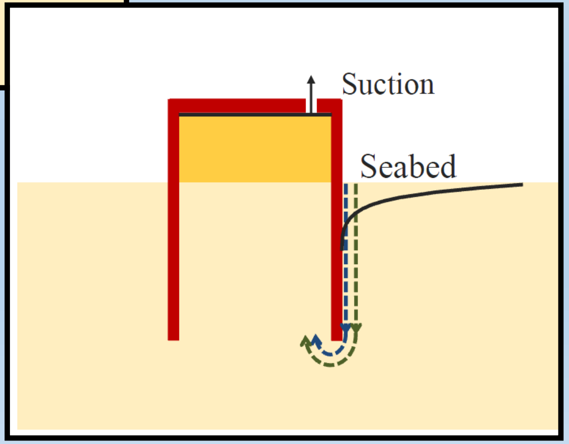
Vryhof Anchors, http://www.vryhof.com/products.html, Accessed July 15, 2014



Anchor Manual 2010, "The Guide to Anchoring," Vryhof Anchors.

Suction Pile Anchor

Sound & Sea Technology, "Advanced Anchoring and Mooring Study," November 30, 2009

Source: API RP 2SK

Figure 16 Multiple Mooring Piles Loaded for Transport

Figure 17 Multiple Suction Piles Installed from Single Vessel

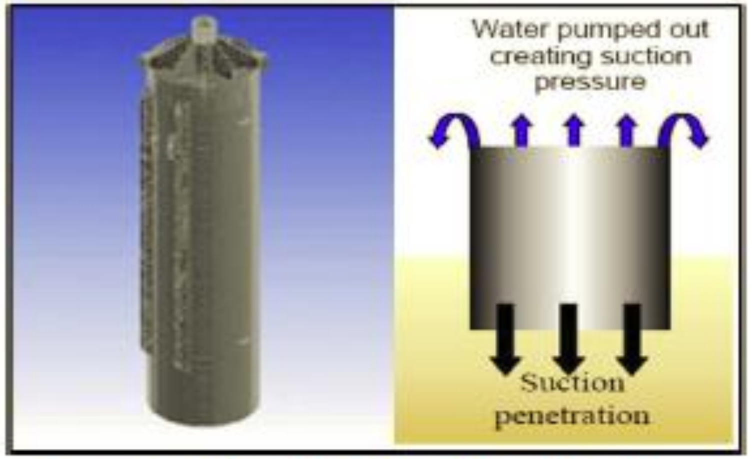
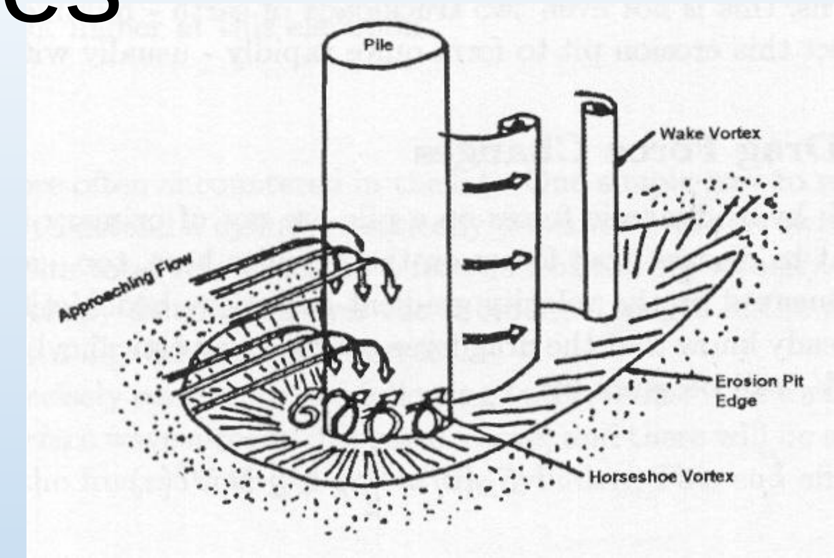


Figure 23 Suction pile example and penetration process

Suction Pile Failures

- Scouring
    - Tilting, loss of friction drag
    - Normalized scour depth reduces quickly with increase of pile diameter
    - Actual scour depth depends on caisson diameter and “stick-up” height
- Prevention
    - Geotechnical Analysis (depends on bottom type, other factors)
    - Add skirts, artificial fronds at base of caisson



Open Course, "Offshore Windfarm Design, Foundations" OE 5662, Delft University Wind Energy Research Institute

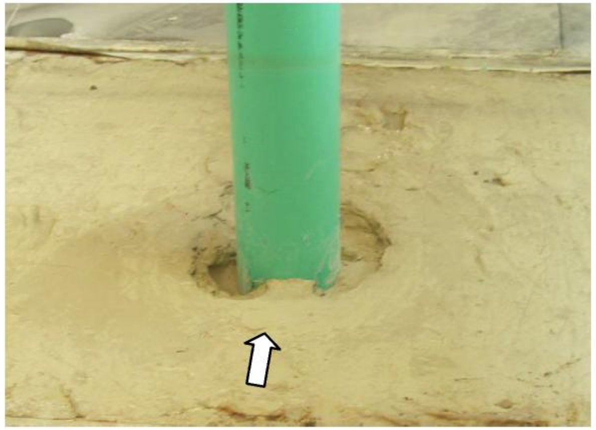
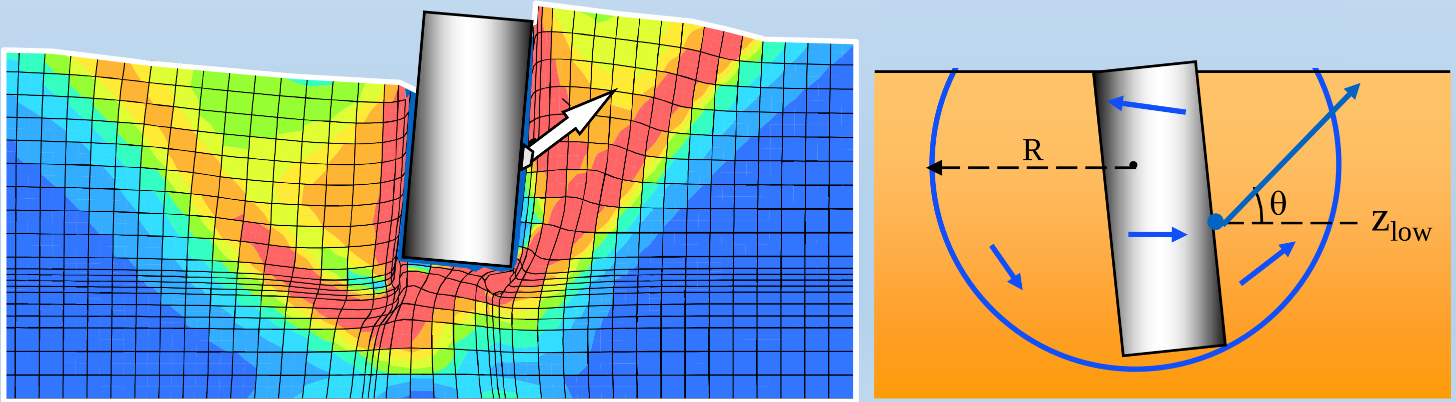


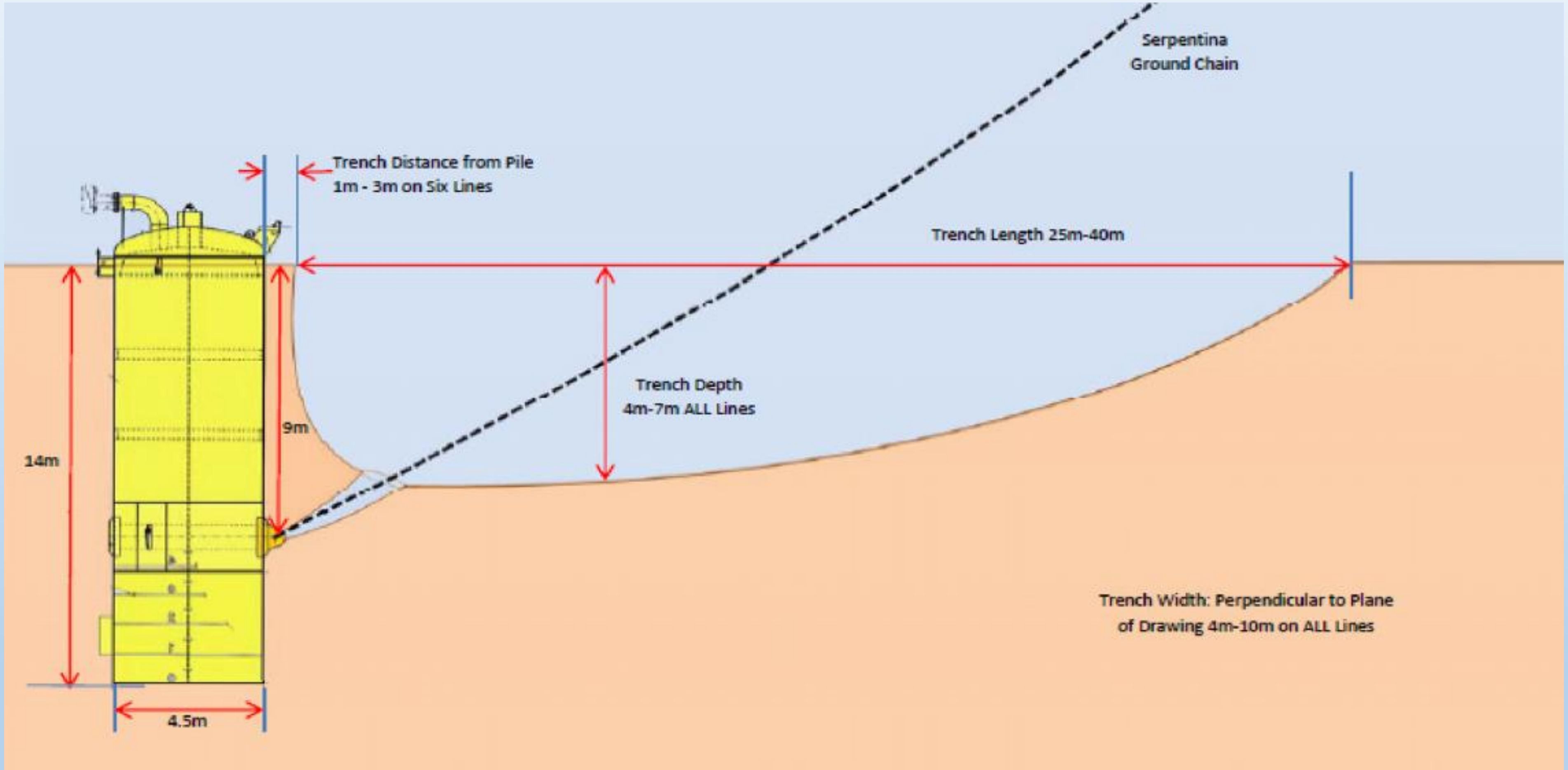
Fig 2 Local Scour around a Cylindrical Pile in Cohesive Soils from Flume Test

Li, Y., et. al., “Is Scour Important for Pile Foundation Design in Deepwater?,” OTC-19906, 2009 Offshore Technology Conference, Houston, TX



Riemers. “Self Installing Wind Turbine (SIWT),” SPT Offshore, Network Event Paris, November, 2011.

