ISFOG 2025

5TH
INTERNATIONAL
SYMPOSIUM ON
FRONTIERS IN
OFFSHORE
GEOTECHNICS

The 7TH ISSMGE McClelland Lecture: Learning from Offshore Field Performance

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9TH-13TH JUNE 2025
LA CITÉ NANTES CONGRESS CENTRE

HOW LUCKY CAN YOU GET?

API (AMERICAN PETROLEUM INSTITUTE) GEOTECHNICAL RESOURCE GROUP, OCTOBER 1993

October 28, 1993

Members, Geotechnical Resource Group:

MINUTES OF OCTOBER 18, 1993 API GEOTECHNICAL RESOURCE GROUP RG5

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Thank you to the first 6 ISSMGE McClelland Lecturers!

J.D. Murff

Met in 1990

M.F. Randolph

Met in 1993

K.H. Andersen

Met in 1994

A.G. Young

Met in 1993

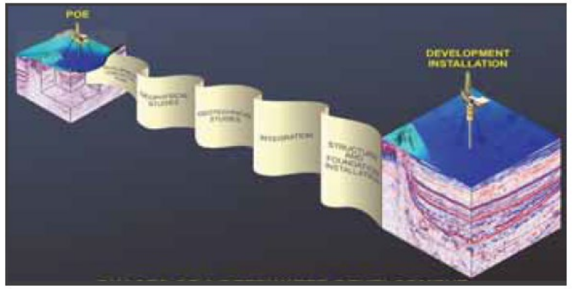
E.C. Clukey

Met in 1998

R.J. Jardine

Met in 1999

THE GOAL



In-situ site characterization

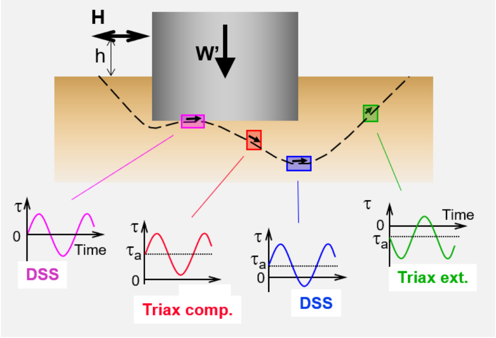
A. Young: 4th McClelland Lecture

Understanding the full potential of an integrated geoscience study

Laboratory Testing

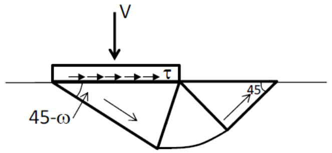
K.H. Andersen: 3rd McClelland Lecture

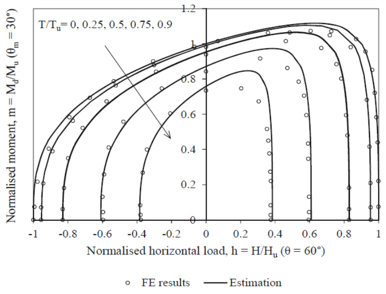
Cyclic soil parameters for offshore foundation design



Goal

Predict the field performance of the seafloor and full-size foundations under full-size loads





Numerical/Analytical Modeling

D. Murff: 1st McClelland Lecture

Estimating capacity of offshore foundations

M. Randolph: 2nd McClelland Lecture

Analytical contributions of offshore geotechnical engineering

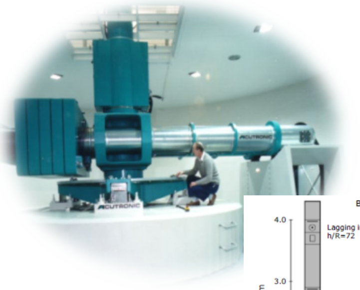
Physical Testing

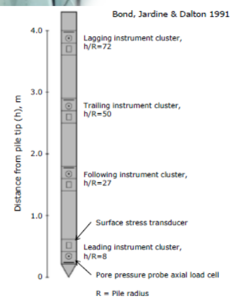
E. Clukey: 5th McClelland Lecture

The role of physical modeling in offshore geotechnical engineering

R. Jardine: 6th McClelland Lecture

Time-dependent vertical bearing behaviour of shallow foundations and driven piles





Content of written version of lecture

1. Deepwater submarine mass-movements with anthropogenic (man-made) triggers
2. The Valhall 2002 pile buckling incident
3. Performance of anchors and piles during hurricanes at the ALS (Accidental Limit State):
   - Floating structures: drag anchors, VLAs, suction piles, and torpedo anchors
   - Fixed structures: free-standing caisson and jacket foundations driven piles
4. Performance of foundations at the SLS (Serviceability Limit State):
   - Magnus foundation monitoring in North Sea during a winter storm
5. Performance of foundations at the FLS (Fatigue Limit State):
   - Tripods, deepwater drilling riser systems

Content of oral version of lecture

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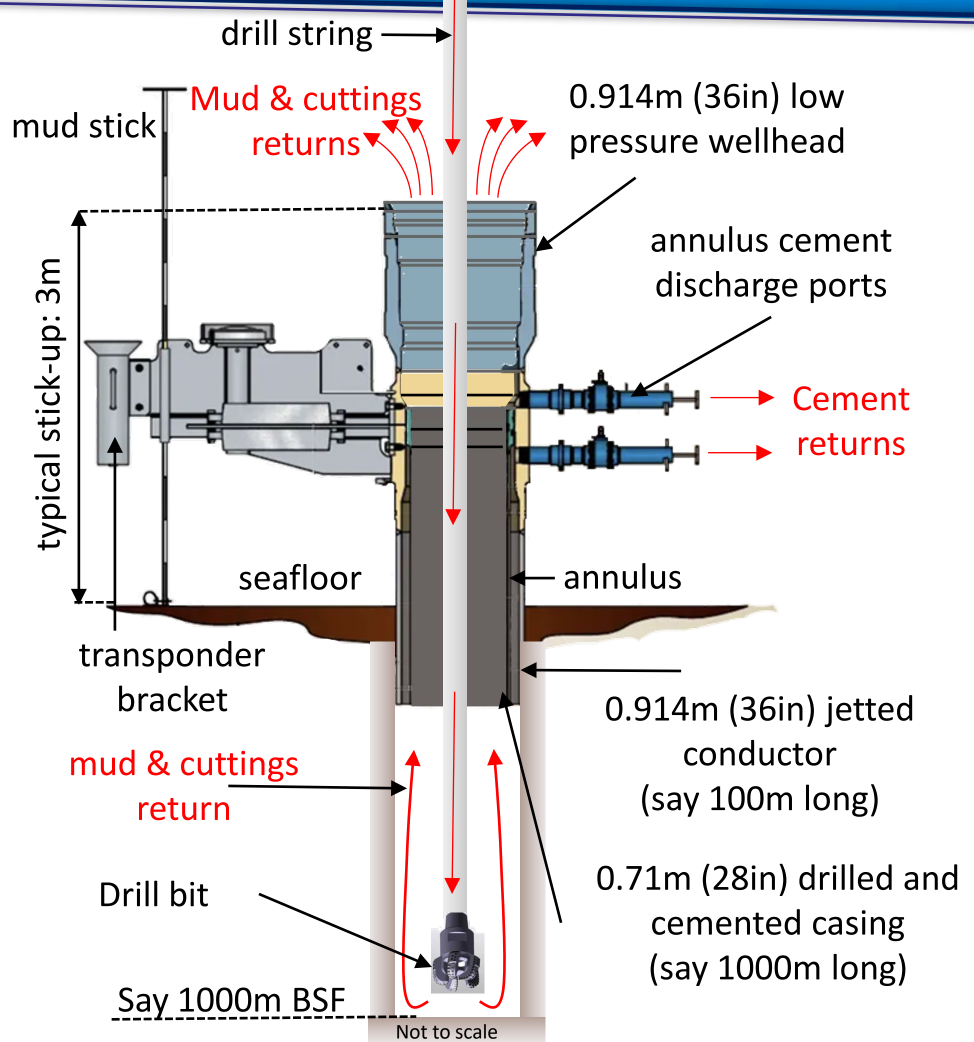
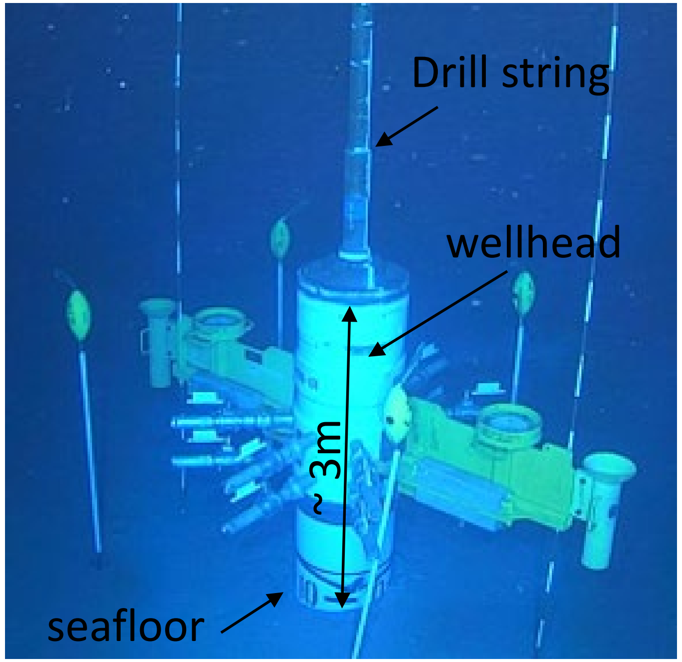
OFFSHORE GEOHAZARDS AND SUBMARINE MASS MOVEMENTS:

OPEN LITERATURE ENTIRELY FOCUSED (ALMOST) ON NATURAL TRIGGERS

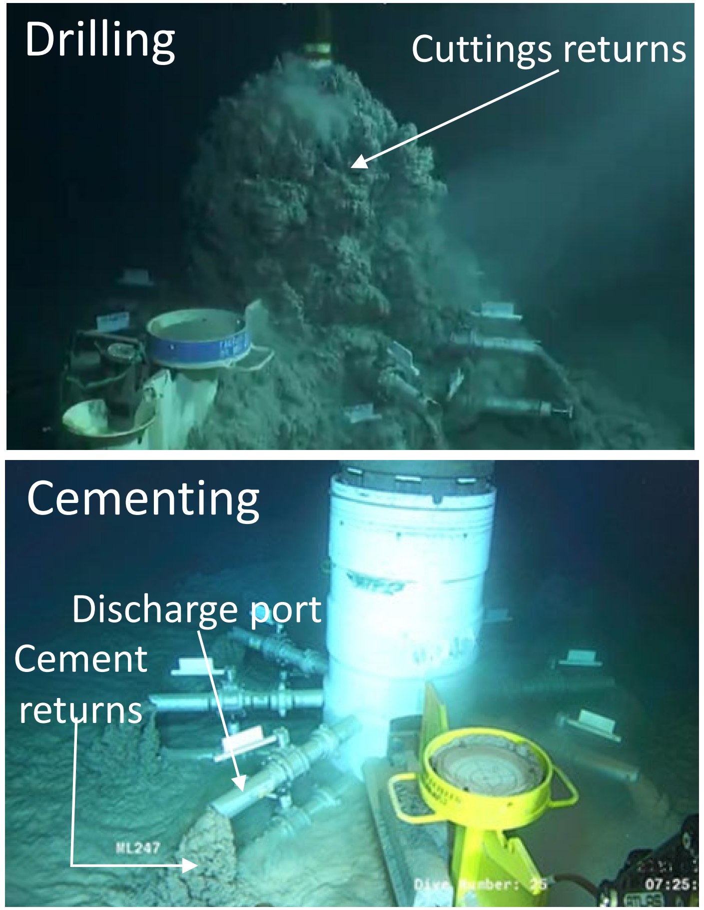
ANTHROPOGENIC (MAN-MADE) OFFSHORE TRIGGERS

DEEPWATER RISERLESS OPEN-HOLE DRILLING: PUMP AND DUMP (SOILS ARE TOO SOFT TO USE RISER AND BOP)



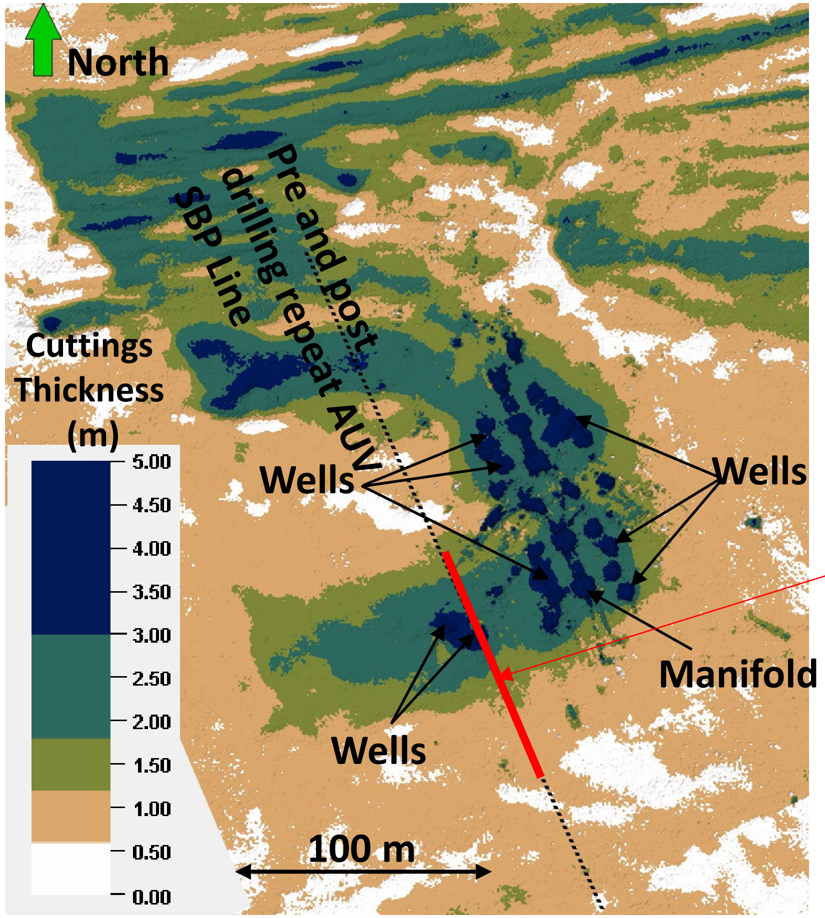


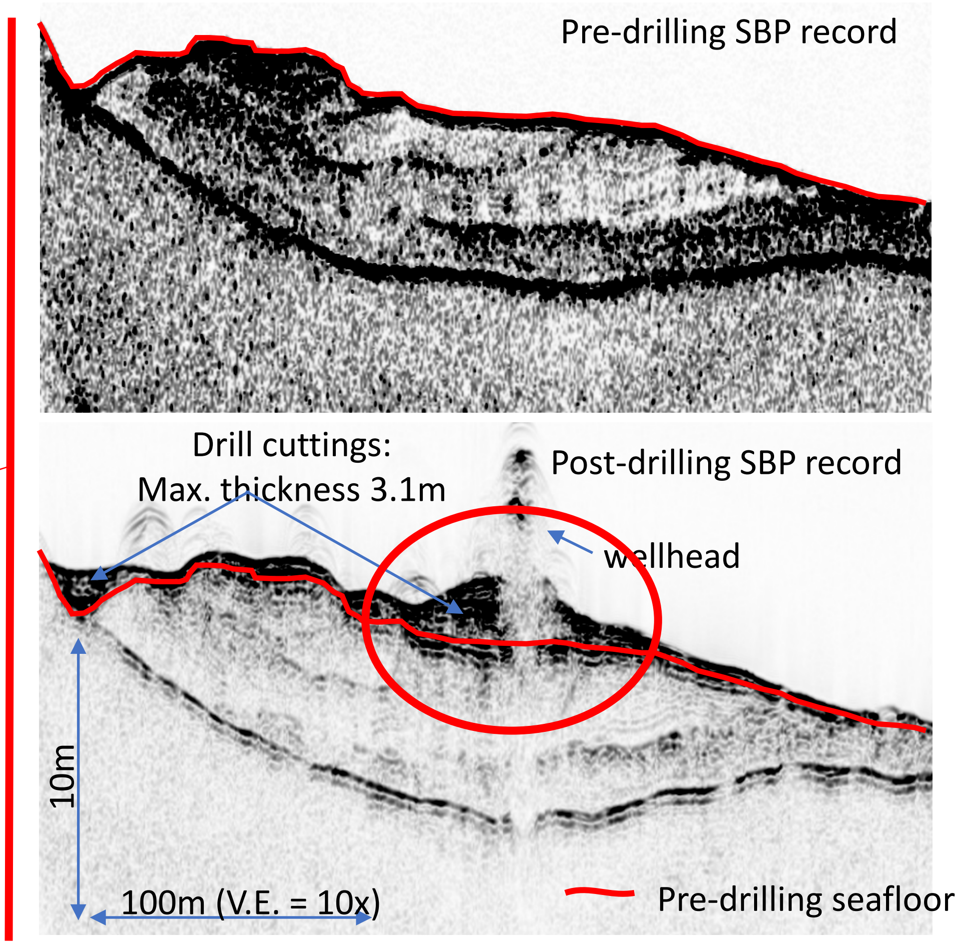
Typical low-pressure wellhead system in deepwater