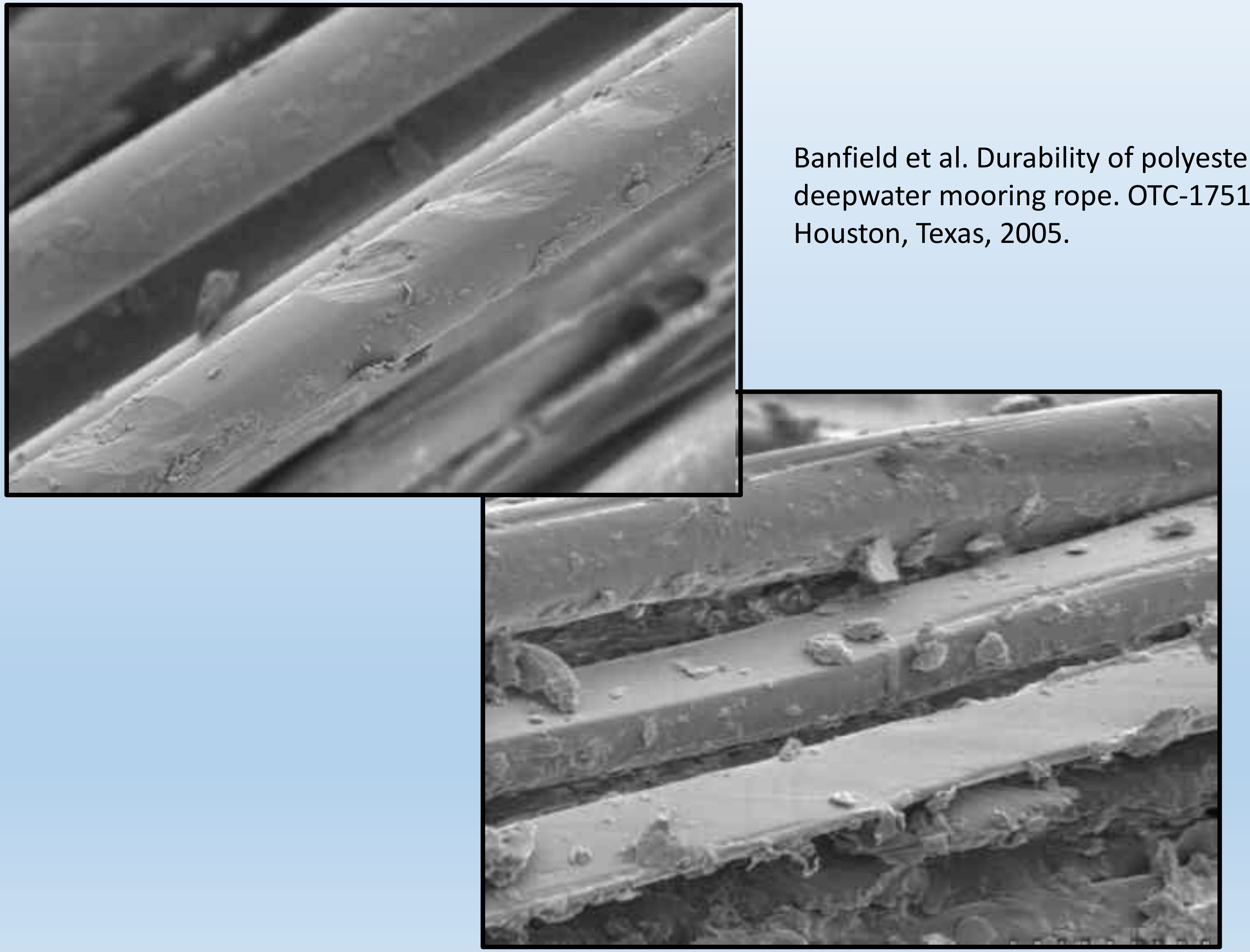
Suction Pile Failures



Bhattacharjee et al. 2014. Serpentina FPSO mooring integrity issues and system replacement: unique fast track approach. OTC-25449, Houston, Texas, 2014.

Abrasion Failure: Synthetic Rope

Ayers et al. Effects of fiber rope – seabed contact on subsequent rope integrity. OTC-25136, Houston, Texas, May 5-8, 2014.



Banfield et al. Durability of polyester deepwater mooring rope. OTC-17510, Houston, Texas, 2005.

Mooring Failure Mechanisms
Excessive Loads

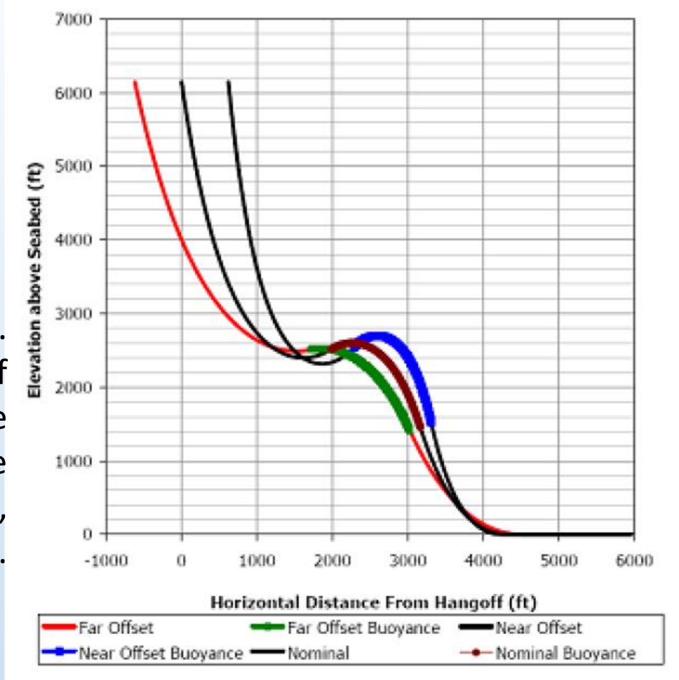
- Load exceeds breaking strength of mooring components
- Cause/physics
  - Extreme storm events
  - High pretension causes higher tension from wave motions
  - Decrease in breaking strength due to fatigue
  - Line goes slack and snaps
- How to avoid it (case studies, examples)
  - Recommended practice
    - API, DNV, ABS mooring design guidelines
  - Software analysis
    - Accurate model and appropriate choice of environmental conditions
  - Model tests

Jean et al. Failure of chains by bending on deepwater mooring systems. OTC-17238, Houston, Texas, May 2-5, 2005.

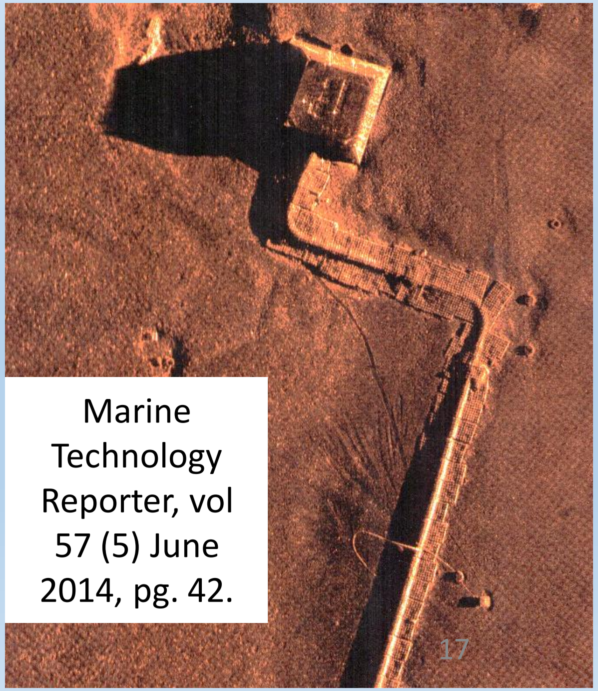
Mooring Failure Mechanisms
Umbilical Failure

- Cause/physics
  - Extreme weather
  - Low pre-tension leads to excessive offset
  - Platform excursion so large that umbilical snaps
- How to avoid it
  - Umbilical bend restrictors and other accessories
  - Umbilical designed to survive bending, offset, and tensions

Li, S., Nguyen, C. 2010. Dynamic Response of Deepwater Lazy-Wave Catenary Riser. Deep Offshore Technology International, Amsterdam, Netherlands.



"Ship's anchors and trawlers can cause damage and failure of undersea cables," www.soundandsea.com/OceanEngineeringPages/Survivability.html, downloaded 07/2014

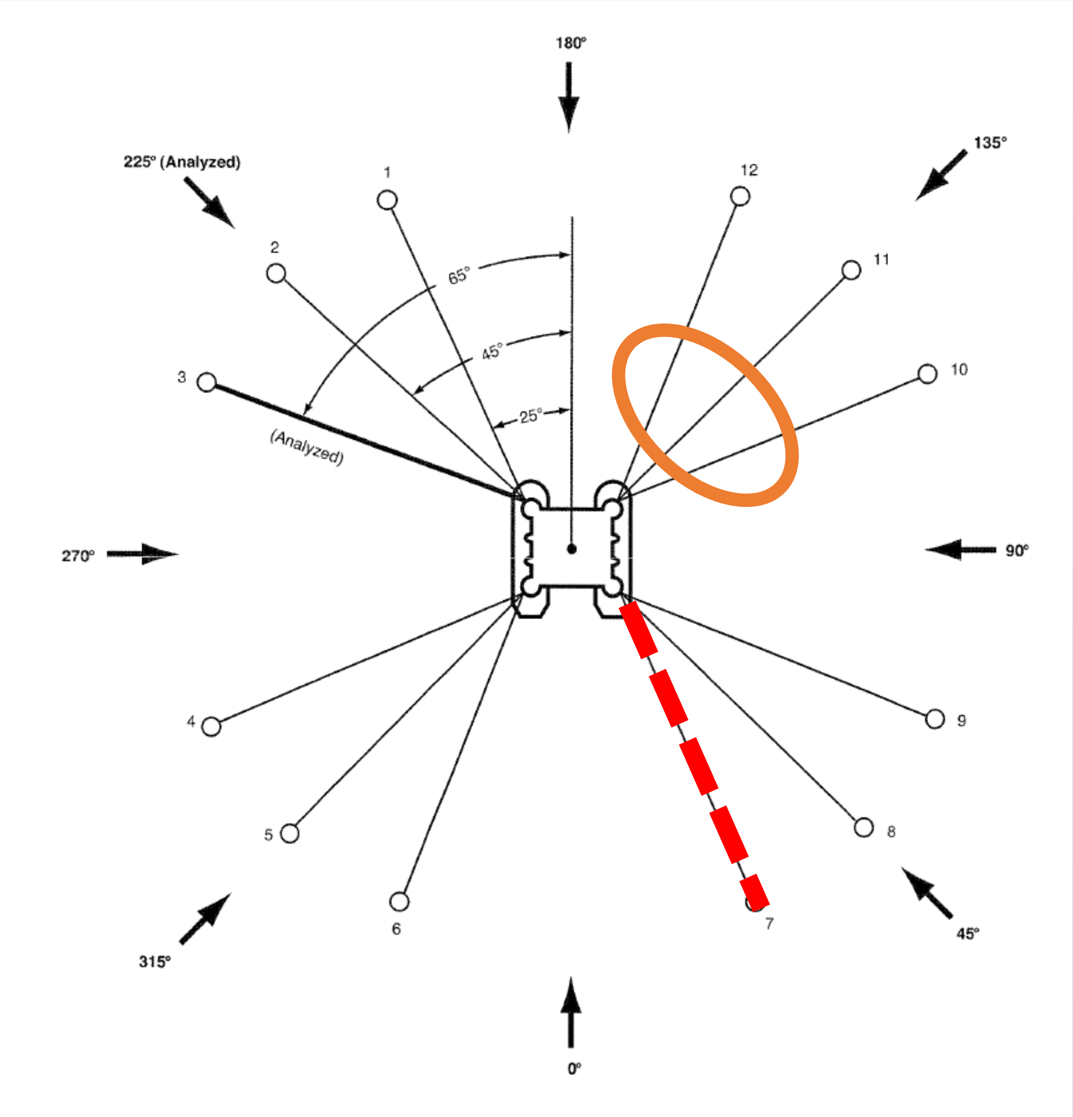


Marine Technology Reporter, vol 57 (5) June 2014, pg. 42.