Thickness of drill cuttings & cement: up to 3m

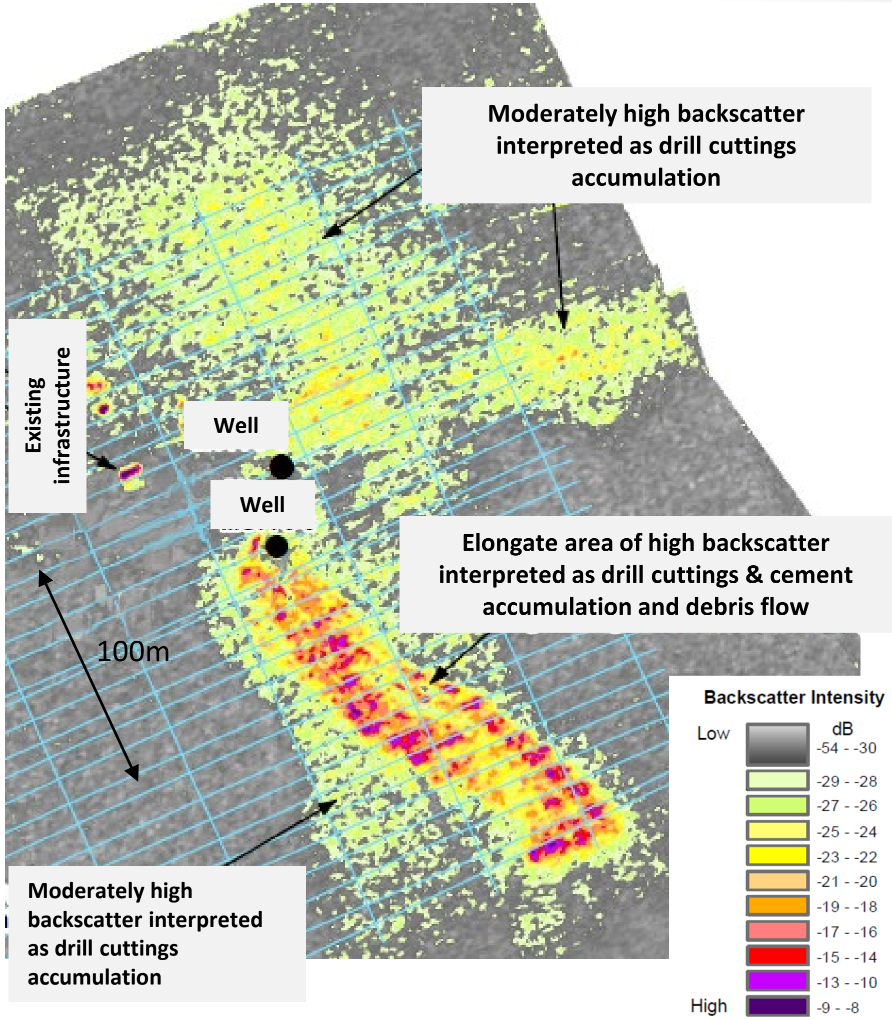
imaged with pre and post-drilling AUV surveys (bathymetry and sub-bottom profiler (SBP) data)

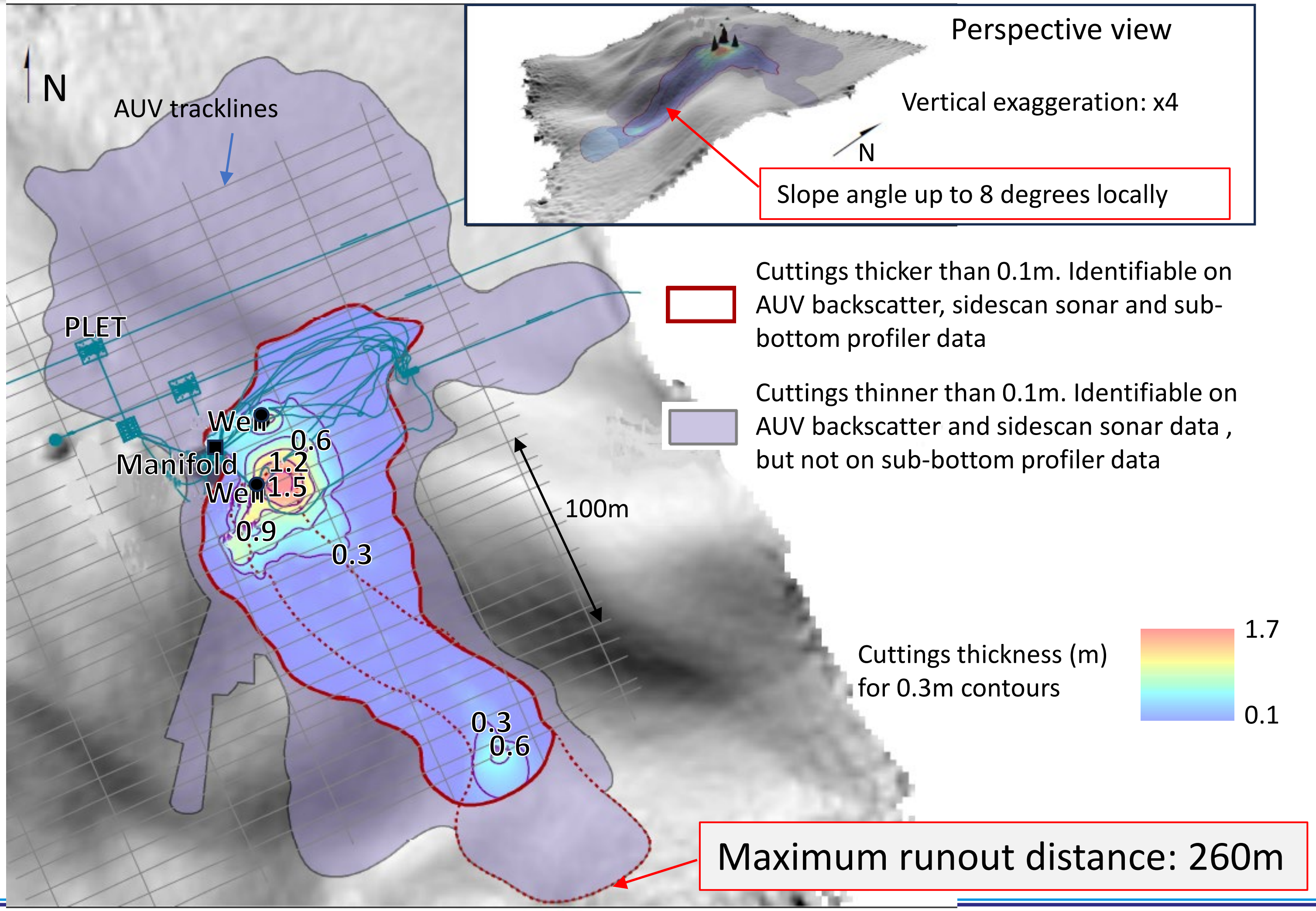




MASS MOVEMENT WITH ANTHROPOGENIC TRIGGER:

CUTTINGS ACCUMULATION CAUSES DEBRIS FLOW





Deepwater mass movement with anthropogenic trigger:

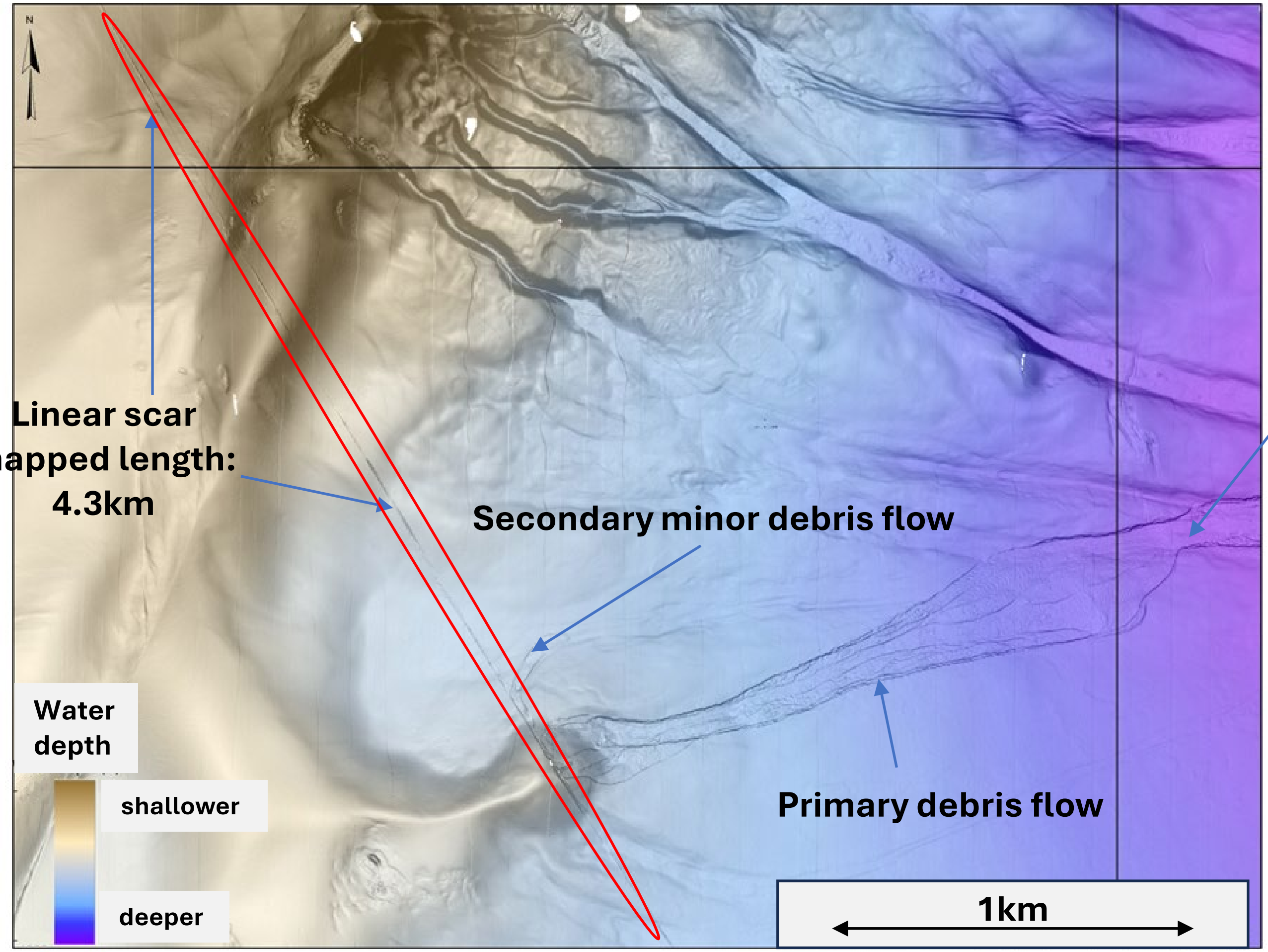
Event captured on ROV (Remotely Operated Vehicle) video

DEEPWATER MASS MOVEMENT WITH ANTHROPOGENIC TRIGGER:

EVENT CAPTURED ON ROV VIDEO – SLOW MOTION

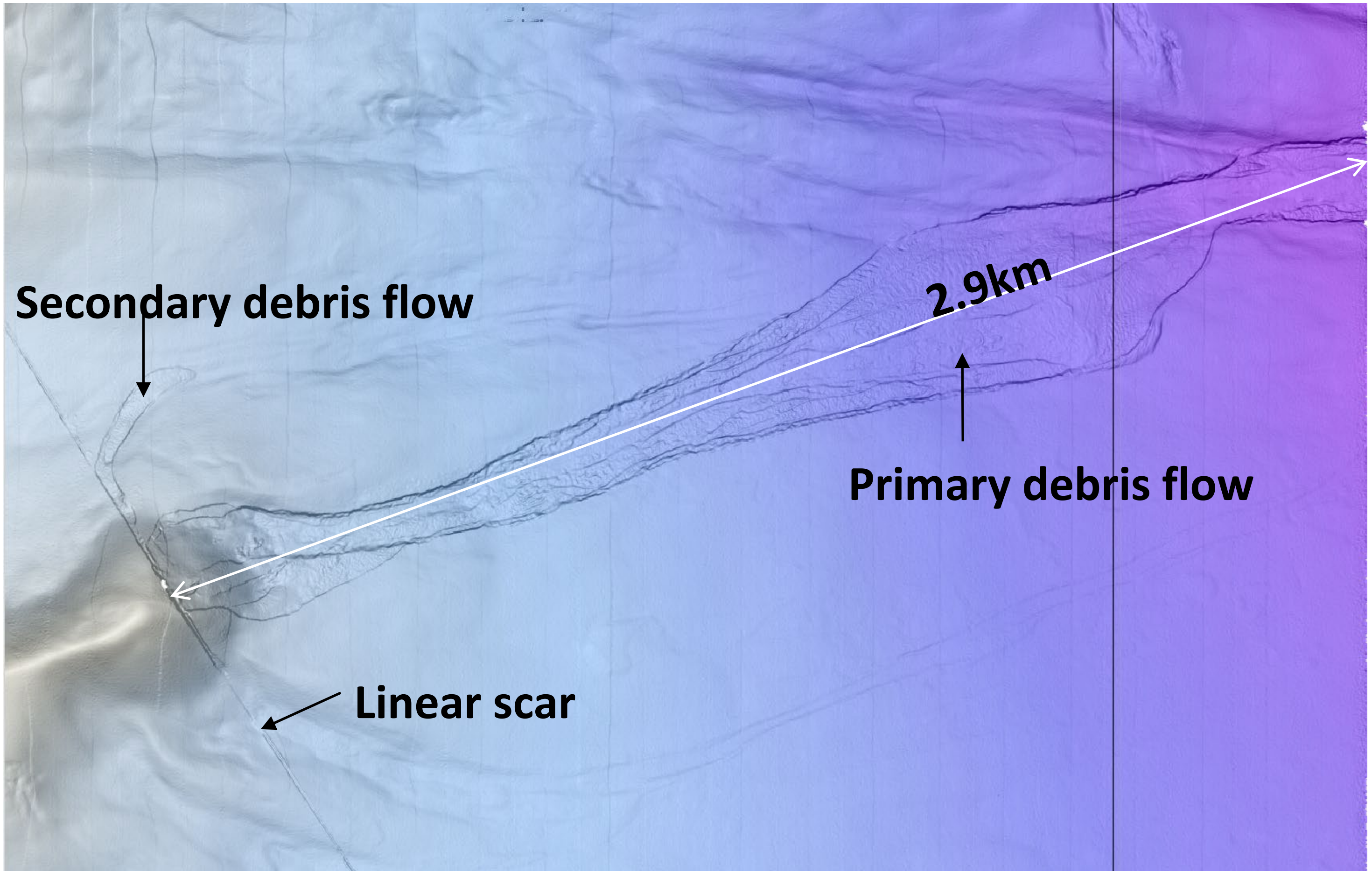
Seafloor instability with anthropogenic trigger

Bathymetry from AUV survey



SEAFLOOR INSTABILITY WITH ANTHROPOGENIC TRIGGER

HEADWALL OF SLIDES COINCIDES WITH LINEAR SCAR



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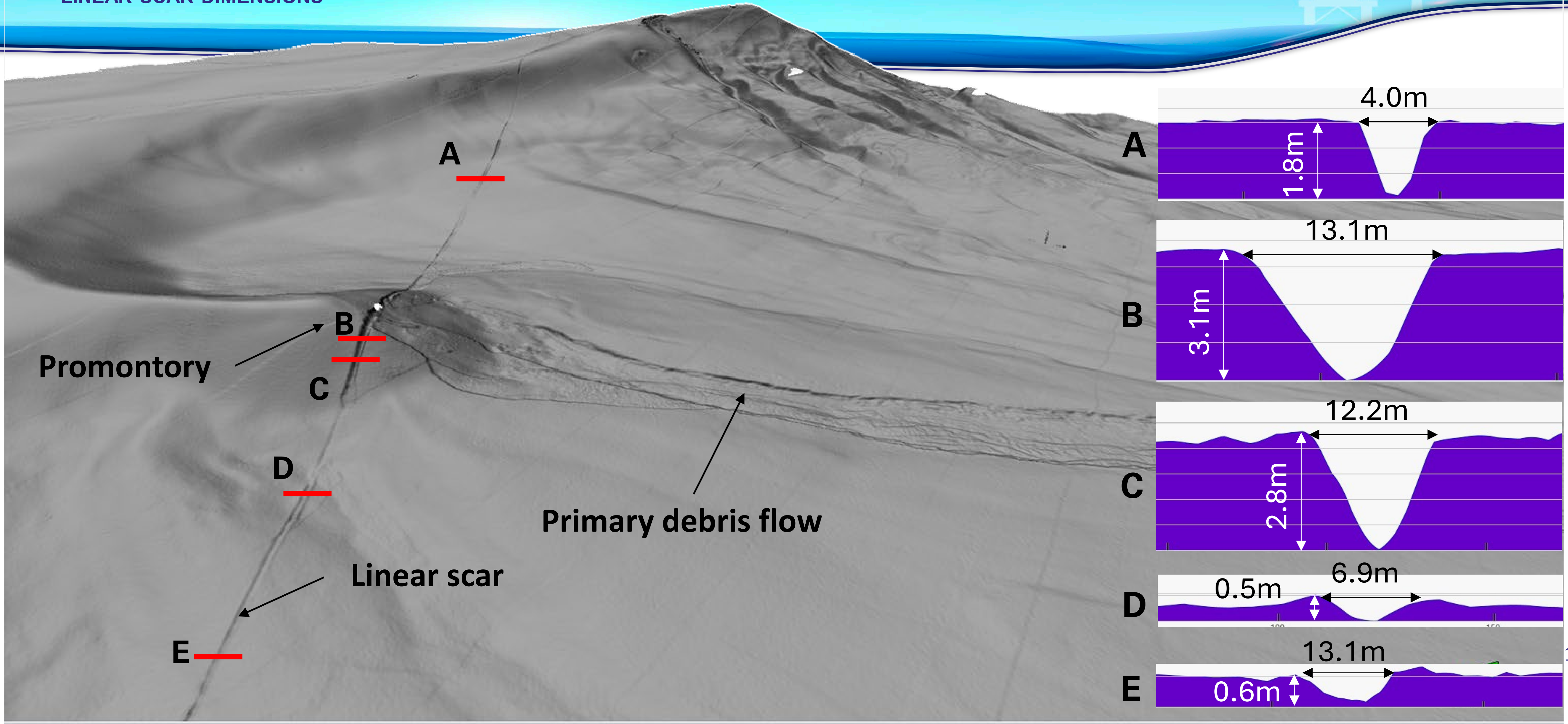
Seafloor instability with anthropogenic trigger

LINEAR SCAR DIMENSIONS



Potential anthropogenic triggers

1. 2001 3D bathymetry data strongly suggest, albeit not conclusively, that the two debris flows were not present in 2001, making them less than 24years old.
2. Potential triggers include:
   - The laying of a cable or fiber optic line : scar is too deep and too wide
   - The dragging of a survey sled during a deep-tow geophysical survey: scar is too deep and too wide
   - The dragging of a pipeline bundle sled during a bottom-towed installation: no records could be located and the well-known tow route is well outside are of interest.
   - The dragging of a drilling rig anchor after the rig broke its mooring, lost position, and drifted during a hurricane.

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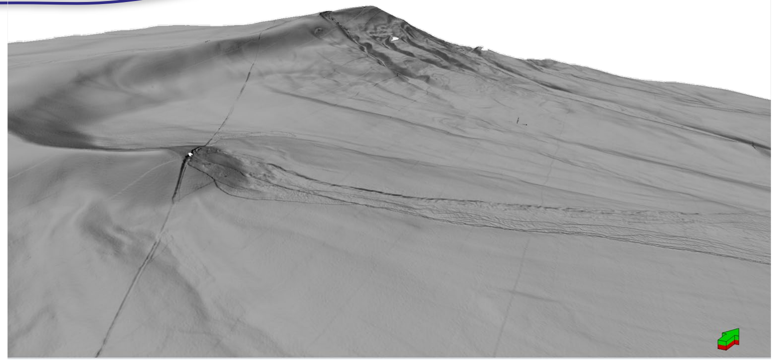
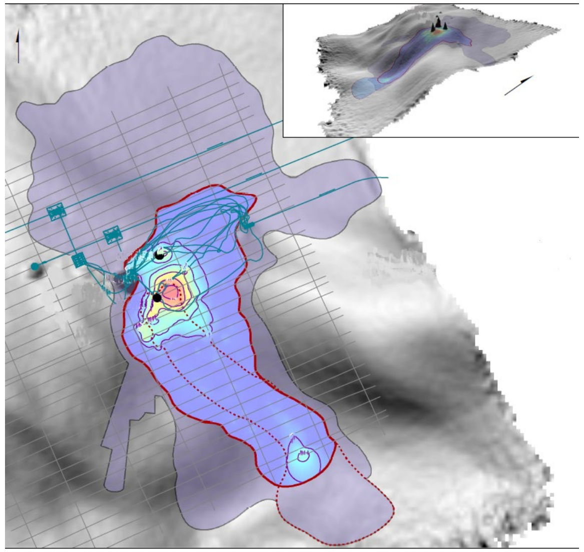
PERFORMANCE OF SEAFLOOR UNDER ANTHROPOGENIC TRIGGERS

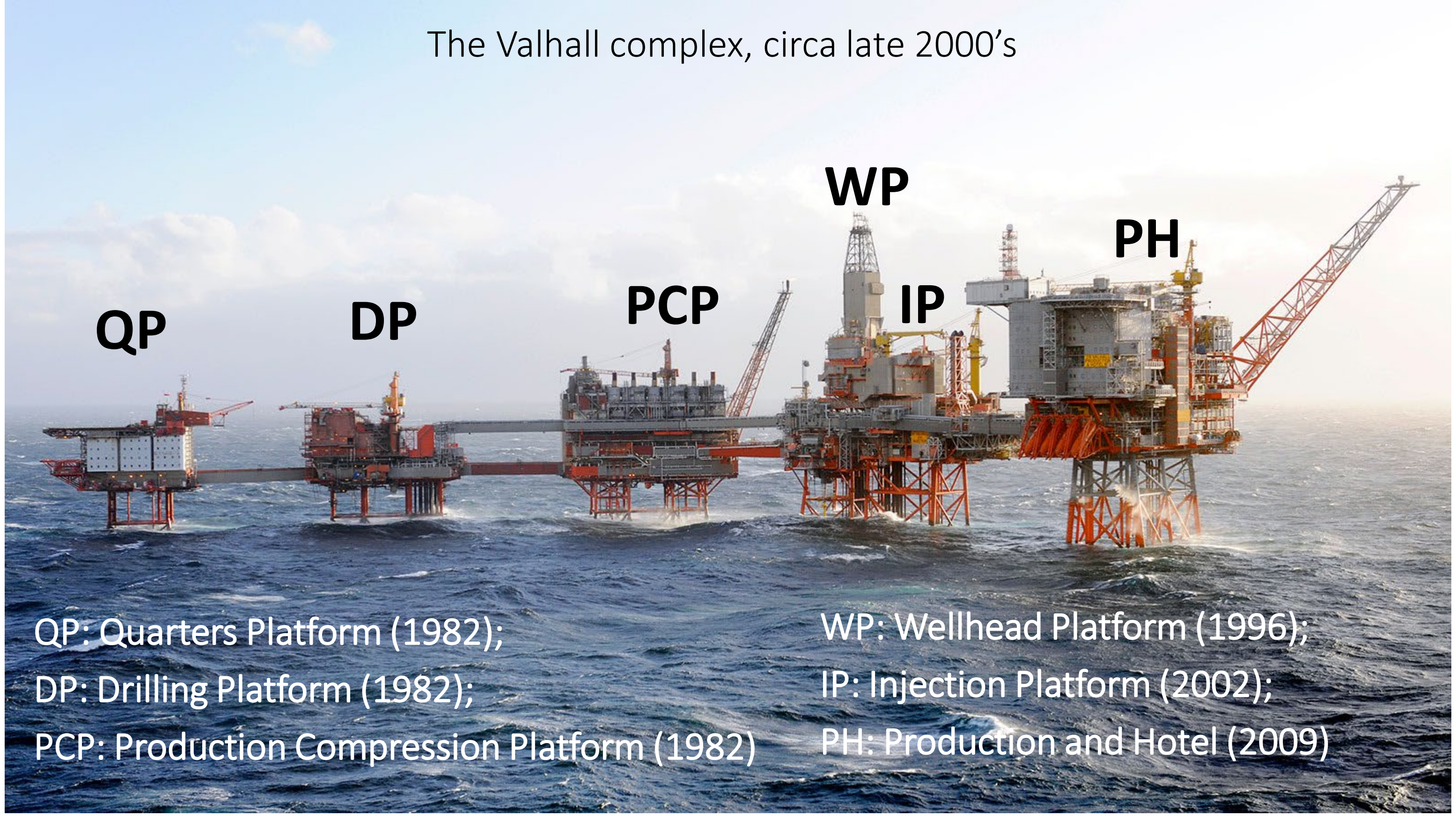
SUMMARY

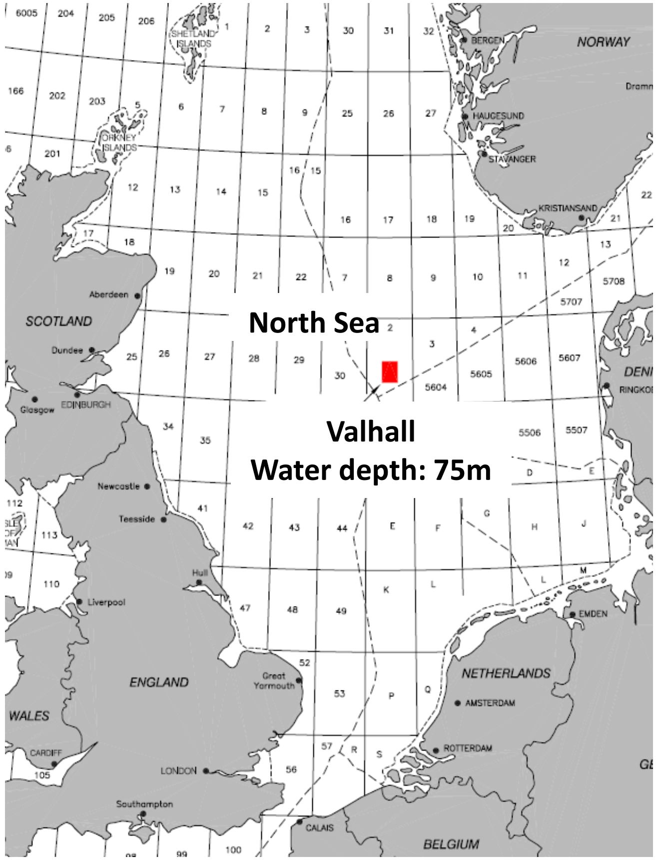


1. Case records of deepwater mass movements with anthropogenic triggers are under-represented in the literature
2. Such triggers include:
   - Accumulations of drilling cuttings near wellhead
   - Dragging of objects on the seafloor
3. Application to new energy projects include:
   - Carbon capture projects can involve drilling offshore wells for CO_2 gas storage
   - Offshore floating wind projects will include laying numerous cables on seafloor, potentially in deepwater soft sediments on steep slopes



THE VALHALL IP PILE REFUSAL 2002 EVENT





The Valhall IP pile refusal 2002 event

We =

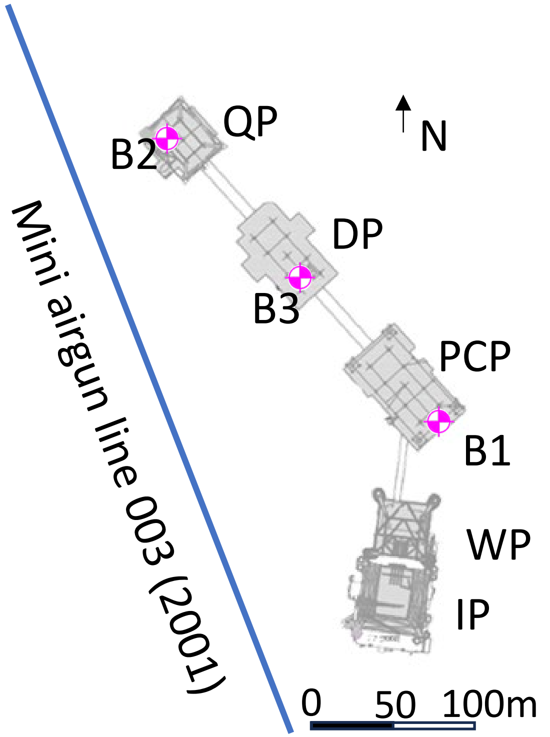
One of more individuals from one or more of the following entities (in alphabetical order);

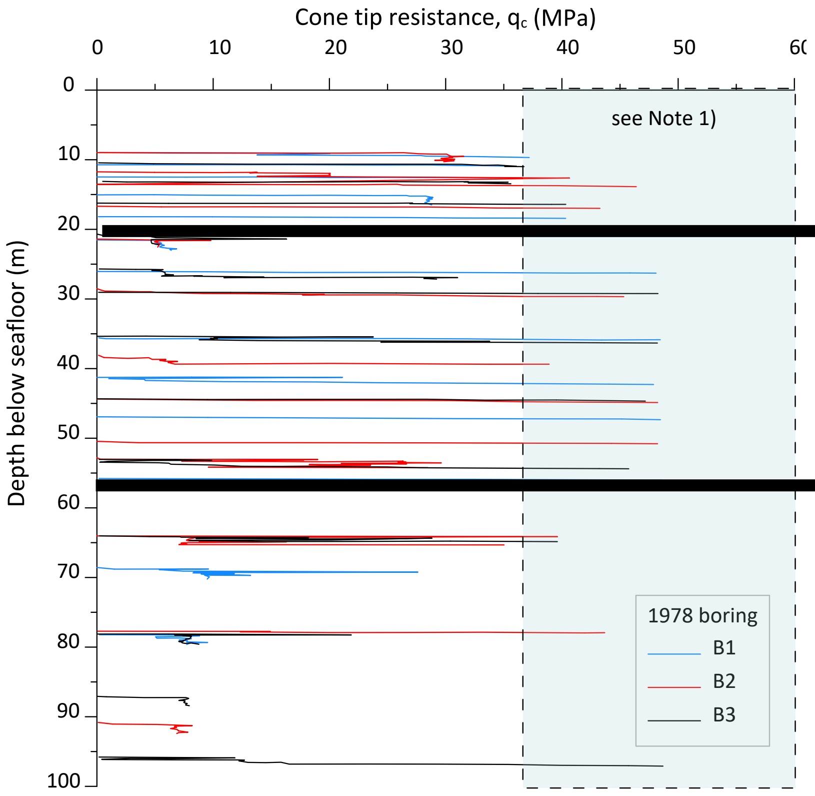
Aker Maritime, Aker Kvaerner, Aker Stord, Advanced Geomechanics, Arup Energy, BP Amoco, Det norsk Veritas (DnV), Fugro Ltd, GCG, Geo Survey AS, Heerema Marine Contractors, Imperial College, Norwegian Geotechnical Institute (NGI), Norwegian University of Science and Technology (NTNU), Rowan Drilling Inc., Seacore Ltd., Sintef, Saipem, the University of Western Australia (UWA) and many individual consultants.

Contributions are acknowledged globally.

VALHALL 1978 CPTS AND GROUND MODEL

FOUNDATION ZONE AFFECTED BY 2 GLACIATIONS





Note: 1) All q_c values greater than 37 MPa were measured at CPT refusal.
They do not represent actual in-situ values.

Formation	Description
Forth	Dense to very dense fine to medium sand. Gravel can occur
Fisher	Hard to very hard silty clays interbedded with dense to very dense sands
Ling Bank	Predominantly very hard silty clays with occasional very dense sand layers

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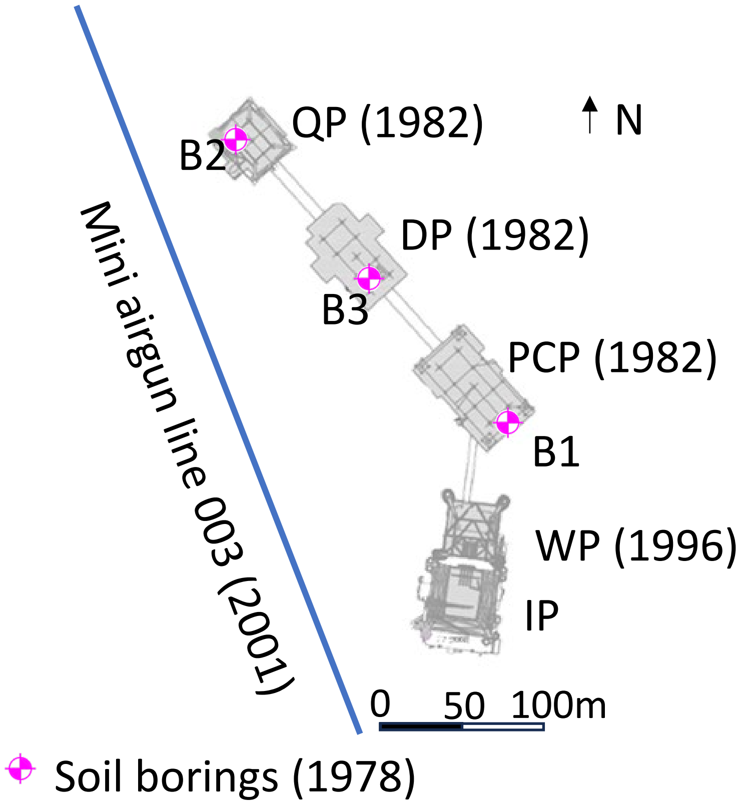
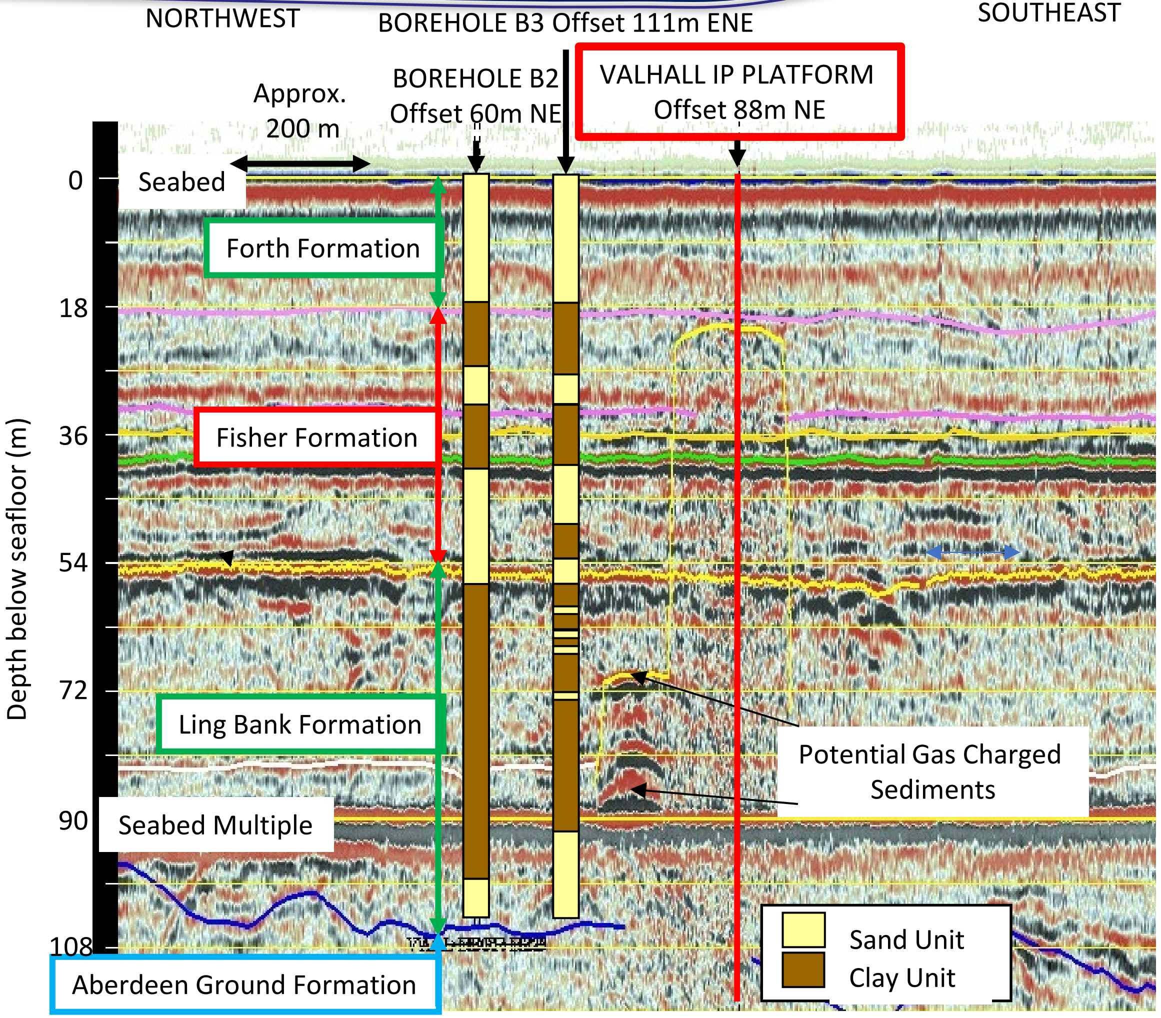
Geophysical tie line from 1978 boreholes to IP location