Mooring Failure Mechanisms

Cascading damage

- Cause/physics
  - Line snaps, FOWT moves to new position
  - Secondary umbilical or line failure
  - Loss of stationkeeping
  - Worse for FOWTs than oil and gas platforms (less redundancy)
- How to avoid it
  - Mooring design should account for
    - Stationkeeping with one/two failed lines
    - Transient effects of a line breaking event



Source: API RP 2SK

Fatigue Damage

- Cause/Physics
  - Accumulated damage due to cyclic loading
  - Loss of strength/increase in stresses due to material loss (crack growth, corrosion, abrasion)
- How to Avoid it
  - Proper mooring design
    - Avoid rope contact with the seafloor
    - Corrosion protection of wire rope
  - Fatigue analysis
    - Rainflow counting of time domain tension history
    - Application of S-N/T-N curve
    - Palmgren-Miner Damage Rule

Brown et al. Phase 2 Mooring integrity JIP – summary of findings. OTC-20613, Houston, Texas, May 3-6, 2010.

Fontaine et al. 2012. Investigation of severe corrosion of mooring chain in west African waters. Proceedings of the Twenty-second International Offshore and Polar Engineering Conference, Rhodes, Greece, pp. 389-394.

Fatigue Damage

Corrosion of Chain

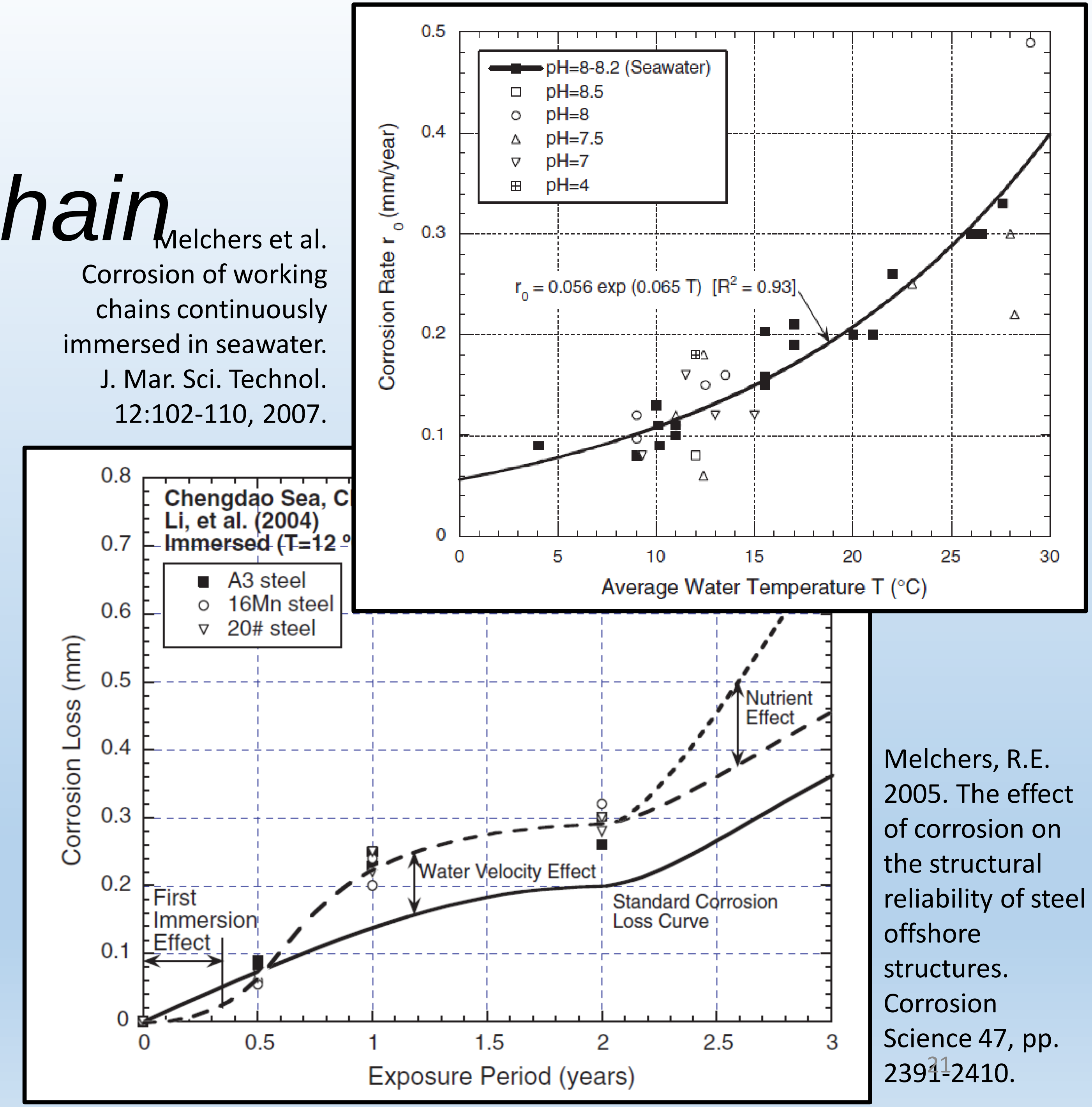
- Cause/Physics
  - Water temperature
  - Water velocity (can disrupt rust build-up & marine growth)
  - Dissolved oxygen
  - Abrasion (can disrupt rust build-up marine growth)
  - Microbiologically Influenced Corrosion
  - Other factors that have less effect
    - Alloy composition of steel
    - Water pH

Duggal, A.S and Fontenot, W.L. 2010. Anchor Leg System Integrity – From Design through Service Life, Offshore Technology Conf., Houston, TX, pp. 1-5.

Fontaine et al. SCORTH JIP – Feedback on MIC and pitting corrosion from field recovered mooring chain links. OTC-25234, Houston, Texas, May 5-8, 2014.

Fatigue Damage
Corrosion of Chain

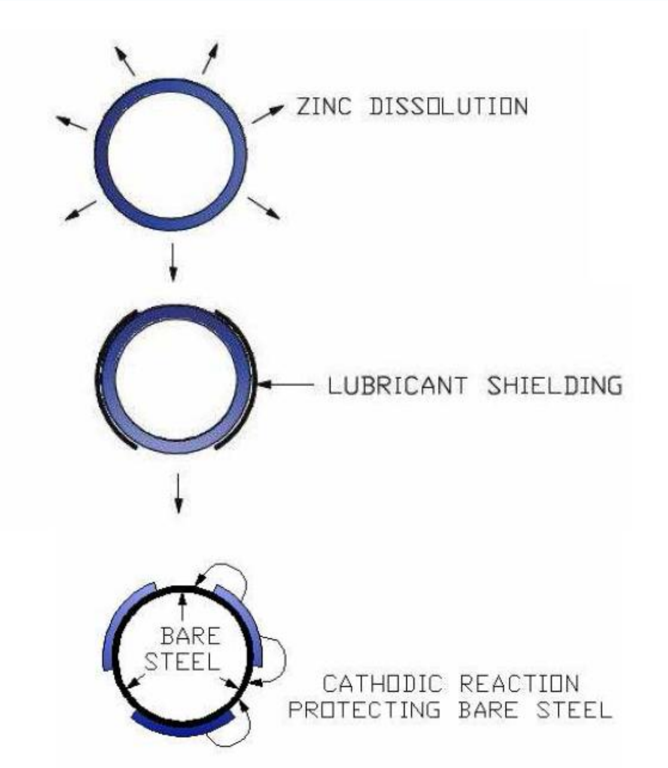
- How to Avoid it
  - Design practice: over-design chain to account for material loss
    - Empirical models exist for prediction of corrosion rate
    - Current standards suggest corrosion/wear allowances based on only a few factors
    - Several case studies show corrosion can exceed allowances in standards
  - Routine inspection

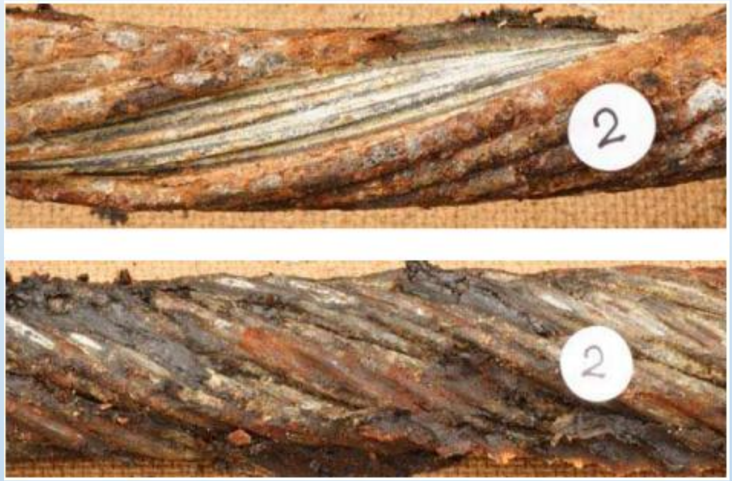


Melchers et al. Corrosion of working chains continuously immersed in seawater. J. Mar. Sci. Technol. 12:102-110, 2007.

Melchers, R.E. 2005. The effect of corrosion on the structural reliability of steel offshore structures. Corrosion Science 47, pp. 2391-2410.