Stratigraphy is continuous w/o channels

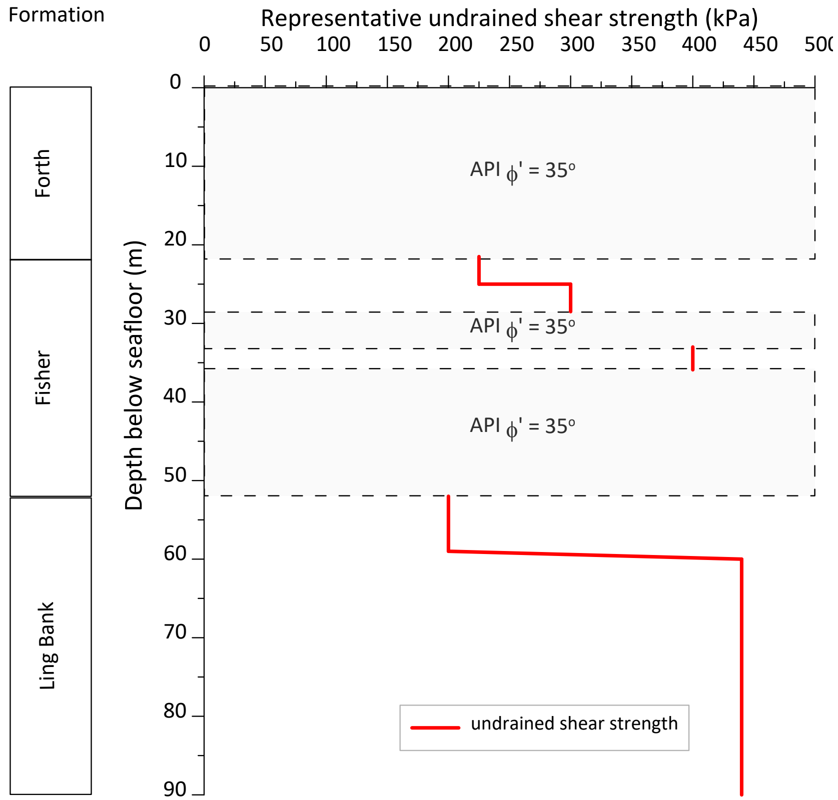


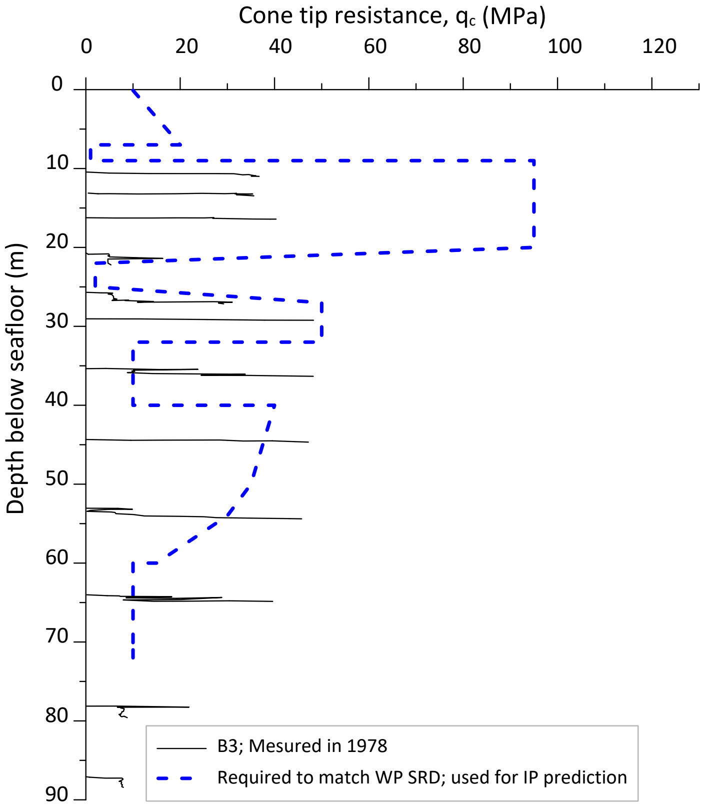


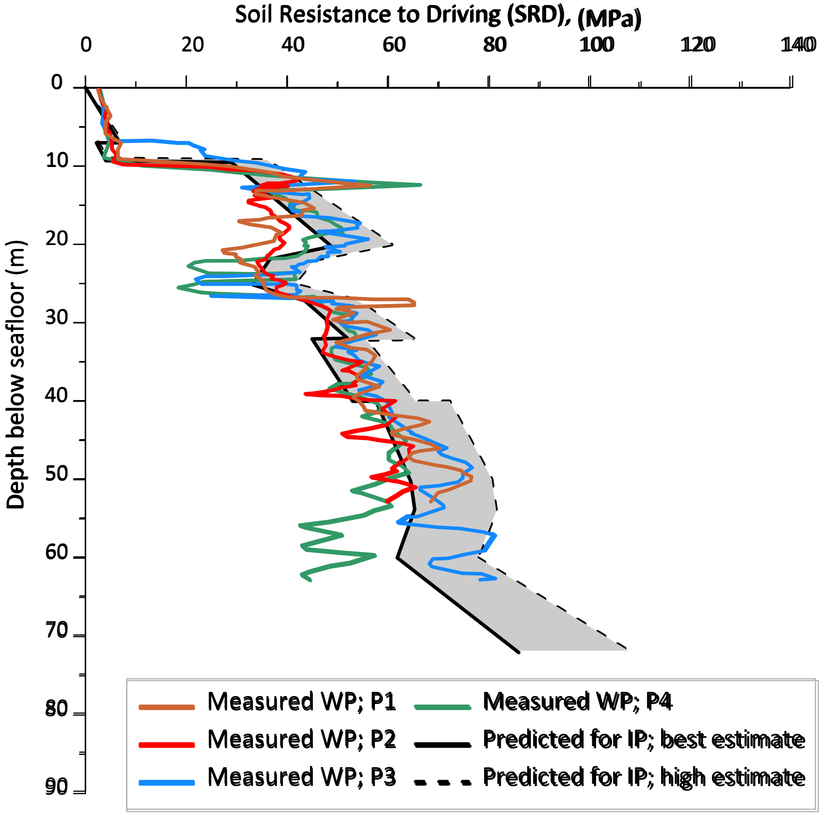
Calibration of WP SRD and predictions for IP

Soil Resistance to Driving (SRD) predicted with the Alm & Hamre (2001) method

- Pile capacity calculated with API RP2A (1993)

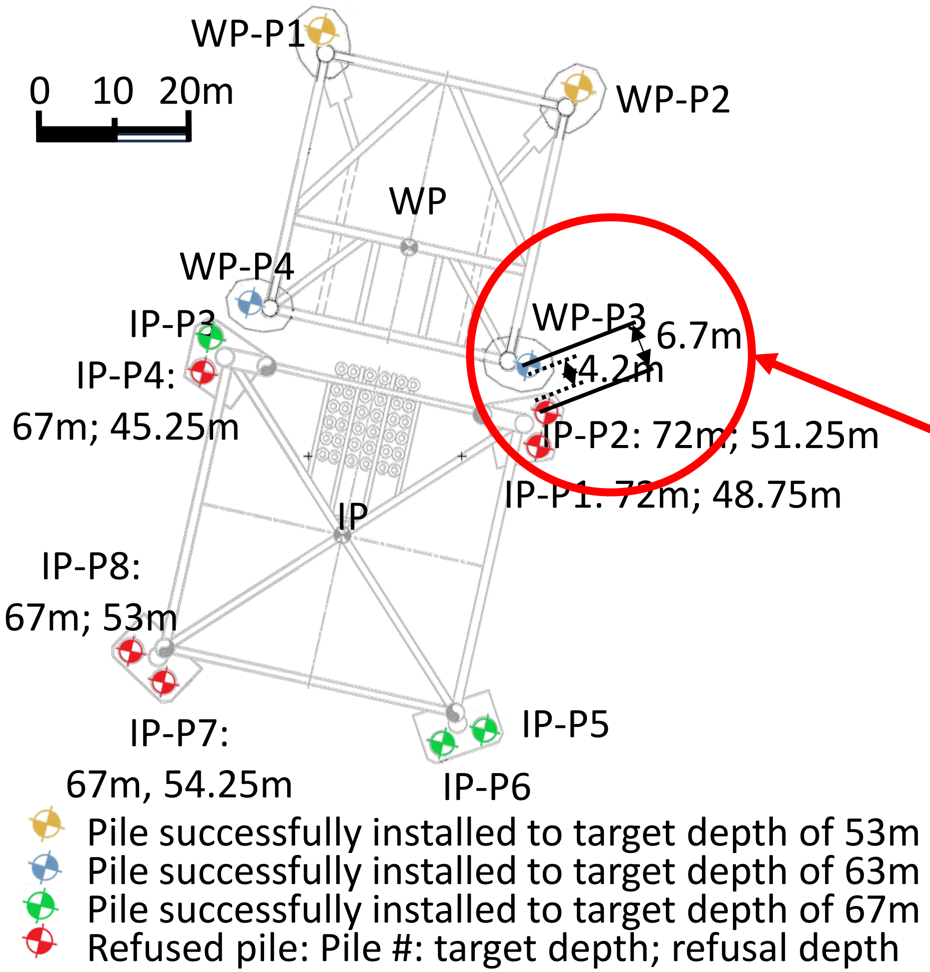


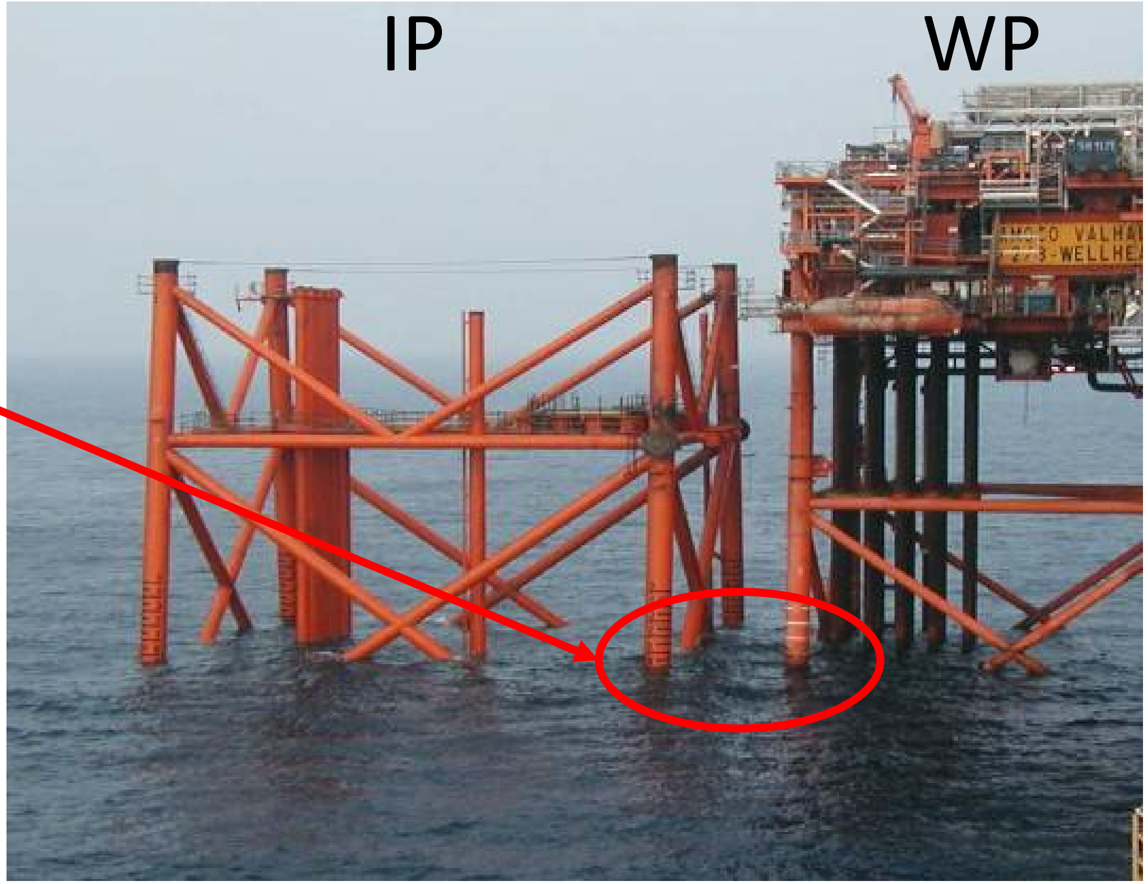




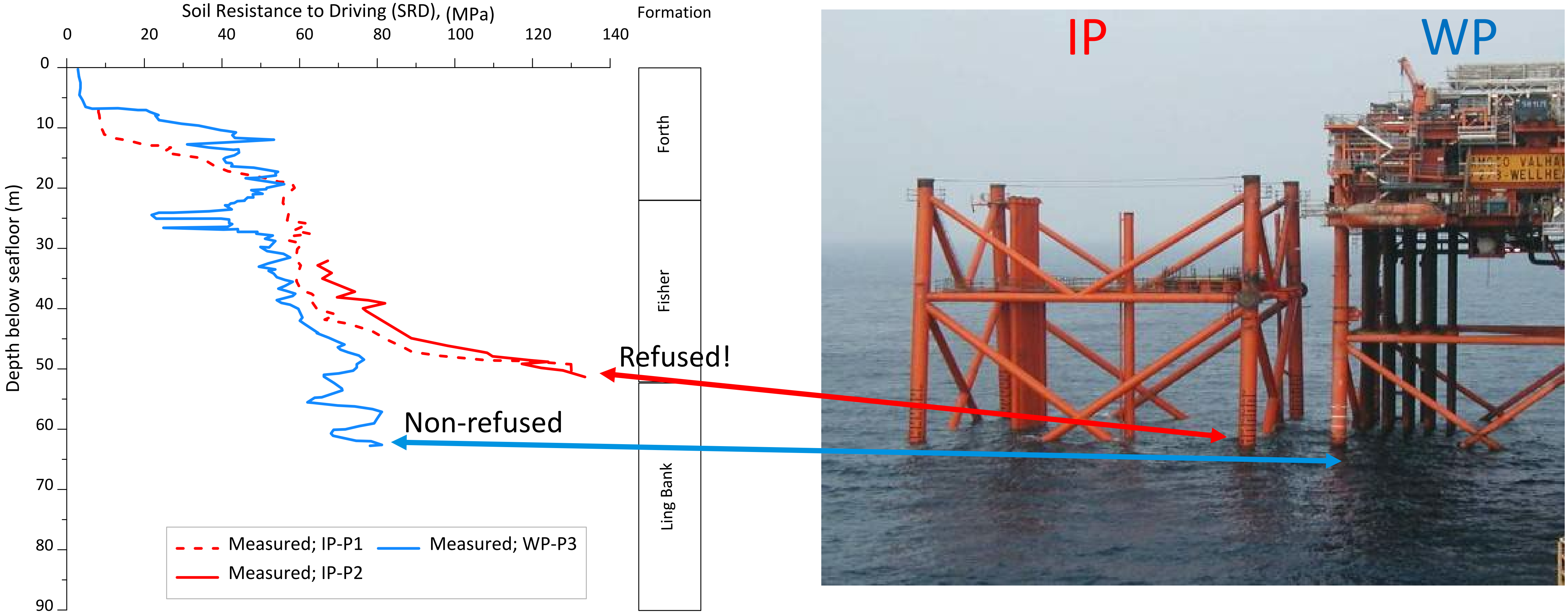
IP PILES INSTALLATION: 5 OUT OF 8 PILES REFUSED

13M TO 23M SHORT OF TARGET PENETRATION



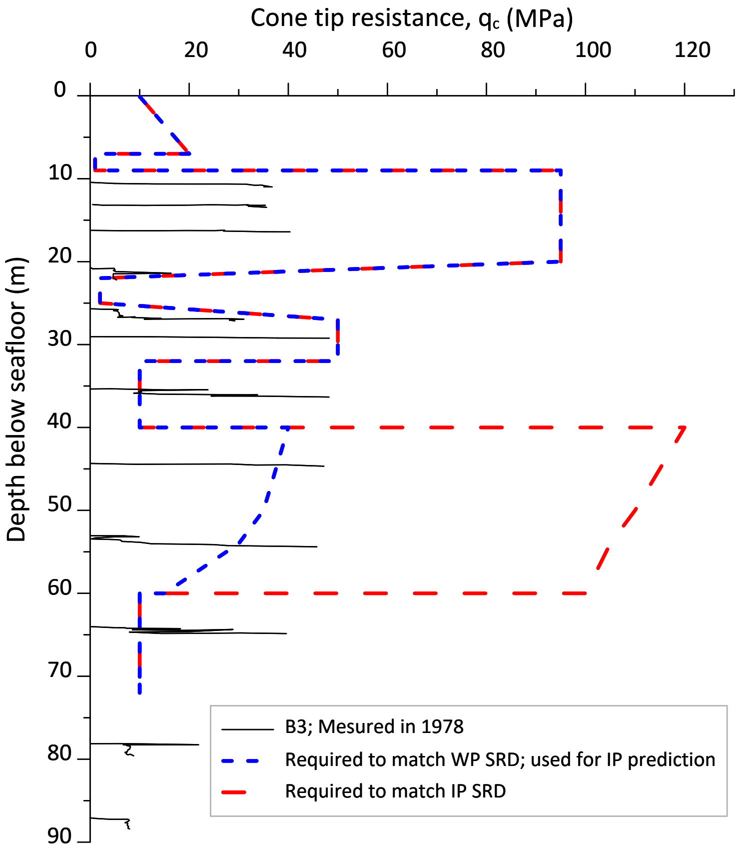


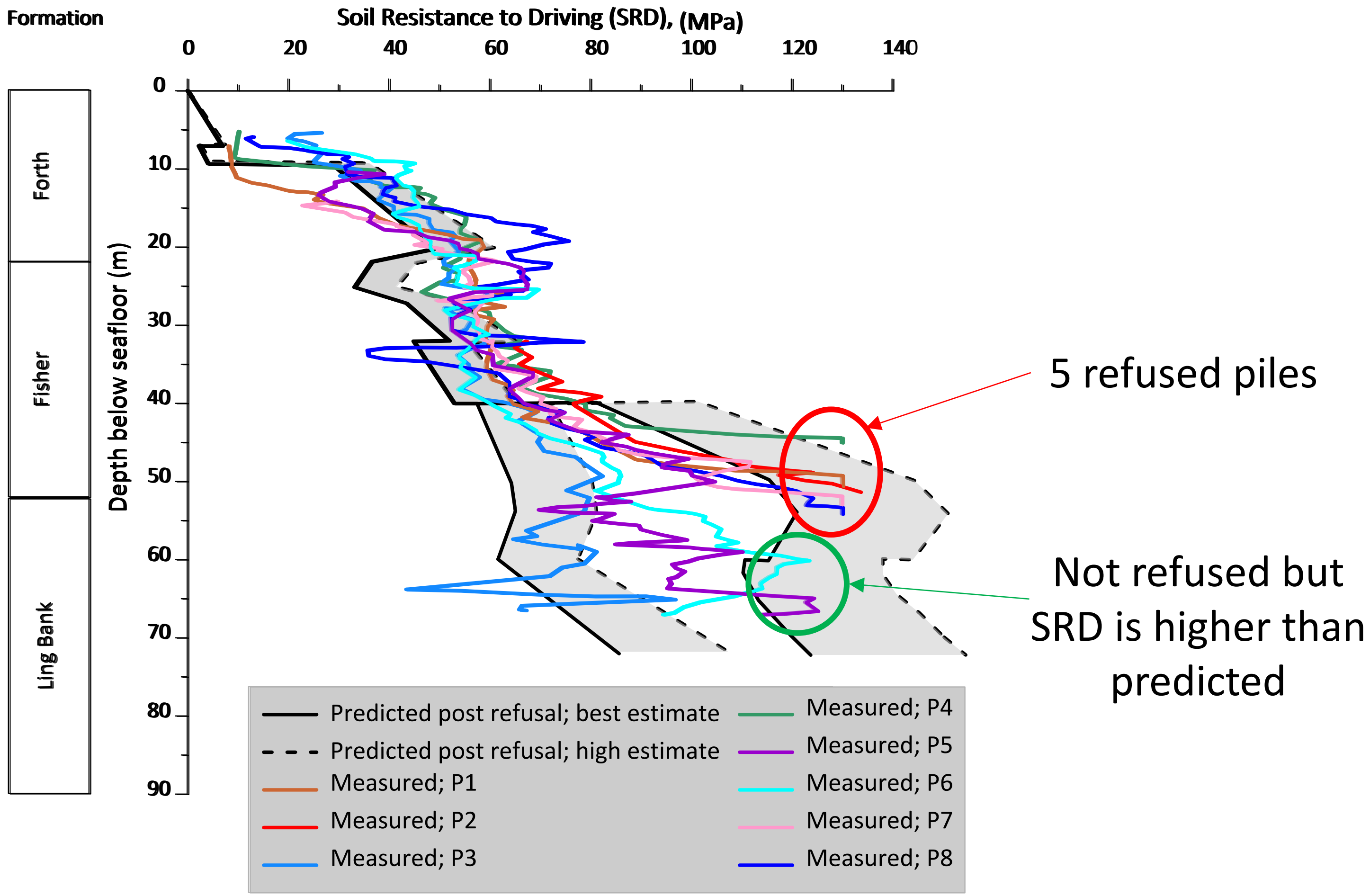
IP vs WP SRD: same diameter piles; only 4m apart!



Higher CPT values required to match recorded IP SRD

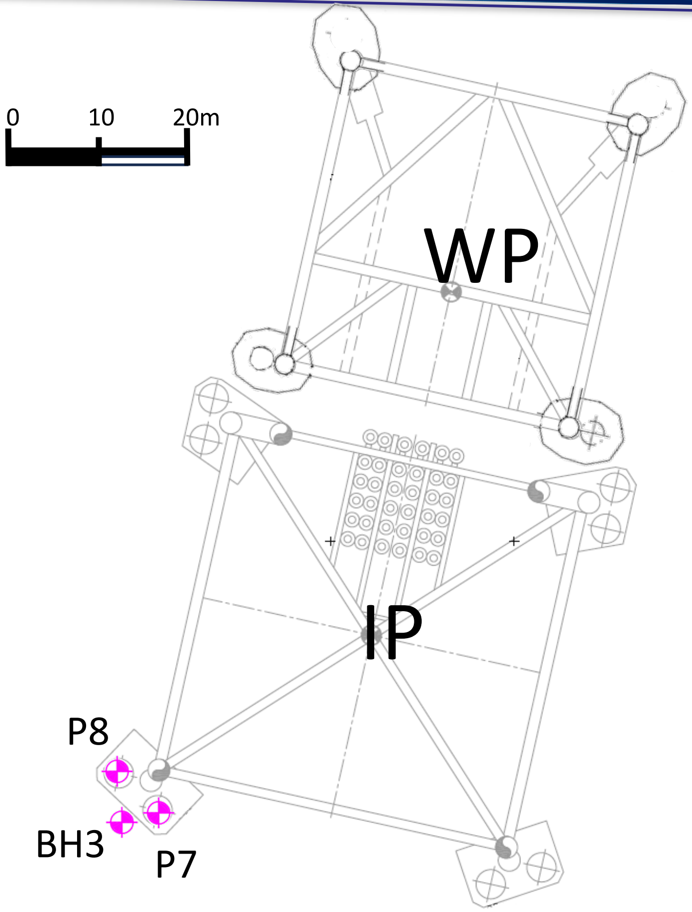
Alm & Hamre (2001) method used



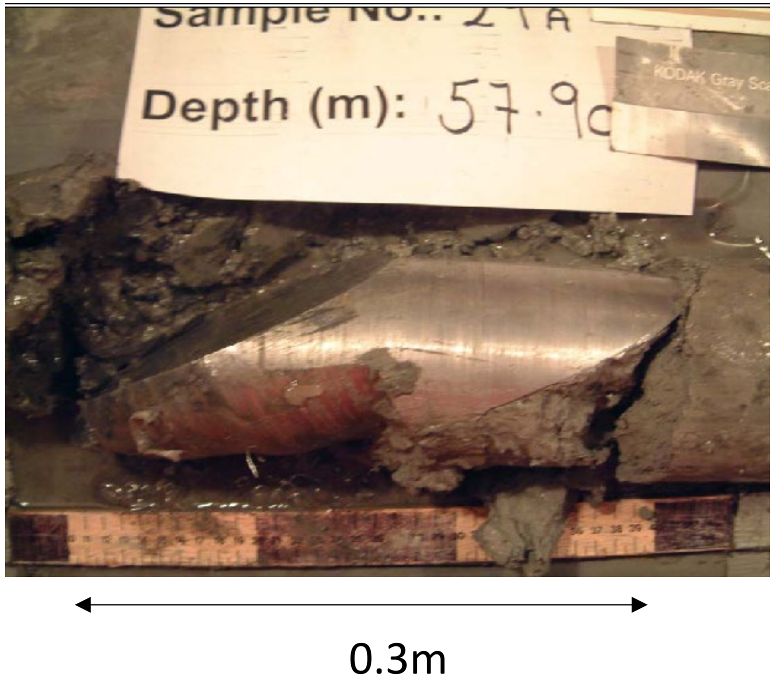


INVESTIGATION WITH JACK-UP RIG

NO UNUSUAL SOIL CONDITIONS (E.G. CEMENTED LAYERS, BOULDERS) ENCOUNTERED BUT CORED THROUGH THE BUCKLED PILE!



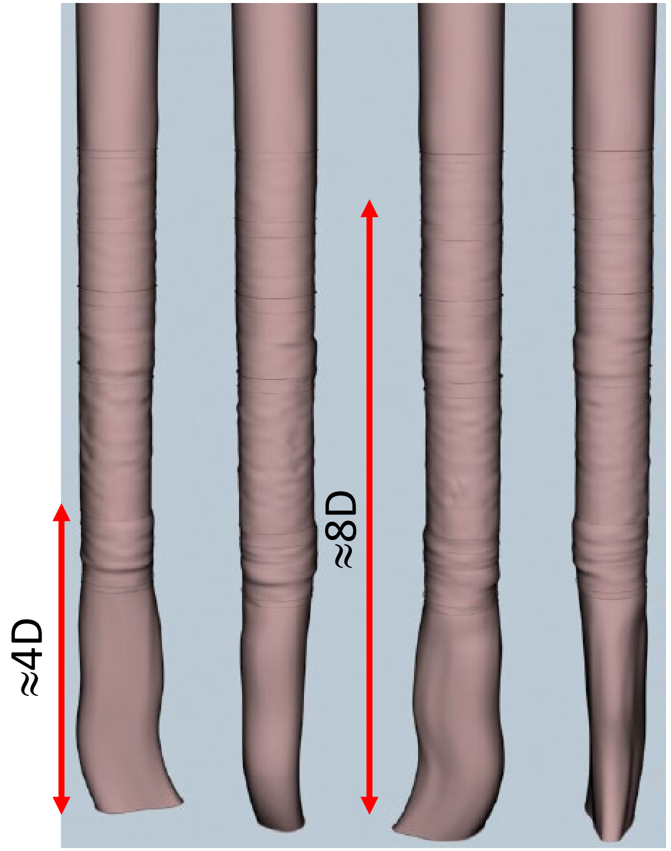
Borings performed from jack-up

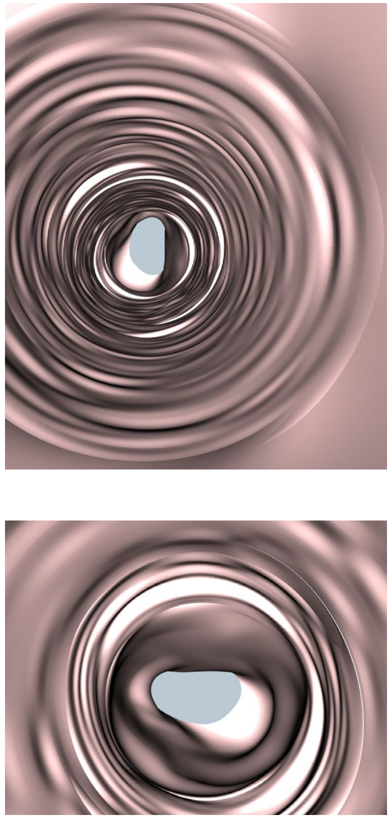


Section of pile from borehole drilled in the center of refused pile P7

IMAGING OF BUCKLED PILES WITH DOWNHOLE SONAR

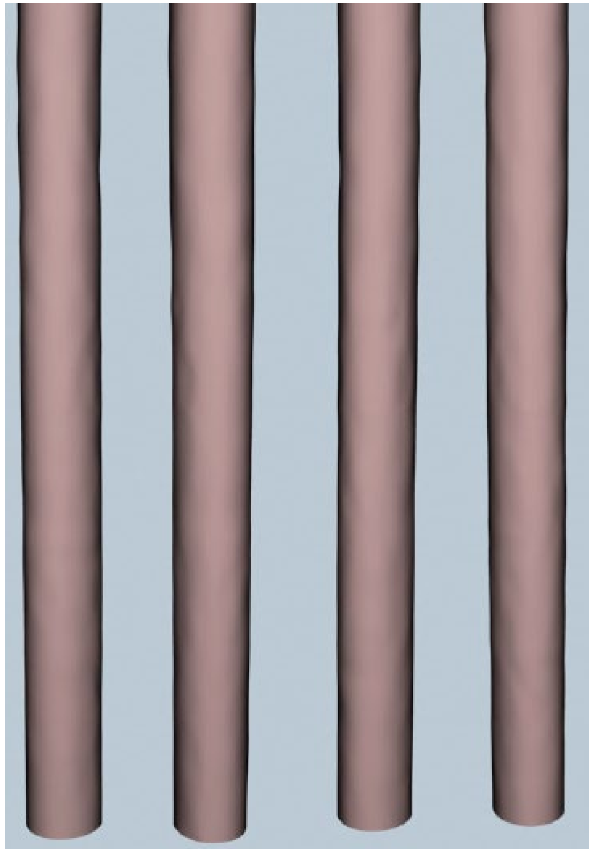
Pile P7: highly deformed section in bottom 4D

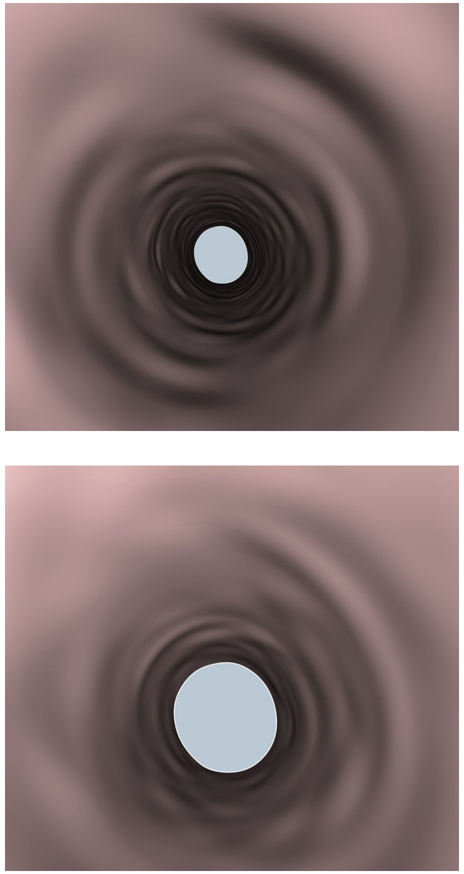




Front Left Back Right

Pile P8: buckled in last 0.5D (from video camera)