Fatigue Damage
Corrosion of Wire Rope





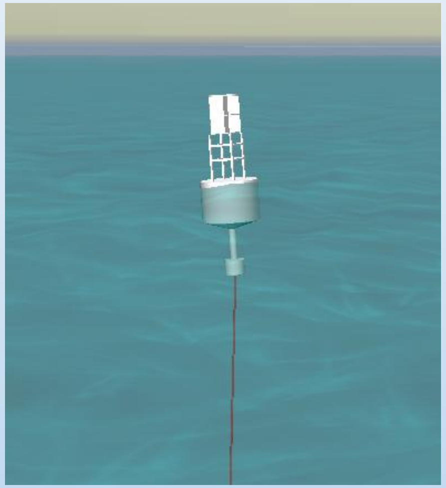
- Cause/Physics
  - Driven by environmental factors
    - Water temperature
    - Water velocity
    - Dissolved oxygen
    - Effectiveness of lubricant
    - Rate of zinc dissolution
- How to Avoid it
  - Protective measures
    - Protective zinc coating
  - Empirical models have been proposed to predict
    - Corrosion rates
    - Rate of deterioration of protective elements

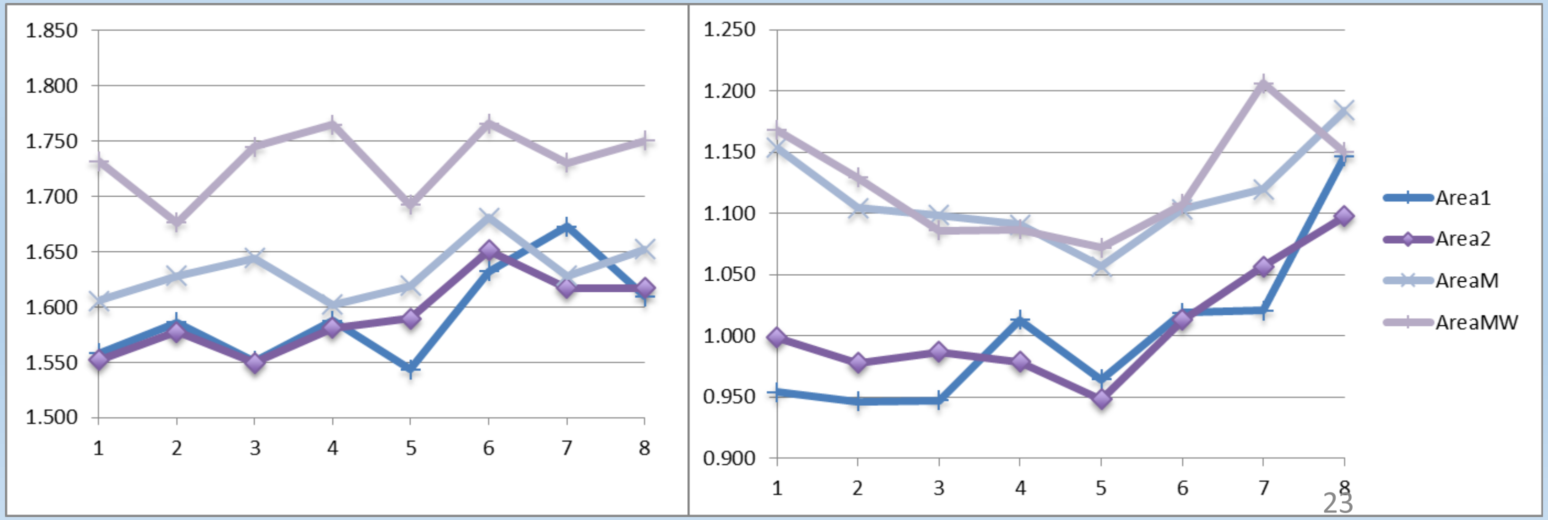
Fontaine et al. Semi-empirical modeling for seawater corrosion of wire rope. ISOPE, Osaka, Japan, June 21-26, 2009.

Case Study

MMC Investigation of Chain Corrosion

- Investigation of corrosion of US Coast Guard aid-to-navigation (ATON) buoys
- Significant loss of chain link material in touchdown region
    - Believed to be caused by corrosion & abrasion
    - Prevention of rust build-up by abrasion
    - Increased contact roughness by sand/shell on seafloor
- Current investigation efforts by MMC
    - Field measurements to quantify material loss
    - Examination of logs to assess trends
    - Computer models of ATON chain dynamics in chafe zone



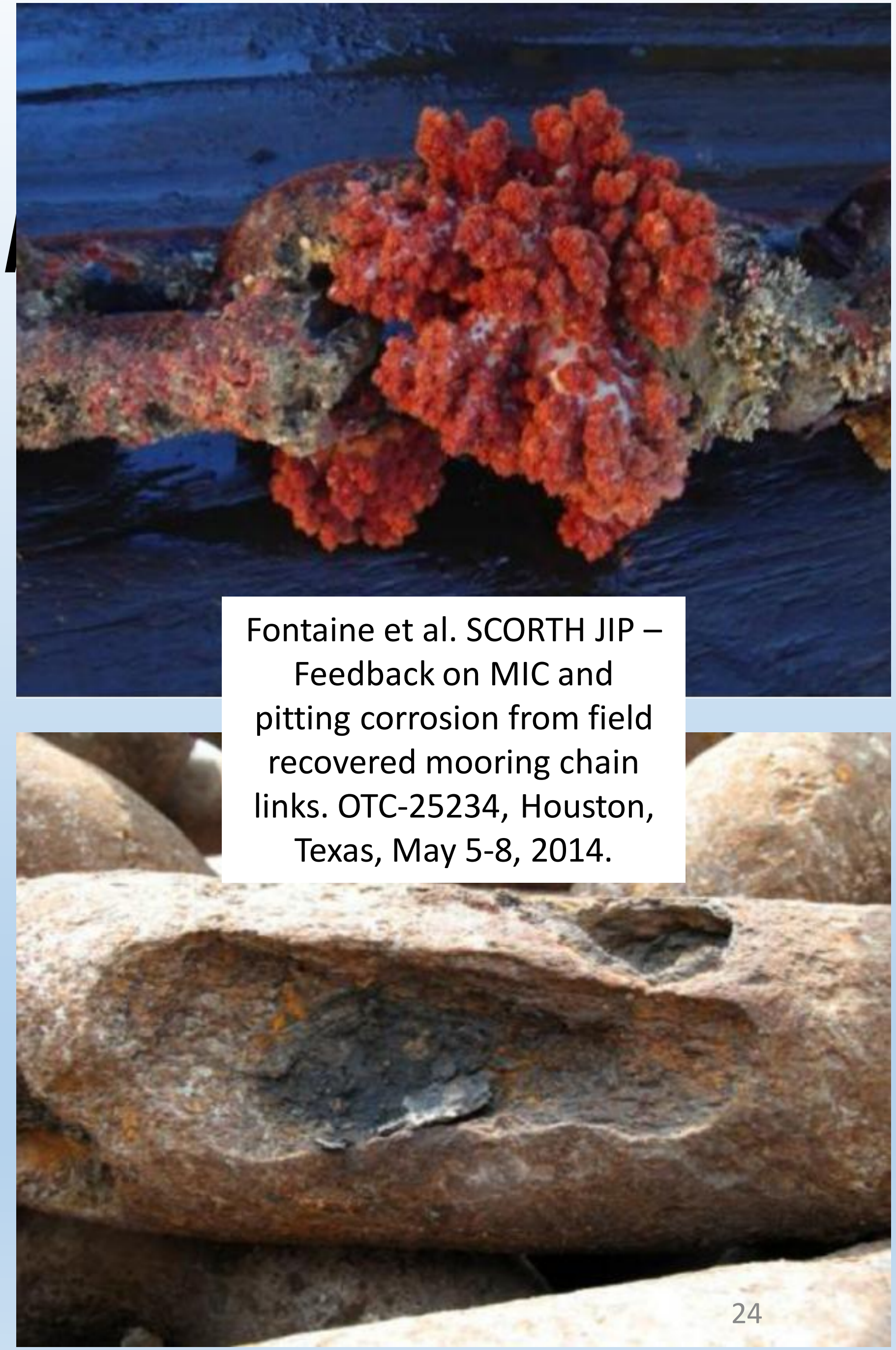


Case Study

Severe Pitting Corrosio

- Investigation of FPU off tropical West Africa
- Pitting corrosion discovered in mooring chain
  - 35% decrease in cross-section after 7 years
  - Significantly higher loss than recommended allowances in existing codes
  - Breaking load between 80-90% of original
  - Attributed to Microbiologically Influenced Corrosion (MIC)

Reported by Fontaine et al, 2012 (ISOPE) & Fontaine et al, 2014 (OTC) as part of Seawater Corrosion of Rope and Chain (SCORCH) JIP



Fontaine et al. SCORTH JIP – Feedback on MIC and pitting corrosion from field recovered mooring chain links. OTC-25234, Houston, Texas, May 5-8, 2014.

Fatigue Damage
Material Abrasion

- Cause/Physics
  - Contact between surfaces
    - Consecutive chain links
    - Mooring & seafloor
    - Mooring & fairlead
  - Function of
    - Contact force
    - Material hardness
    - Relative motion
- How to Avoid it:
  - Design so rope <u>never</u> contacts seafloor
  - Predict abrasion on chain links based on Chain geometry, mooring line dynamics, steel hardness

$$V_{wear} = \sum_{i=1}^{N-1} \left(\frac{F_{i+1} + F_i}{2} \right) |\varphi_{i+1} - \varphi_i| \left(\frac{\pi}{180} \right) (r)(K_i)$$

(Source: Shoup and Mueller, 1984)