Front Left Back Right

IMAGING OF BUCKLED PILES WITH DOWNHOLE SONAR

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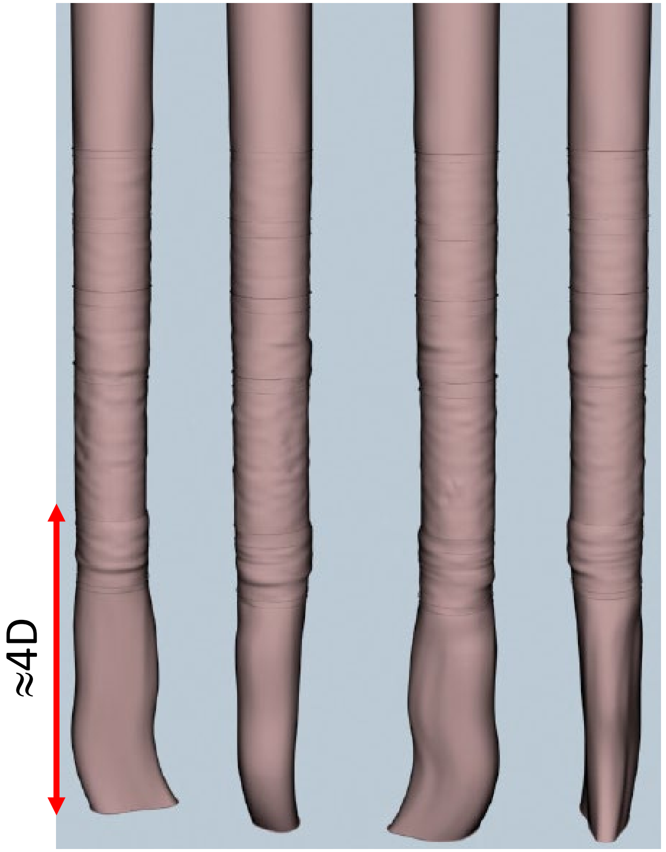
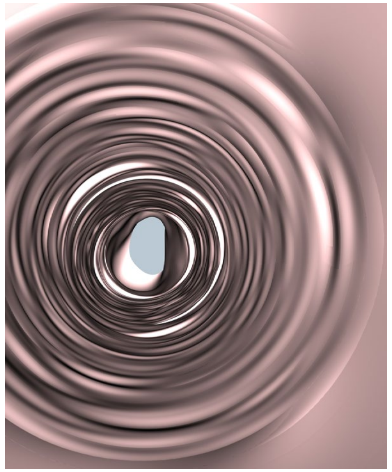
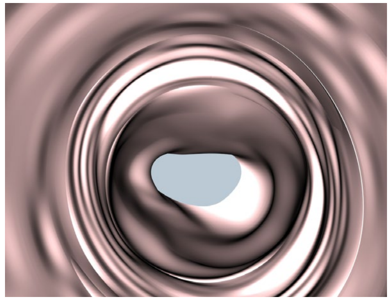
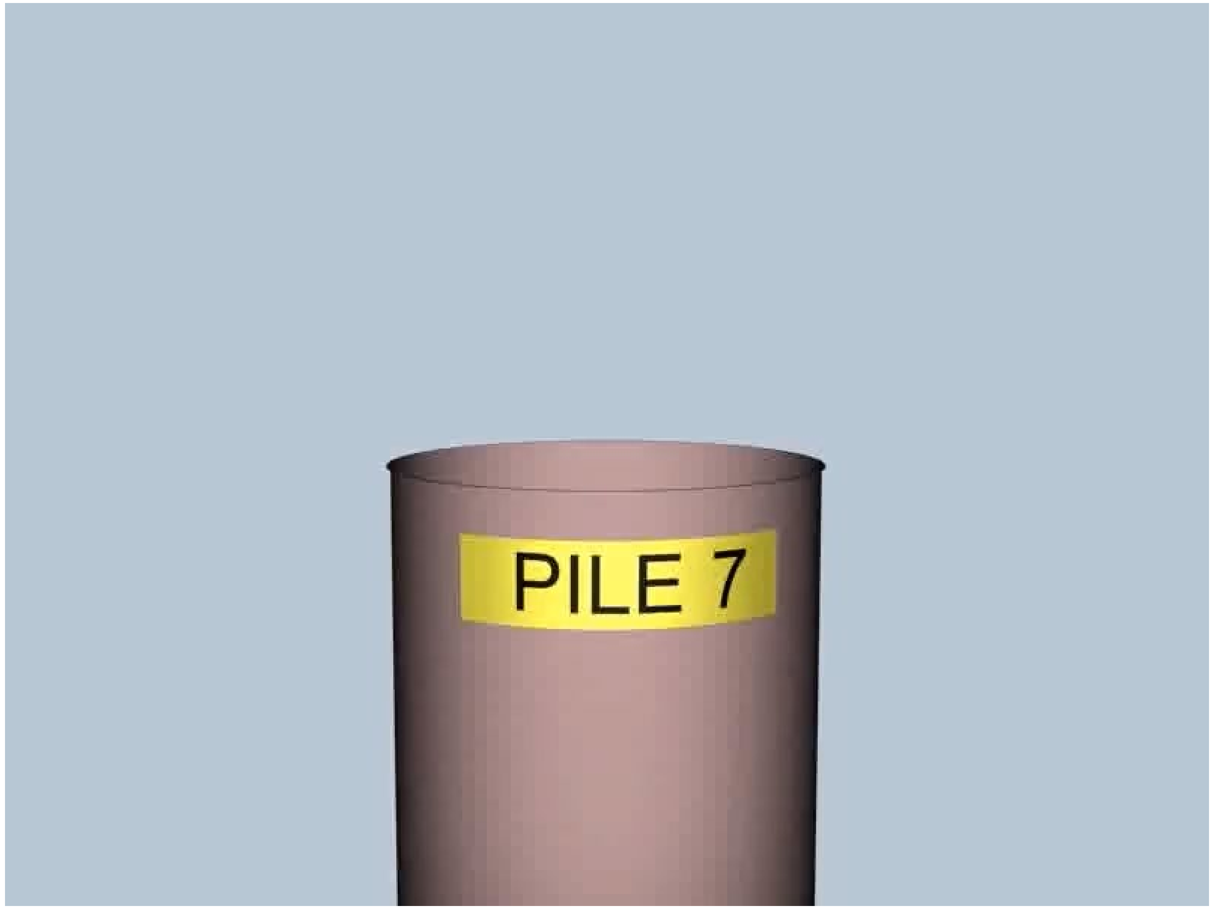


Front Left Back Right





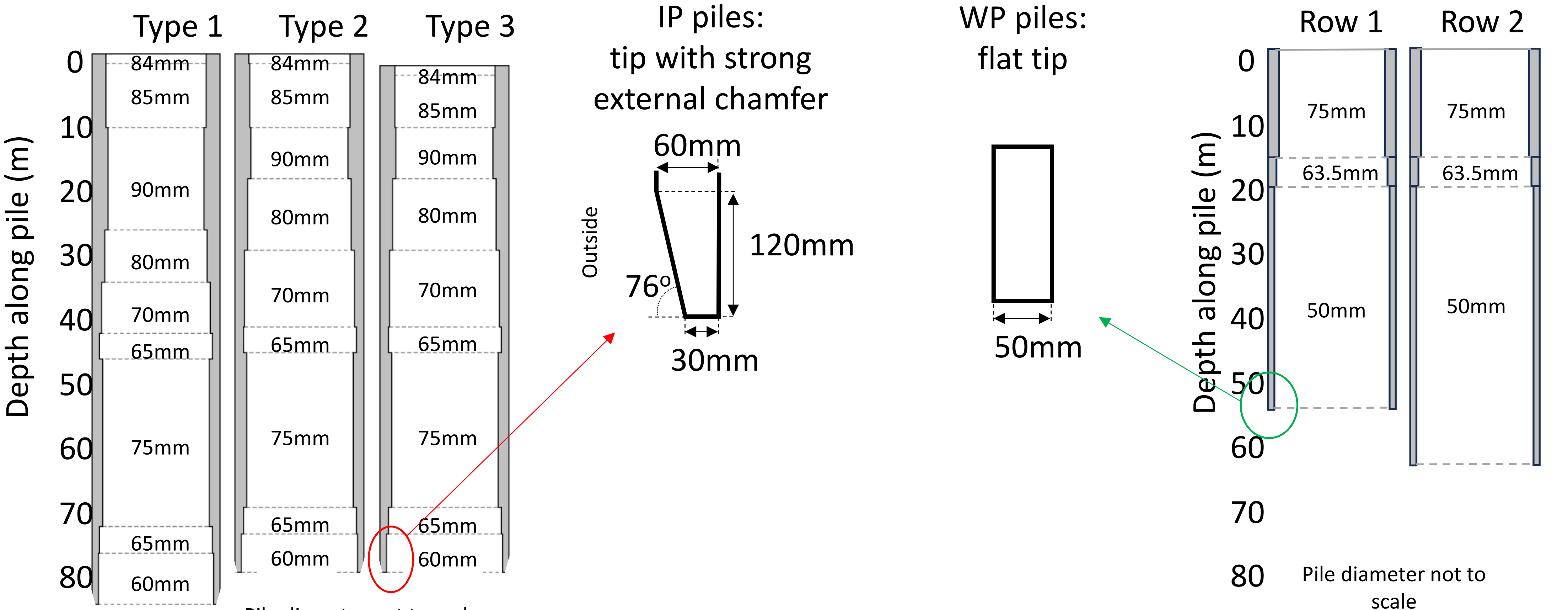


IP vs WP PILE GEOMETRY

SAME 2.348M (96IN) DIAMETER

IP piles: 9 wall thickness sections

WP piles: 3 wall thickness sections

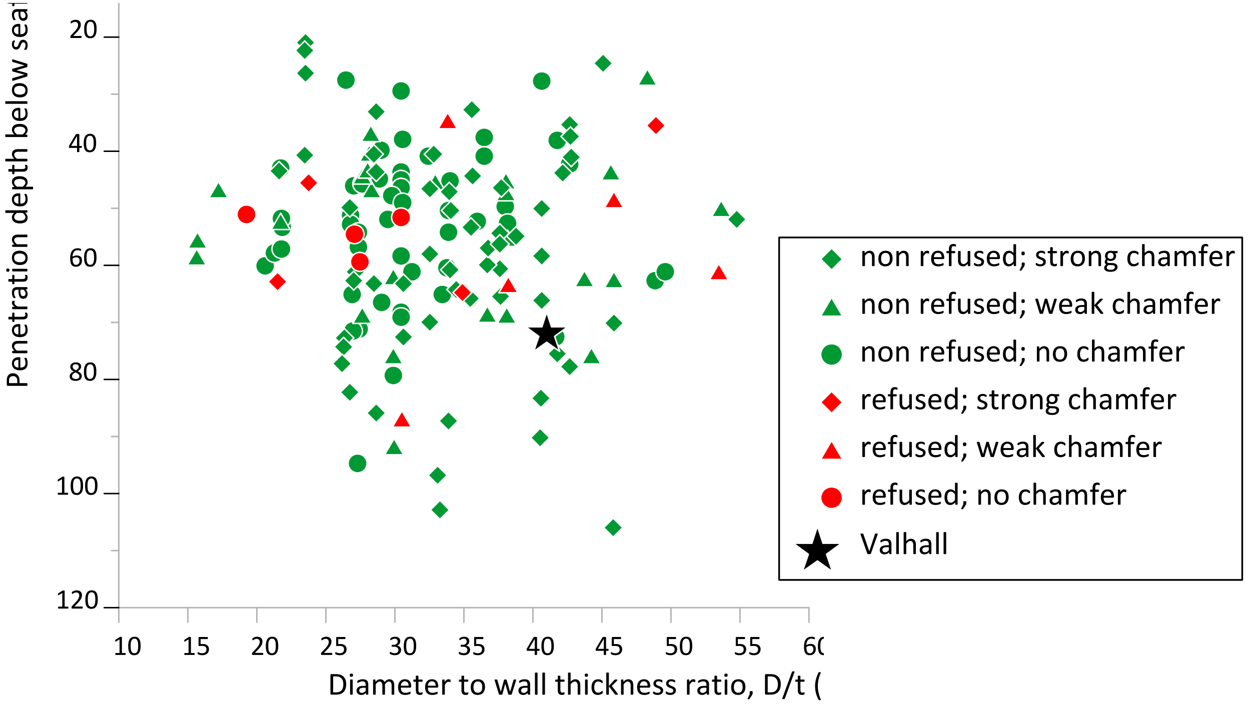


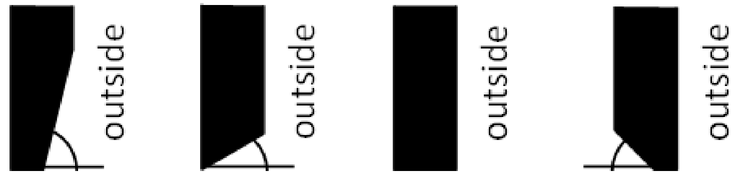
Pile diameter not to scale

Database of refused piles in North Sea – circa 2003

Refusal in dense and very dense sands correlated with the use of external chamfer, not D/t

1. 188 platforms, 72 with piles in dense sands.
2. Strong chamfer used in 40% of platforms overall
   - (50% in UK sector, 64% in Norwegian sector)





	$\alpha > 45^0$ Strong chamfer	$\alpha \leq 45^0$ Weak chamfer	$\alpha = 0^0$ No chamfer	$\alpha < 0^0$ Inward chamfer
No. of platforms with pile tip in very dense sand	16 (D/t=31)	20 (D/t=39)	35 (D/t=32)	1
Refusal1)	5 (D/t=34)	3 (D/t=46)	3 (D/t=28)	0
Percent refusal	31%	15%	9%	0

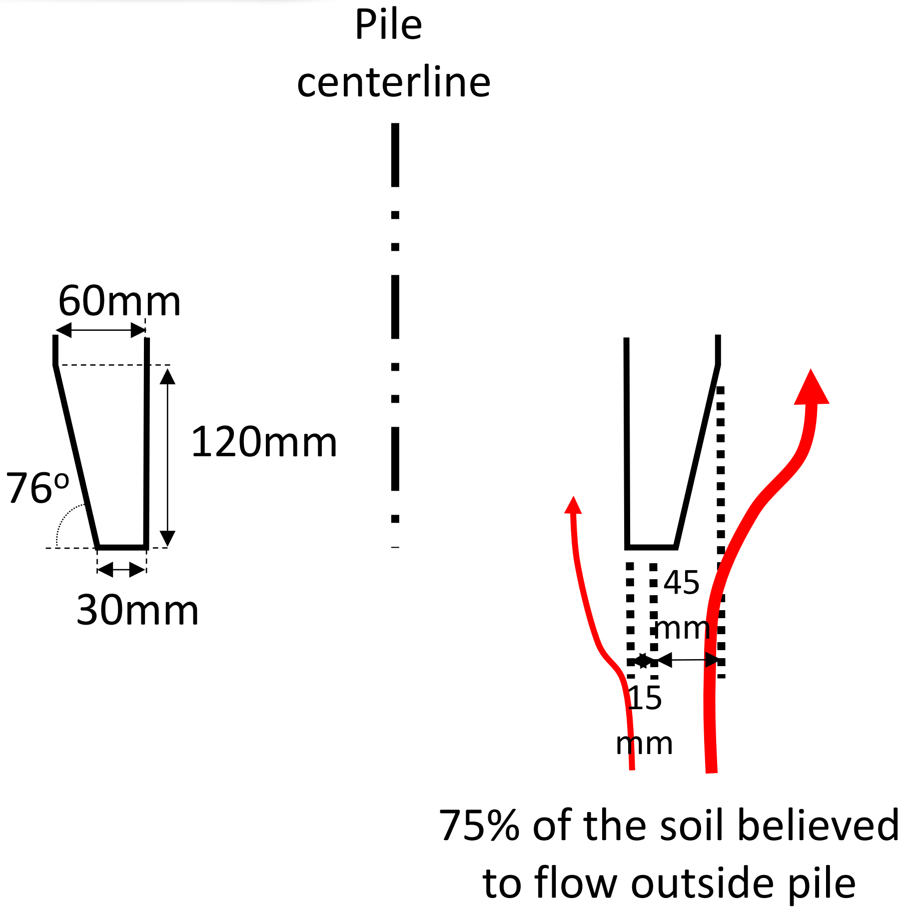
Note 1): "Refusal" refers to the number of platforms with at least one pile that refused

WHY USE AN EXTERNAL CHAMFER?

NONE OF THE THEORETICAL ADVANTAGES PROVEN IN THE FIELD

As of 2003, a strong tip chamfer was often recommended:

1. to aid pile stabbing into the pile sleeve
2. to preserve pile verticality when the pile encountered slopping strata
3. to ease penetration into dense soil, as compared to a flat tip
4. to push more soil to the outside of the pile thereby reducing the risk of plugging.