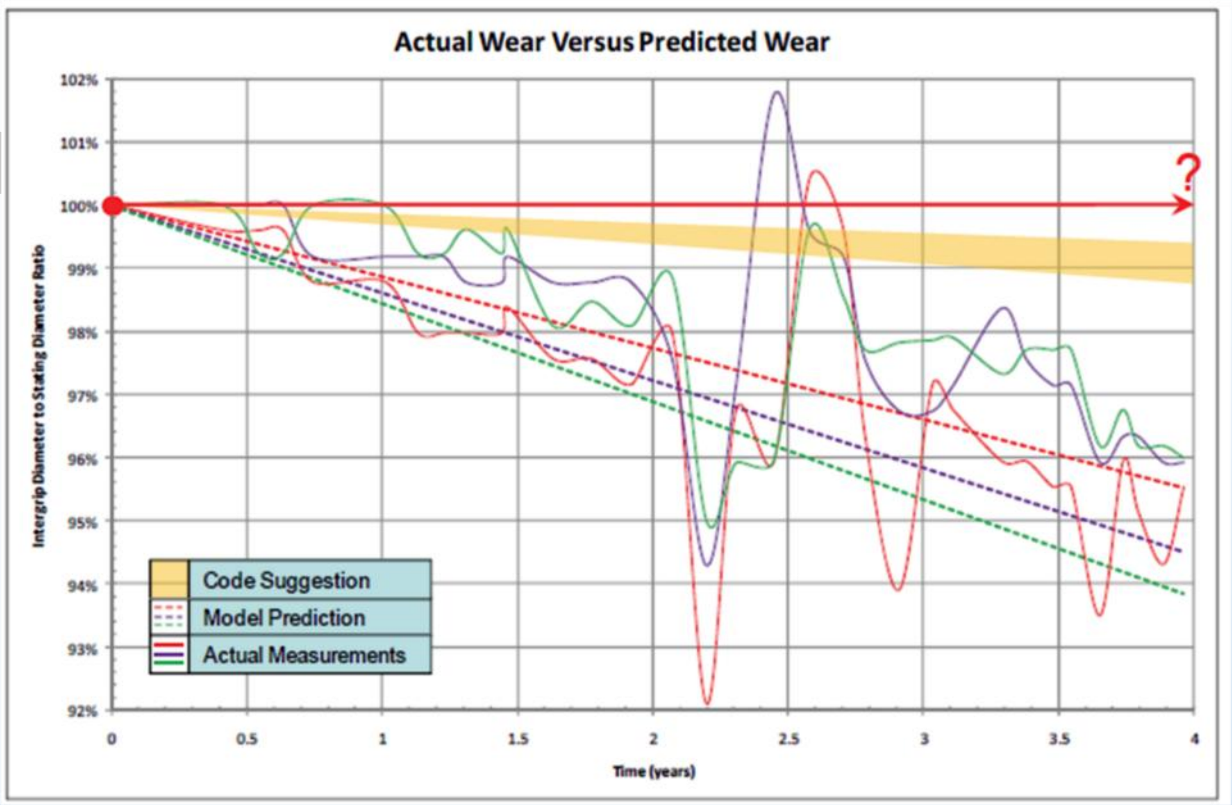



Figure 1: Heavy Narrow Wear

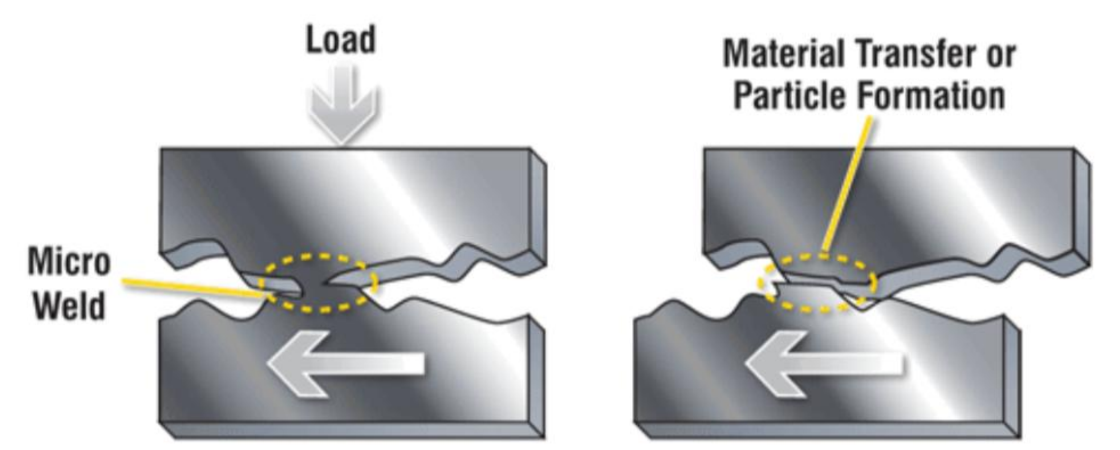

Figure 2: Heavy Broad Wear

Brown et al. Phase 2 Mooring integrity JIP – summary of findings. OTC-20613, Houston, Texas, May 3-6, 2010.

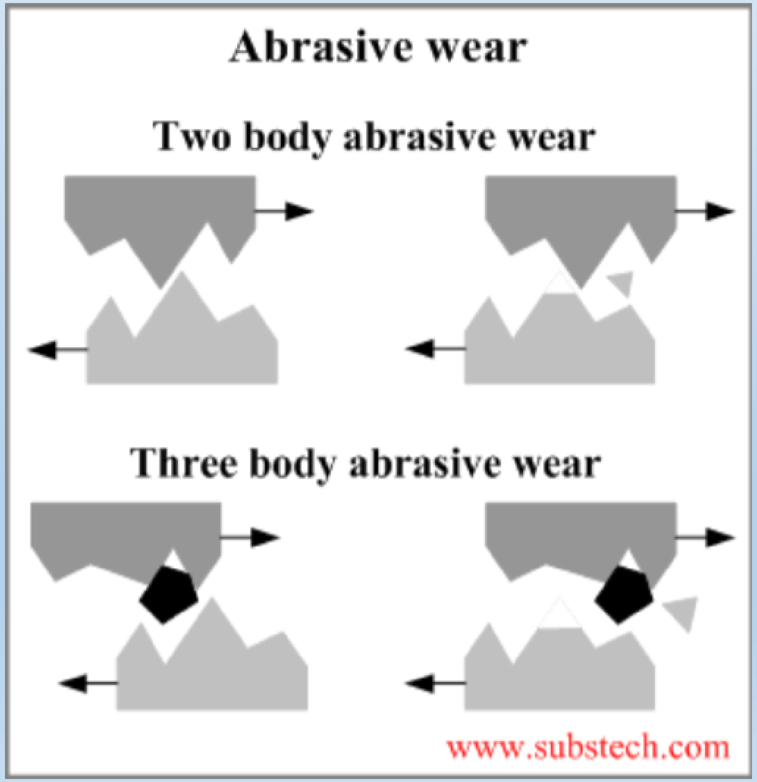
Fatigue Damage

Types of Abrasion

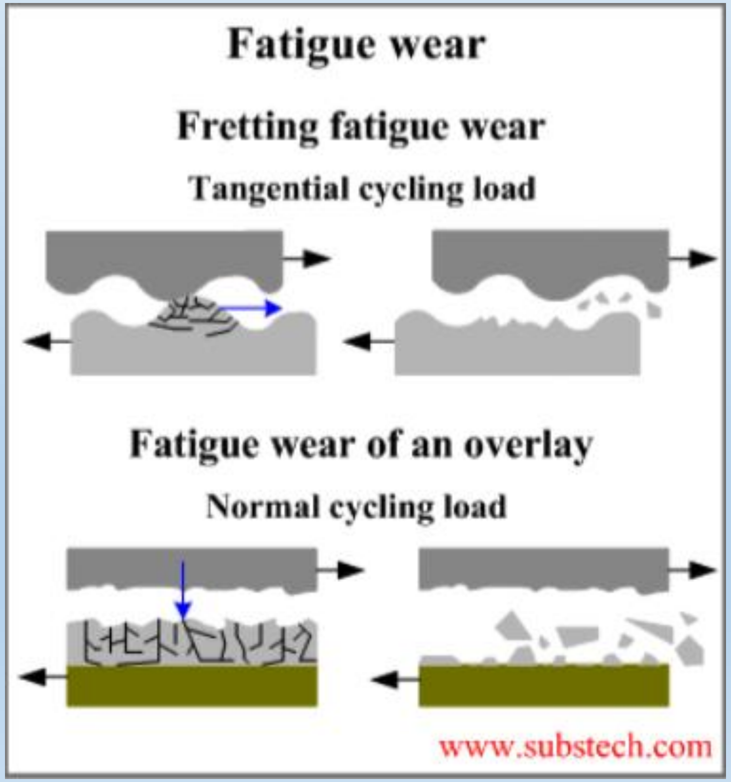
- <u>Adhesive</u> wear: welds form between wearing surfaces and are sheared off
- <u>Abrasive</u> wear: hard material abrades softer one
- <u>Fretting</u>: small oscillations between surfaces cause oxidization



www.machinerylubrication.com



www.substech.com

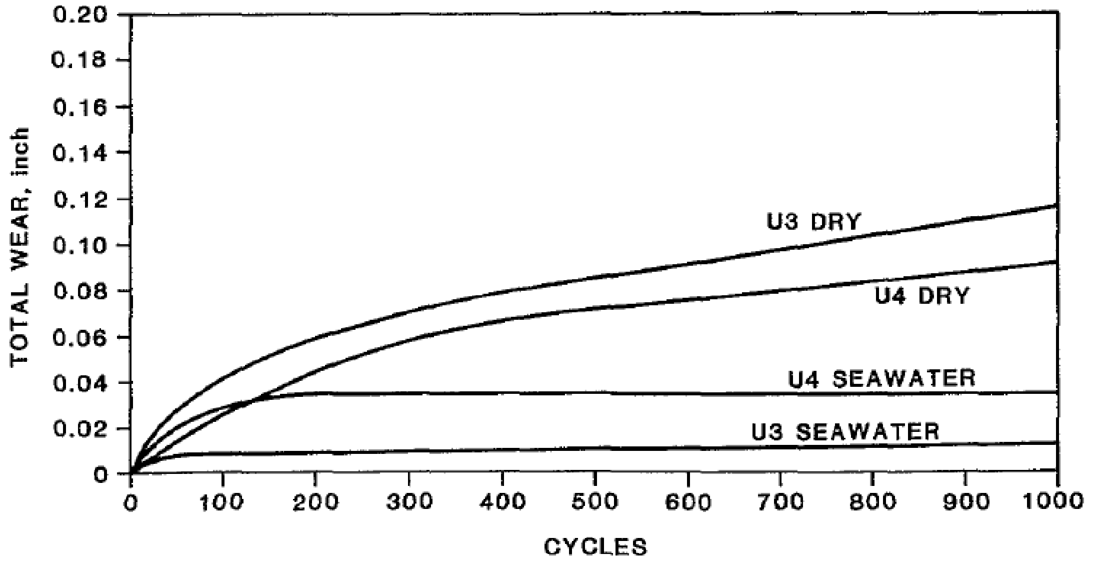


www.substech.com

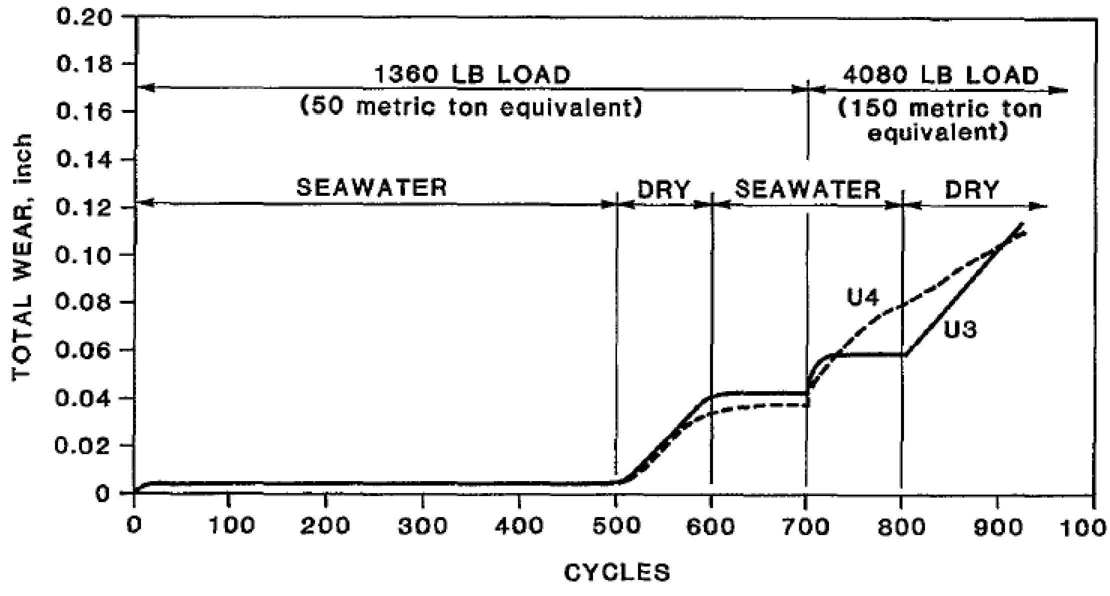
Case Study
Wear on Buoy chain

- Installed in 1982 with asymmetric chain mooring layout
- Failure during typhoon 2 months after installation
  - 40-70 knot winds & 30 ft. waves over 3 day period
- Failure caused by material wear

Shoup & Mueller. Failure analysis of a Calm buoy anchor chain system. OTC-4764, Houston, Texas, May 7-9, 1984.



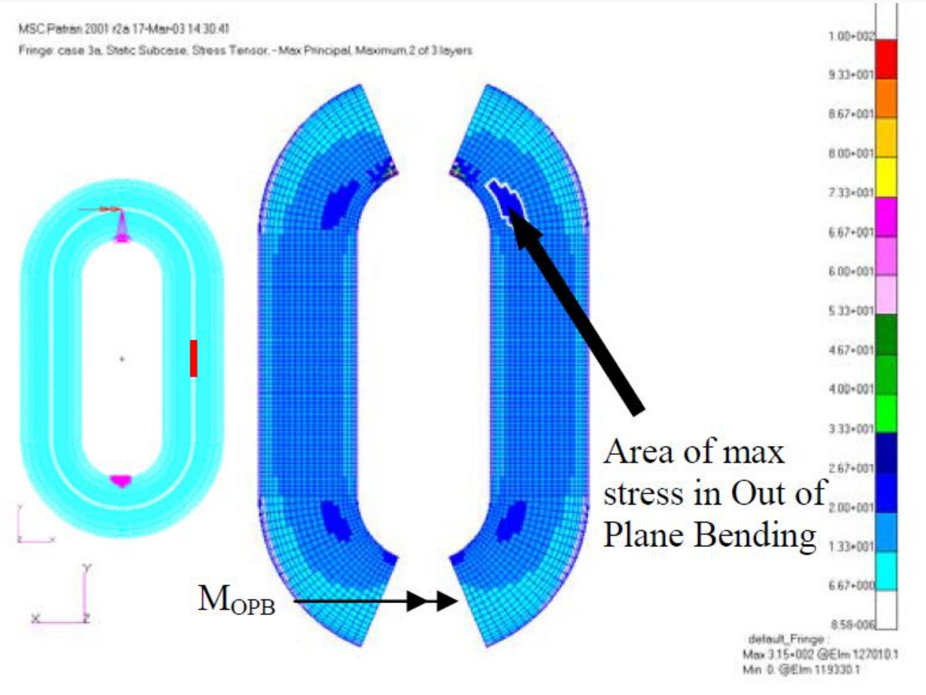
WEAR OF U4 AND U3 CHAIN LINK STEEL
AT 1360 LBS (50 metric ton equivalent)

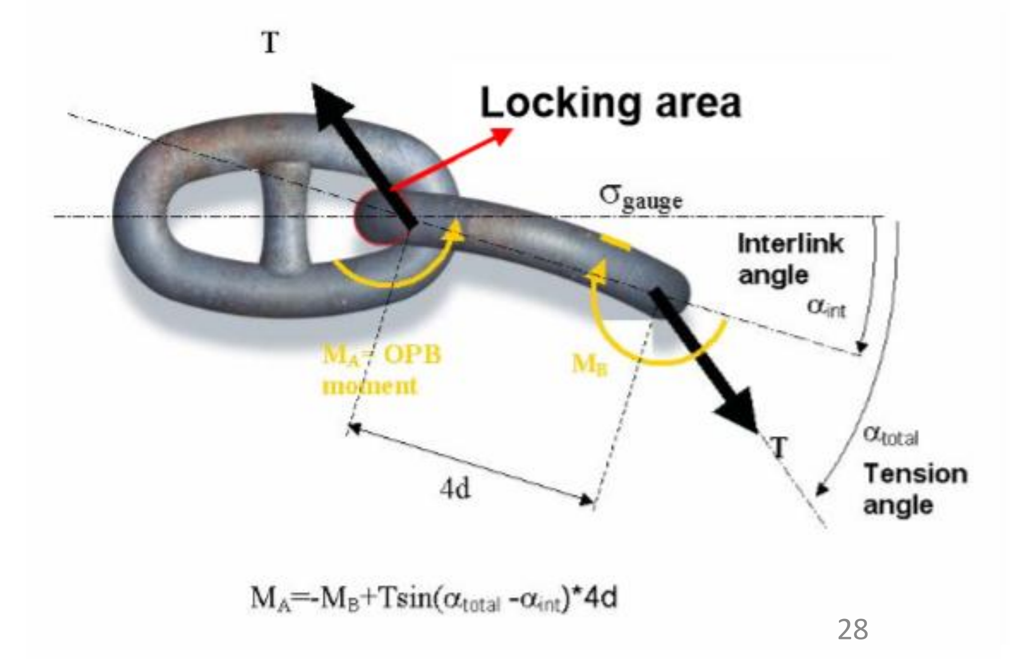


COMPARISON OF U4 AND U3 STEELS UNDER
DRY AND WET SLIDING AT TWO LOAD LEVELS

Fatigue Damage
Out of Plane Bending

- Relatively new source of fatigue
- Cause/Physics
  - Chain bending in chainhawse
  - High pretension in mooring line
  - Deformation of link due to proof loading
  - High loads cause links to behave like solid beam members
- How to Avoid it
  - Prediction
    - Empirical models
    - Analytical beam models
    - Finite element models
    - Hot-spot S-N analysis

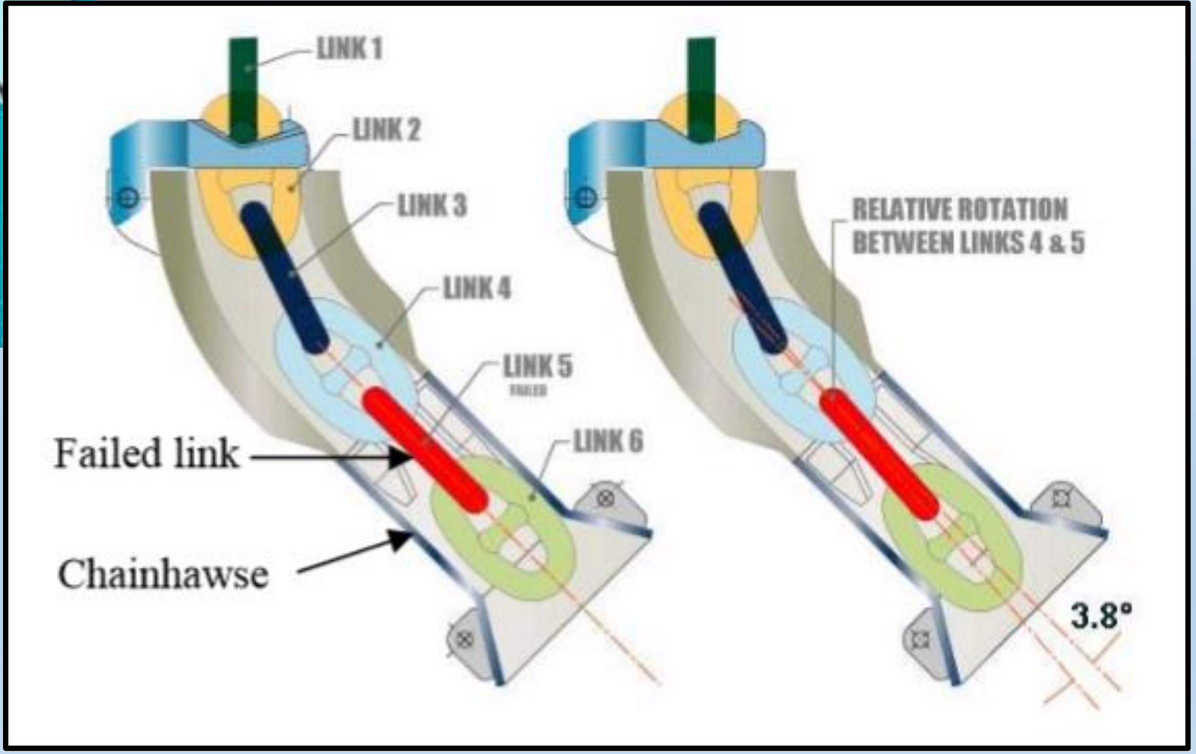




Jean et al. Failure of chains by bending on deepwater mooring systems. OTC-17238, Houston, Texas, May 2-5, 2005.

Case Study
Girassol Offloading Buoy

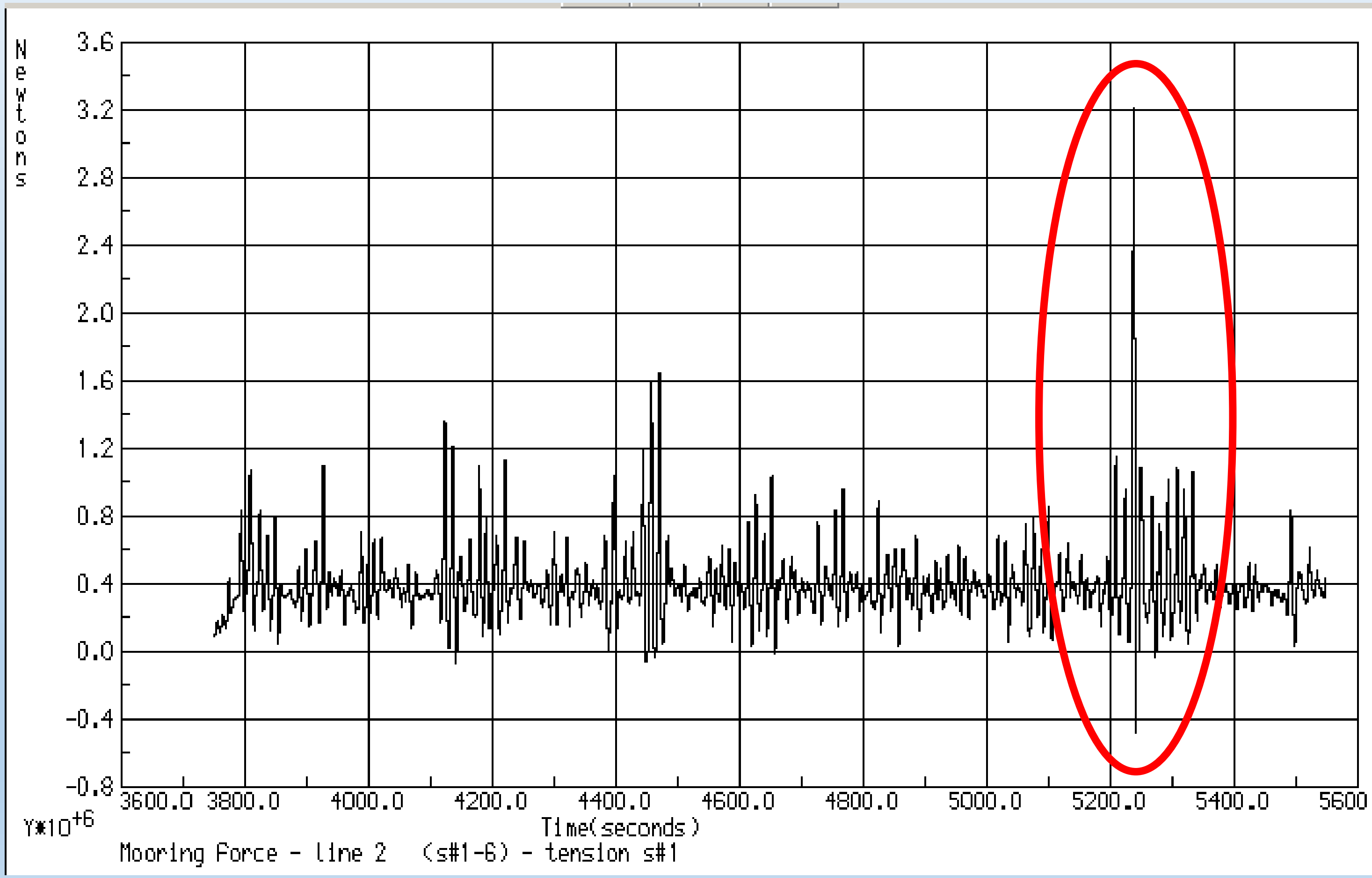
- Offloading buoy designed in accordance with API RP2SK with design fatigue life > 60 years
- Several chains broke within 1 year due to fatigue failure



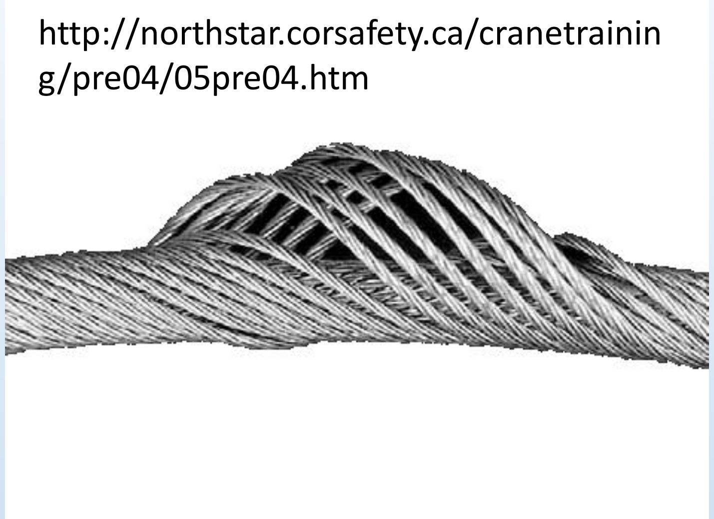
Jean et al. Failure of chains by bending on deepwater mooring systems. OTC-17238, Houston, Texas, May 2-5, 2005.