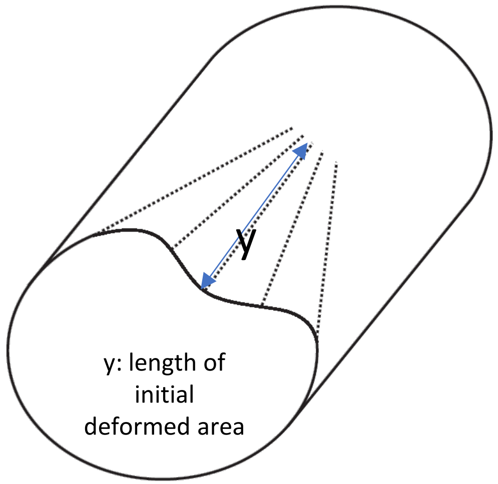


Pile diameter not to scale

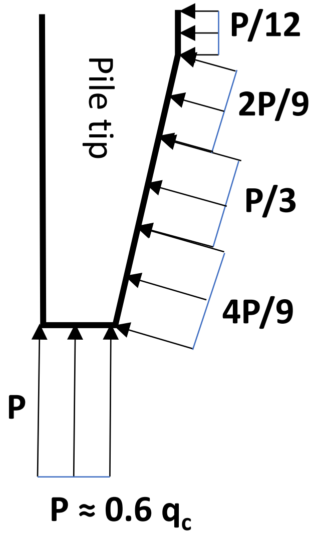
NUMERICAL MODELING OF CHAMFERED TIP

FINITE ELEMENT ANALYSES (FEA) SHOWED LARGE LATERAL STRESS IMBALANCE AT TIP – NOT PRESENT FOR FLAT TIP

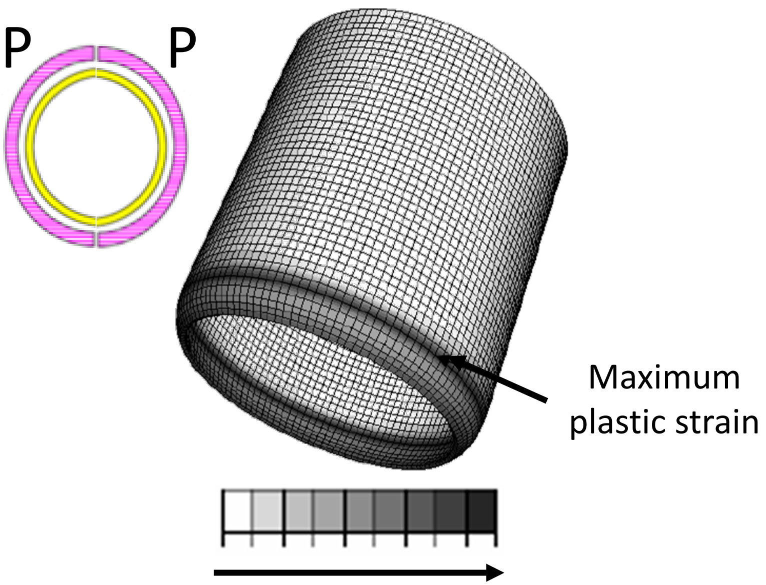
Framework of Aldridge et al. (2005)	FEA performed with ABAQUS, LS-DYNA, Plaxis, ICFEP (Imperial College Finite Element Program)



Cone tip resistance at which pile yielding starts, q_{c_yield}

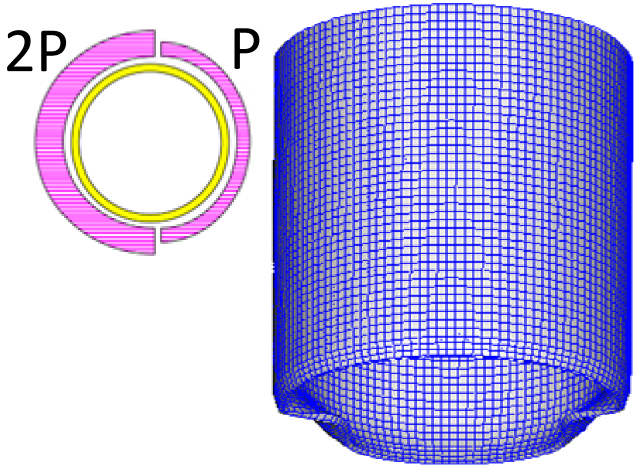


axisymmetric lateral loading



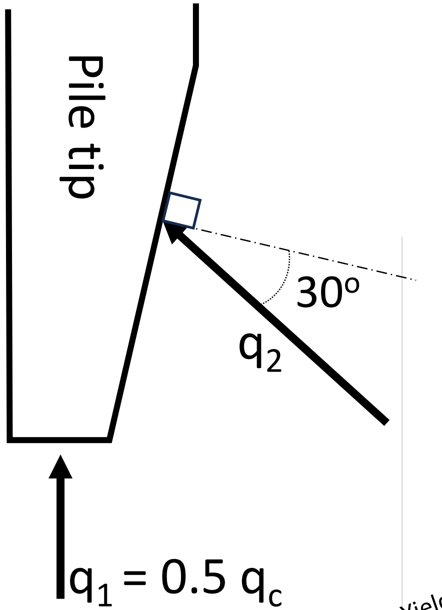
Increased plastic strain

Non-axisymmetric lateral loading

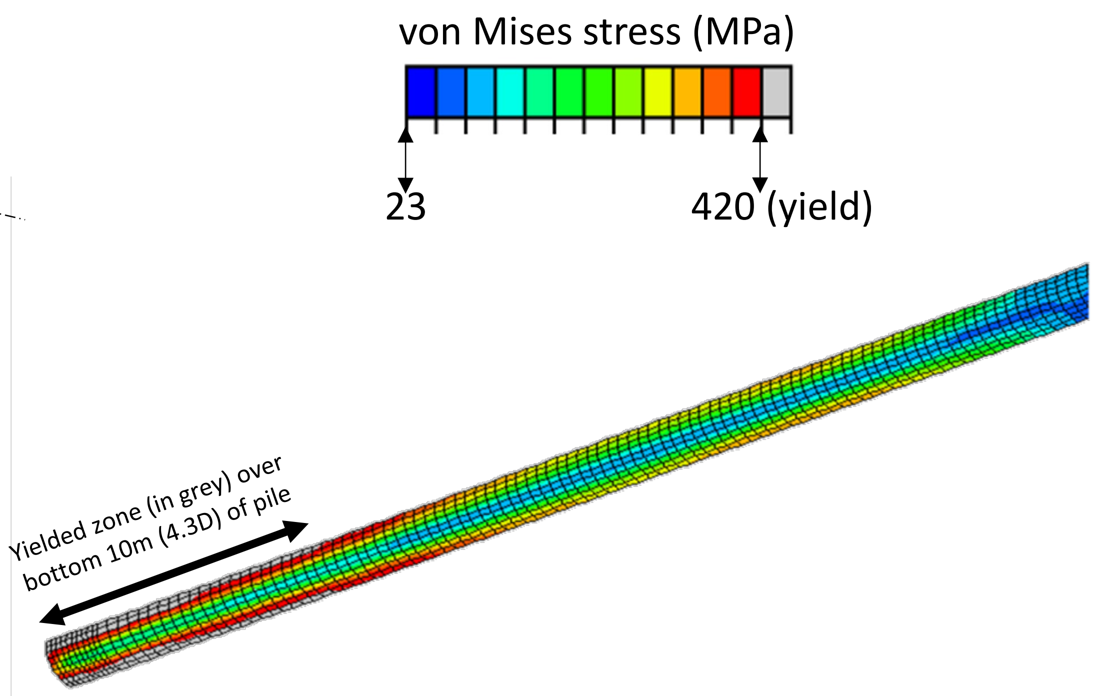


Aldridge et al. (2005)	Axisymmetric lateral loading	Non-axisymmetric lateral loading
q_{c_yield} = 113MPa	q_{c_yield} = 105MPa	q_{c_yield} = 70MPa

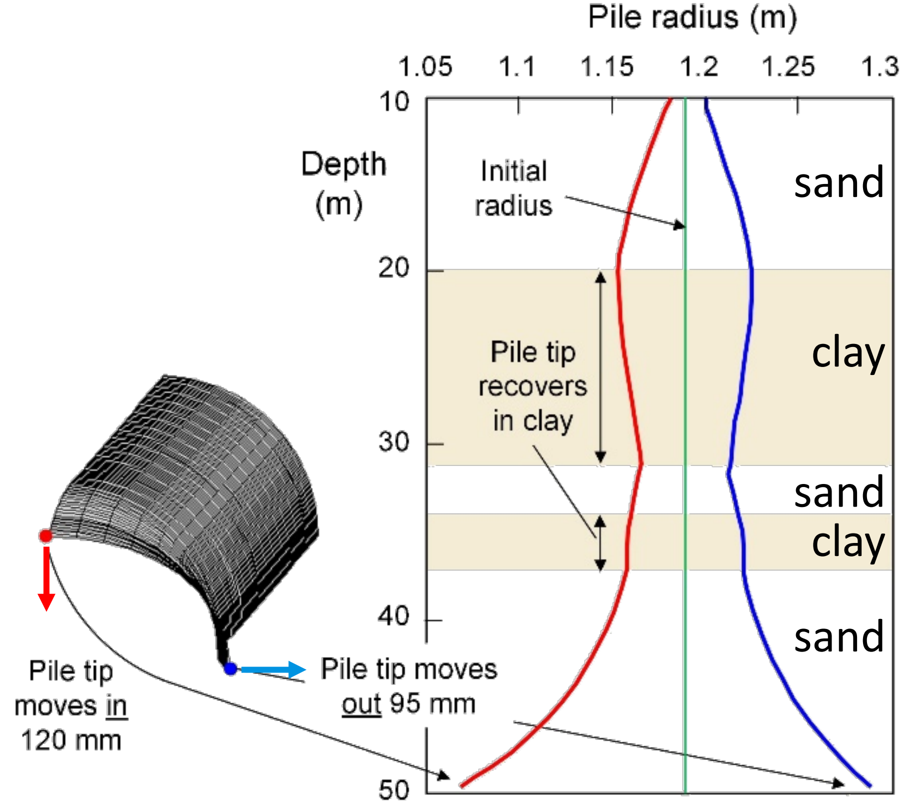
q_{c_yield} = 90MPa



Stresses in pile at 50m penetration



Hindcast of progression of pile distortion with penetration (Randolph, 2018)



CONSENSUS CAUSES OF IP PILE REFUSAL

NOT IN ORDER OF IMPORTANCE

The consensus opinion from 2 independent investigation "Delphi-type" panels was that the main factors that caused the failures were:

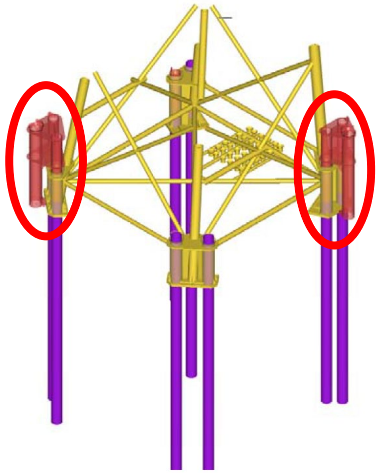
1. A steeply chamfered pile tip.
2. A sand layer of sufficient density and stiffness.
3. A sand layer of sufficient thickness to propagate the initial deformation to the point of collapse.
4. An initial out-of-roundness or tip deformation upon entering the very dense sand stratum in which the pile refused.

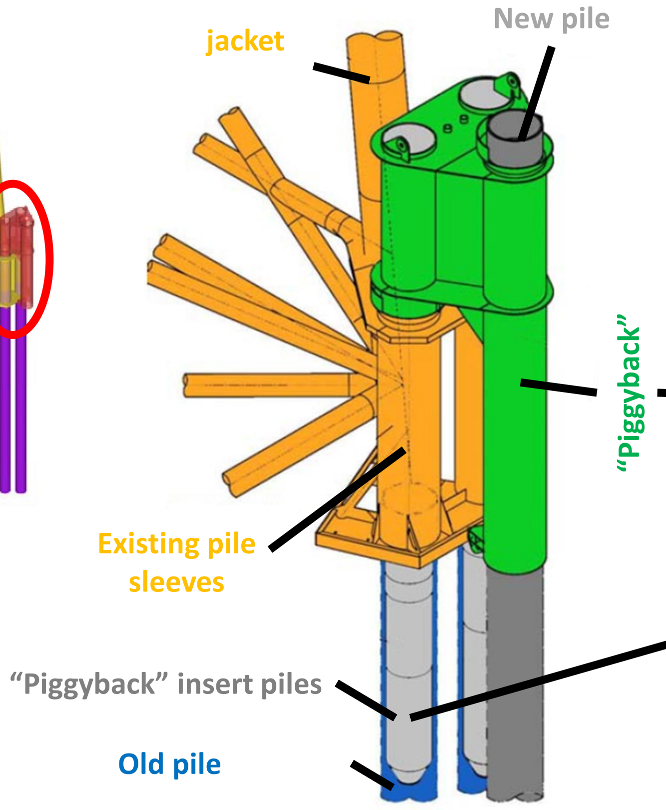
5. Lesson learned captured in ISO 19901-4:2025:

8.7.6 Selection of pile hammer and stresses during driving

d) The tip of the pile or the driving shoe should be flat or bevelled towards the inside of the pile. Pile tips and driving shoes with bevels toward the outside of the pile shall not be used when driving through dense and very dense sands as they have been shown to be a contributing factor in observed pile buckling.

REMEDIATION: THE PIGGY-BACK SYSTEM



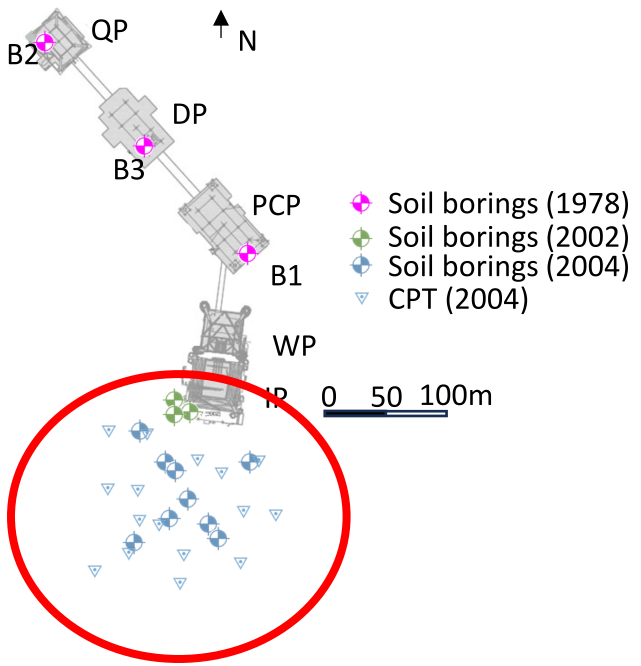


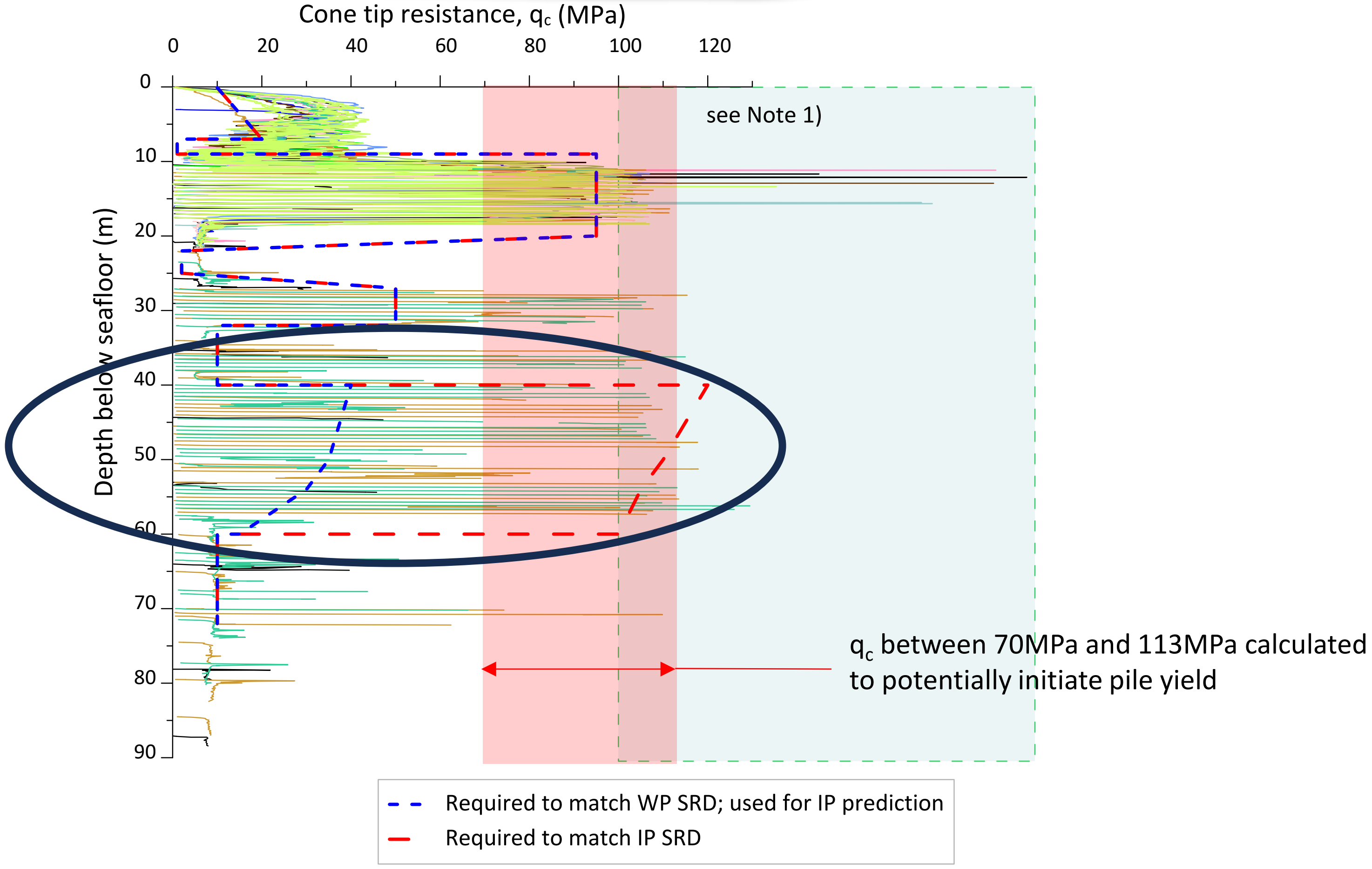
After Alm et al. (2004)

Topsides installation in 2003

2004 Site Investigation for design of PH platform

Confirmed the presence of 100+MPa sands. Factor of Safety against collapse was marginal





Note: 1) All q_c values greater than 100 MPa were measured at CPT refusal. They do not represent actual in-situ values.

THE SCIENTIFIC METHOD

ACCORDING TO PROF. R. FEYMAN (1964)

Develop or guess the theory

- Develop foundation design methods

→

Compute the consequences

- Predict field performance of offshore structures and their foundations

→

Compare with experiment

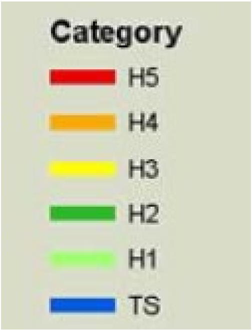
- Compare predicted performance with post-event observations

Can you prove a definite theory wrong? Yes!

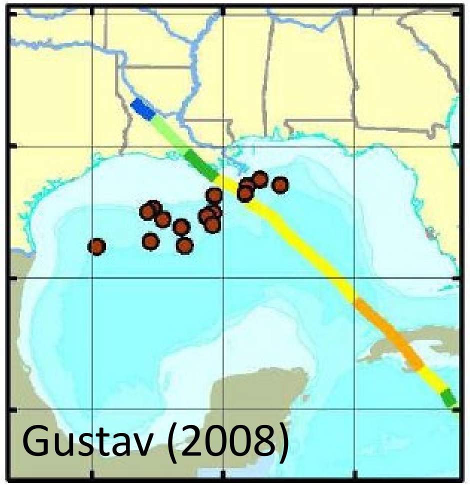
You cannot prove any theory right!