Fatigue Damage
Snap Loads

- Cause/Physics
  - Slack line followed by spike in tension as line goes taut
  - Can lead to large increase in tension close to or above breaking strength
- How to Avoid it
  - Further research needed
    - Determine how snap loads affect fatigue
    - Is Miner's rule violated?



Fatigue Damage
Birdcaging


http://northstar.corsafety.ca/cranetraining/pre04/05pre04.htm

- Cause/Physics
  - Abrupt tension changes and small bend radii in touchdown region
  - Torsion & trenching
  - Changes in line behavior due to corrosive losses
- How to Avoid it
  - Avoid rope contact with seafloor

Duggal, A.S and Fontenot, W.L. 2010. Anchor Leg System Integrity – From Design through Service Life, Offshore Technology Conf., Houston, TX, pp. 1-5.

Case Study *Haewene Brim FPSO*

- Installed with chain/unsheathed wire rope mooring system 1998
- Birdcaging discovered on numerous occasions
- Reported by Leeuwenburgh & Brinkhuis, 2014 (OTC-25232)

Leeuwenburgh & Brinkhuis. Lifetime extension North Sea FPSO, mooring system replacement; integrity and design challenges. OTC-25232, Houston, Texas, May 5-8, 2014.

Rules and Regulations *Standard Based Design to Avoid Failure*

- For good analysis
  - Good metocean model needed
  - Good environmental model needed
  - Pick relevant design and survival load cases
    - Cross between reasonable and worst case
    - Use accepted engineering practices to ensure survival
- Environmental cases
  - Flaws in statistical methods
    - Climate change, growing history of weather events mean changing long term statistics
    - Upper limits to wave conditions are neglected in long term statistics
    - When hurricane size increases to a point waves start to get smaller

- Key Standards for Mooring & FOWT Design:
  - American Petroleum Institute
    - RP 2SK Design and Analysis of Stationkeeping Systems for Floating Structures
  - American Bureau of Shipping
    - Guide for Building and Classing Floating Offshore Wind Turbines
    - Guidance Notes on the Application of Fiber Rope Mooring
    - Guide for the Certification of Offshore Mooring Chain
  - Bureau Veritas
    - 493NI Classification of Mooring Systems for Permanent Offshore Units
  - Det Norske Veritas
    - OS-E301 Position Mooring
    - OS-E302 Offshore Mooring Chain
    - OS-E303 Offshore Fibre Ropes
    - OS-E304 Offshore Mooring Steel Wire Ropes

Rules and Regulations

Standard Based Design to Avoid Failure

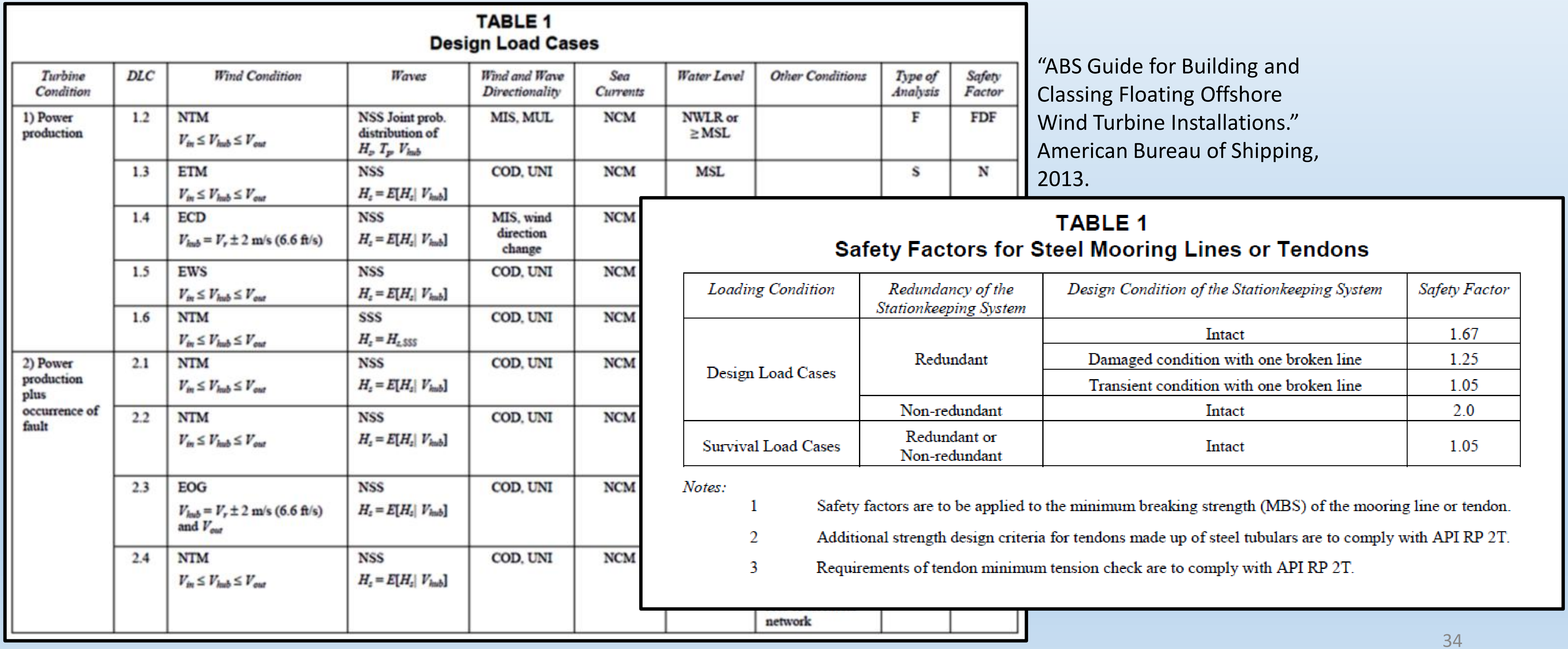


TABLE 1
Design Load Cases

Turbine Condition	*DLC*	*Wind Condition*	*Waves*	*Wind and Wave Directionality*	*Sea Currents*	*Water Level*	*Other Conditions*	*Type of Analysis*	*Safety Factor*
1) Power production	1.2	NTM $V_{in} \le V_{hub} \le V_{out}$	NSS Joint prob. distribution of H_s, T_p, V_{hub}	MIS, MUL	NCM	NWLR or $\ge$ MSL		F	FDF
	1.3	ETM $V_{in} \le V_{hub} \le V_{out}$	NSS $H_s = E[H_s \| V_{hub}]$	COD, UNI	NCM	MSL		S	N
	1.4	ECD $V_{hub} = V_r \pm 2$ m/s (6.6 ft/s)	NSS $H_s = E[H_s \| V_{hub}]$	MIS, wind direction change	NCM				
	1.5	EWS $V_{in} \le V_{hub} \le V_{out}$	NSS $H_s = E[H_s \| V_{hub}]$	COD, UNI	NCM				
	1.6	NTM $V_{in} \le V_{hub} \le V_{out}$	SSS $H_s = H_{s,SSS}$	COD, UNI	NCM				
2) Power production plus occurrence of fault	2.1	NTM $V_{in} \le V_{hub} \le V_{out}$	NSS $H_s = E[H_s \| V_{hub}]$	COD, UNI	NCM				
	2.2	NTM $V_{in} \le V_{hub} \le V_{out}$	NSS $H_s = E[H_s \| V_{hub}]$	COD, UNI	NCM				
	2.3	EOG $V_{hub} = V_r \pm 2$ m/s (6.6 ft/s) and V_{out}	NSS $H_s = E[H_s \| V_{hub}]$	COD, UNI	NCM				
	2.4	NTM $V_{in} \le V_{hub} \le V_{out}$	NSS $H_s = E[H_s \| V_{hub}]$	COD, UNI	NCM		network		

"ABS Guide for Building and Classing Floating Offshore Wind Turbine Installations." American Bureau of Shipping, 2013.

TABLE 1
Safety Factors for Steel Mooring Lines or Tendons

Loading Condition	*Redundancy of the Stationkeeping System*	*Design Condition of the Stationkeeping System*	*Safety Factor*
Design Load Cases	Redundant	Intact	1.67
		Damaged condition with one broken line	1.25
		Transient condition with one broken line	1.05
	Non-redundant	Intact	2.0
Survival Load Cases	Redundant or Non-redundant	Intact	1.05

Notes:

1 Safety factors are to be applied to the minimum breaking strength (MBS) of the mooring line or tendon.

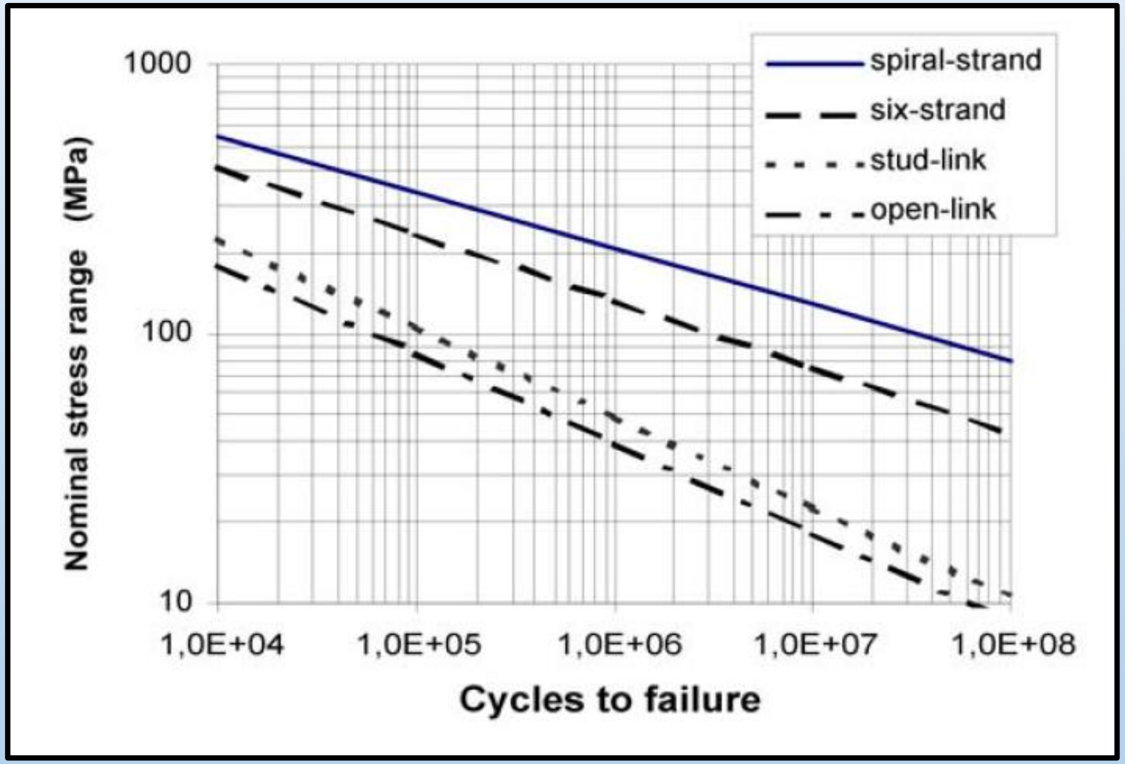
2 Additional strength design criteria for tendons made up of steel tubulars are to comply with API RP 2T.

3 Requirements of tendon minimum tension check are to comply with API RP 2T.

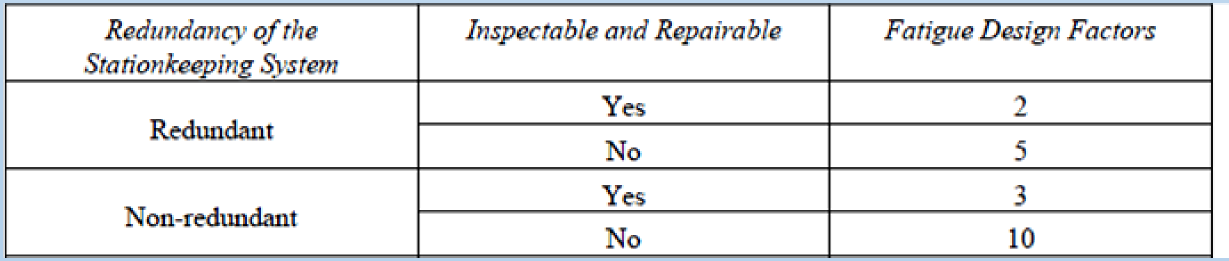
Rules and Regulations

Standard Based Design to Avoid Fatigue

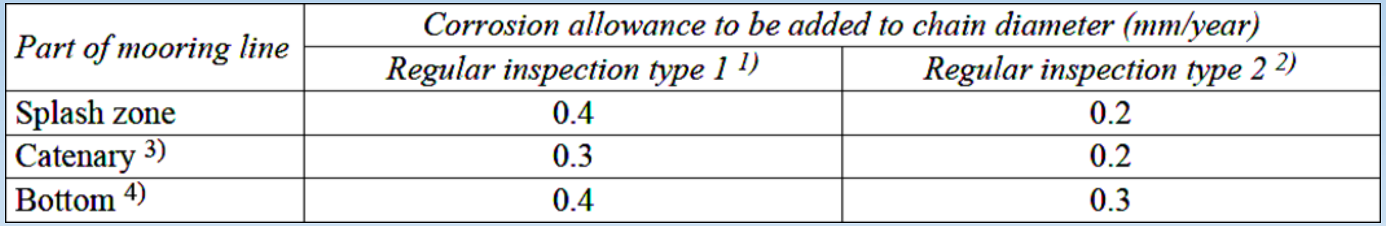
- S-N curves available in standards for mooring components/materials
- Many design standards recommend size corrosion/abrasion allowances for chain
    - Growing number of case studies show allowances are insufficient



Offshore Standard DNV-OS-E301. "Position Mooring," October, 2010.



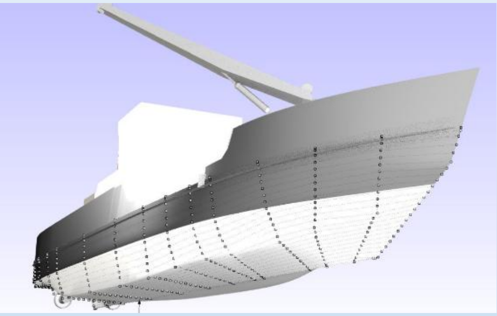
Redundancy of the Stationkeeping System	*Inspectable and Repairable*	*Fatigue Design Factors*
Redundant	Yes	2
	No	5
Non-redundant	Yes	3
	No	10

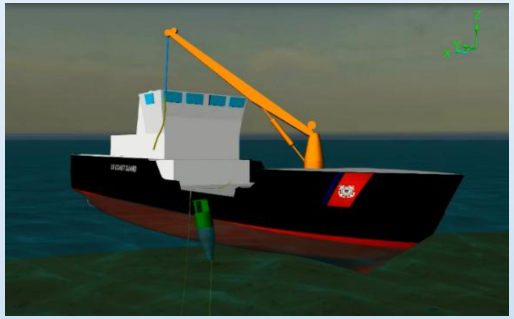


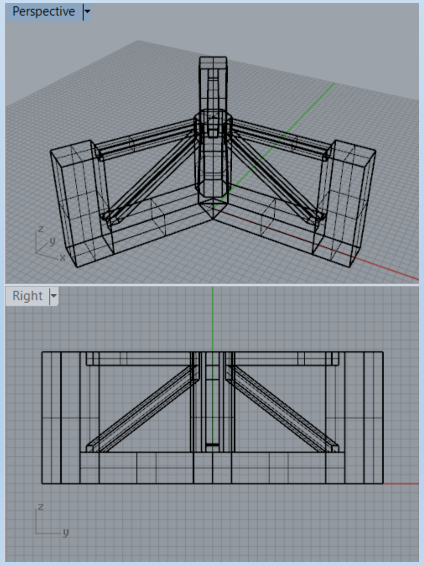
Part of mooring line	*Corrosion allowance to be added to chain diameter (mm/year)*	
	Regular inspection type 1 1)	*Regular inspection type 2 2)*
Splash zone	0.4	0.2
Catenary 3)	0.3	0.2
Bottom 4)	0.4	0.3

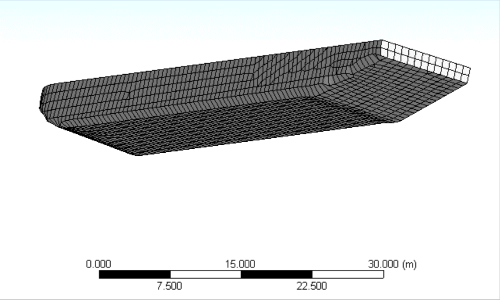
Modeling, Simulation, and Prediction
Stationkeeping Analysis: MMC Tools

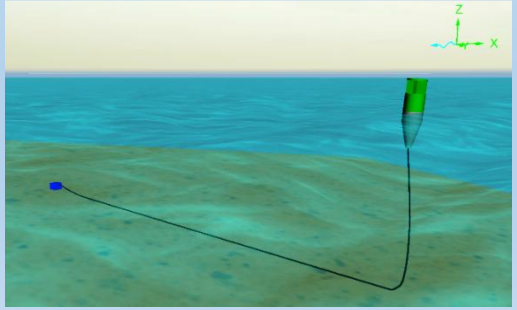
- CAD: Development of platform/hull model
- ANSYS-Aqwa
  - Radiation/Diffraction analysis in frequency domain
  - Determine wave loads, Response Amplitude Operators (RAOs) of platform/vessel
- NREL FAST
  - Analysis of turbine performance & loads in time domain
  - Quasi-static mooring line model
- Orcina OrcaFlex
  - Nonlinear finite element mooring model in time domain
  - Coupled with FAST for best analysis of FOWT hydrodynamics including platform, turbine, moorings











Inspection

- Goals: detect problems, evaluate remaining life (potential life extension)
- Maintenance
  - Retrieve & inspect critical components regularly
  - Rotate/replace chain links
- Inspection
  - Visual Inspection: high level inspection for significant & obvious damage, clean, identify areas of potential risk
  - Measurement: quantify corrosion, abrasion, other observed damage
  - 3D Modeling: assess remaining strength of components
- Monitoring equipment
  - Many floating systems: can’t tell if mooring is intact
  - Some mooring failures detected months after failure
  - Measurement options
    - Line tension measurement using load cells
    - Angle measurement using inclinometers
    - Position & heading measurement using Differential GPS

Allan et al. Mooring system life extension using subsea inspection technologies. OTC-24184, Houston, Texas, May 6-9, 2013.

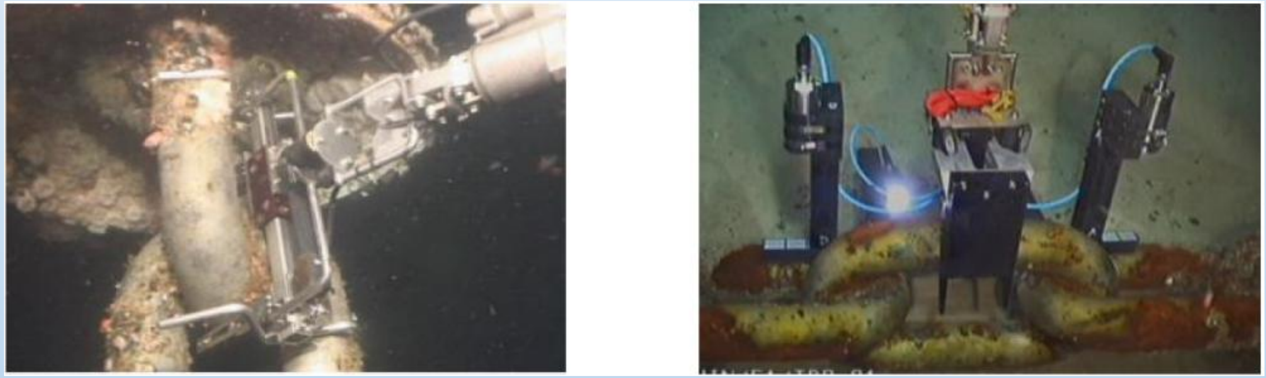


Figure 4-10: Model of studlink with severe corrosion

Figure 4-11: Standard chain link with loss of material

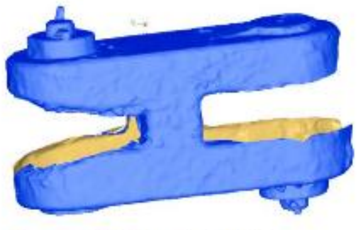


Figure 4-12: Standard H-link

Conclusions

- Mooring systems are underappreciated
- Design standards lack details
  - Corrosion/abrasion allowances
  - Affect of snap loads
  - Selecting environmental conditions
- Inspection needed to prevent failures
- Significant additional research needed
  - Cause of corrosion/abrasion
  - Selection of design load & survival conditions
  - Effect of snap loads on mooring integrity

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