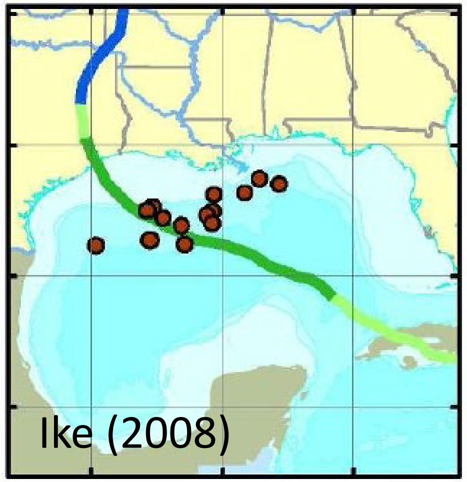
Performance of floating drill rigs mooring system

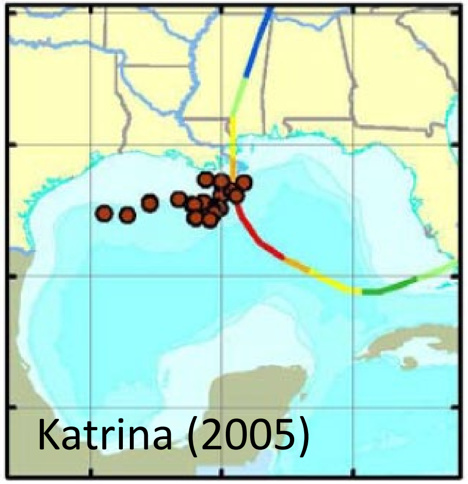
Hurricane	Number of floating MODU (Mobile Offshore Drilling Units) with mooring failures
Ivan	5
Katrina	8
Rita	12
Gustav	1
Ike	5

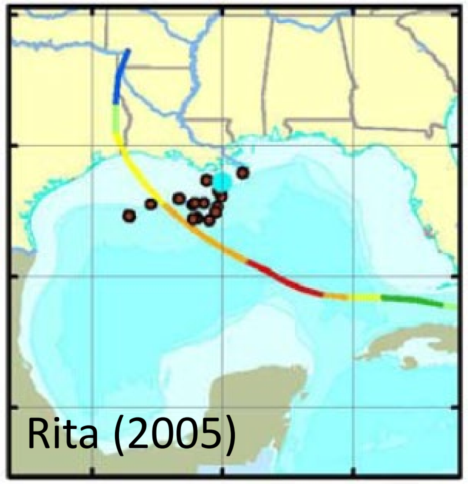


- Floating rigs exposed to hurricane









Modified from ABS (2012)

Jim Thompson rig drilling in Block MC383

Mooring designed for 10-year event, as per code requirements of the time

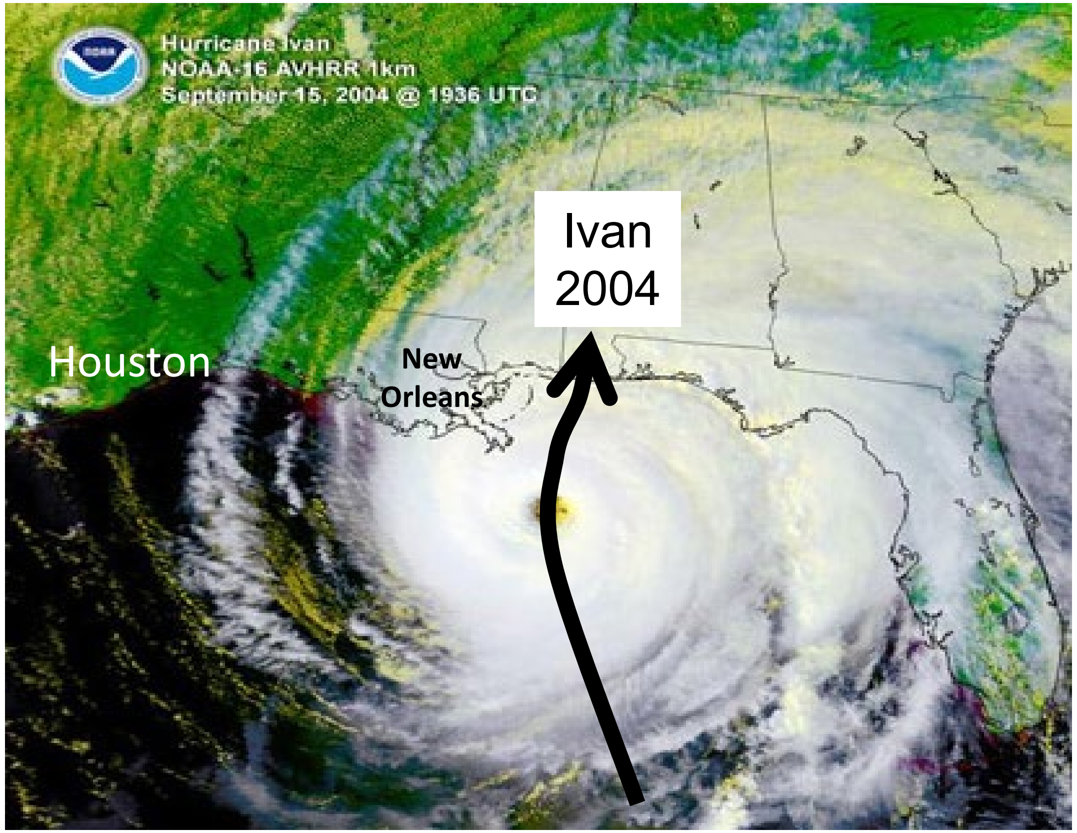
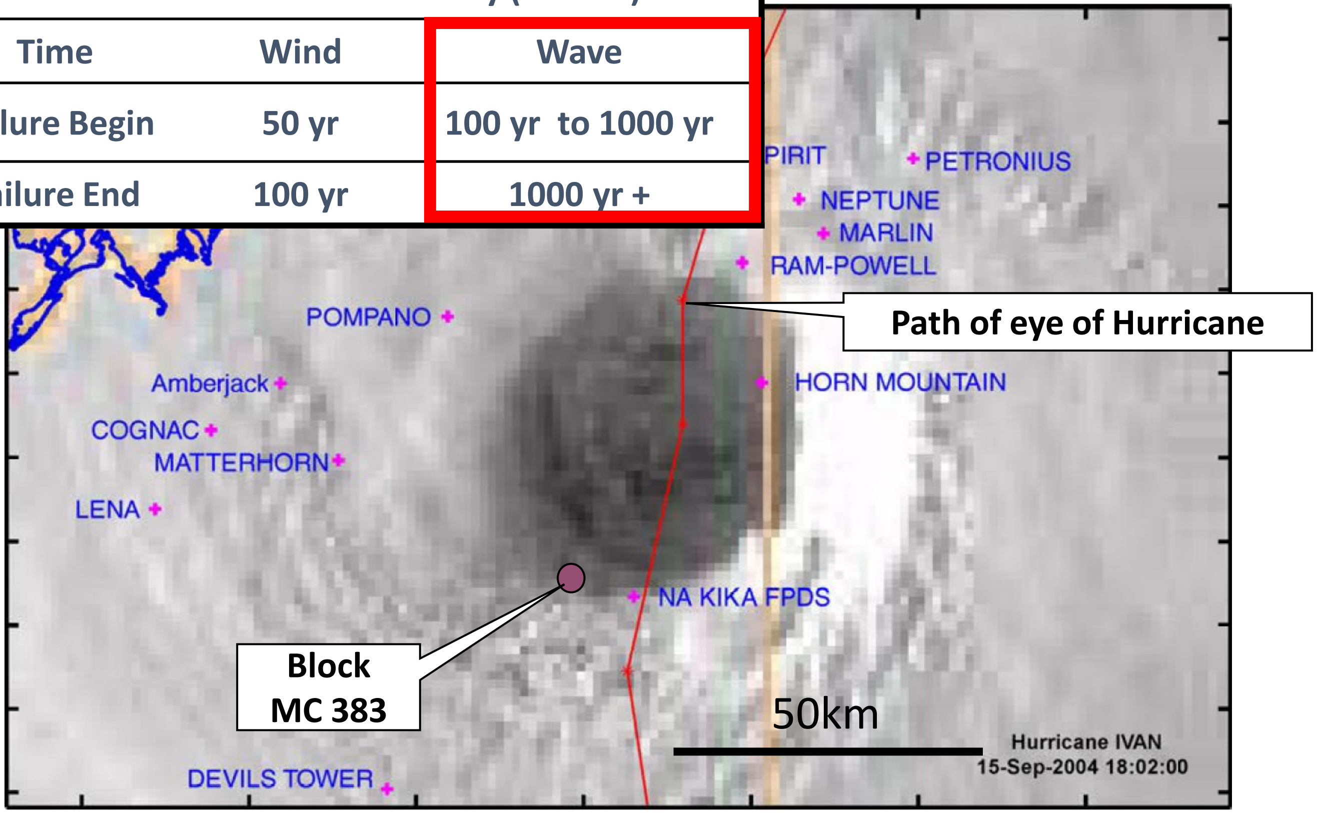


Photo of Hurricane Ivan, Sept. 15, 2004, 19:36hrs UTC
Credit: NOAA

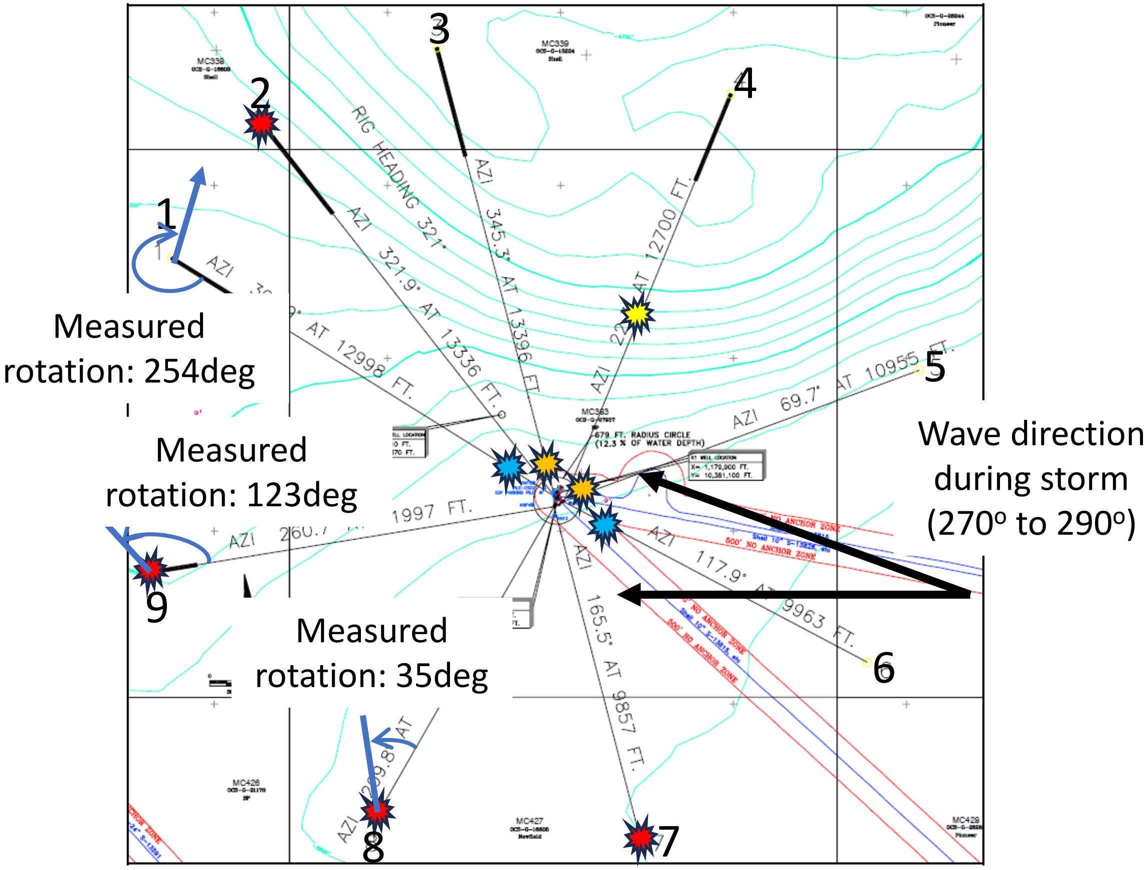
Estimated Ivan Storm Intensity (MC383)		
Time	Wind	Wave
Failure Begin	50 yr	100 yr to 1000 yr
Failure End	100 yr	1000 yr +



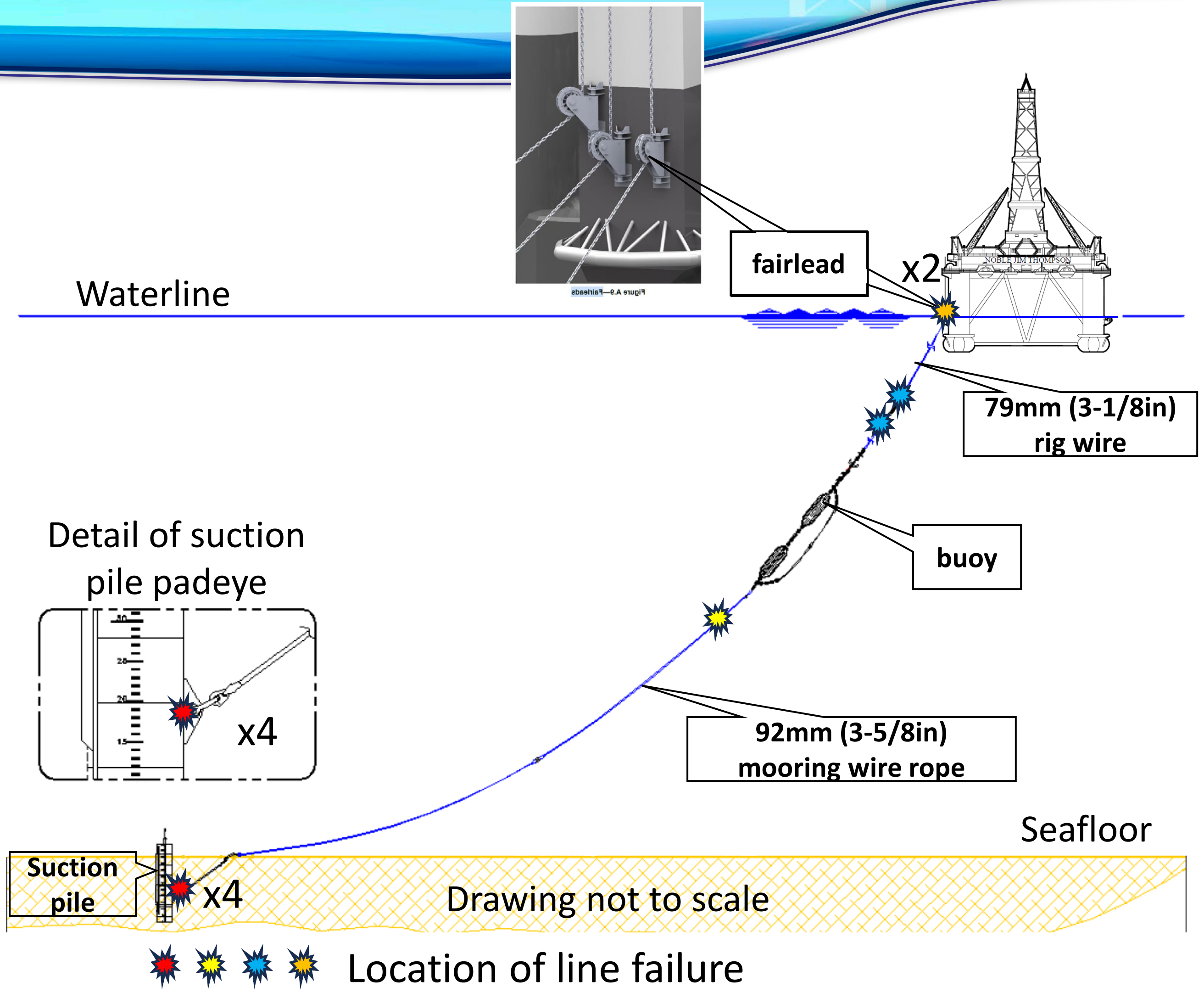
From Sharples (2006) & Petruska (2005)

MOORING FAILURE MECHANISM

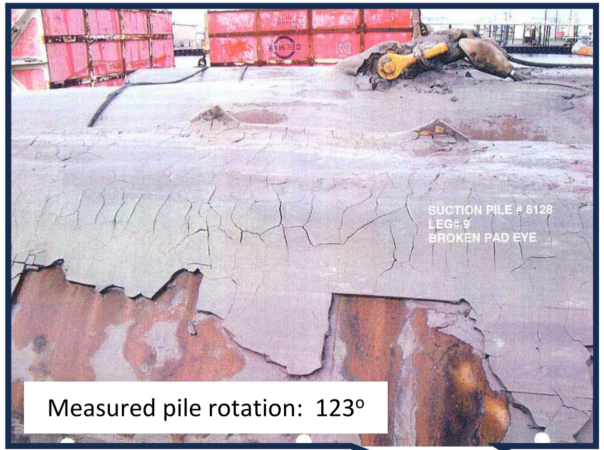
5 LINES BROKE AT THE FAIRLEAD OR IN THE WIRE ; 4 ANCHOR STRUCTURAL FAILURES AT PADEYE

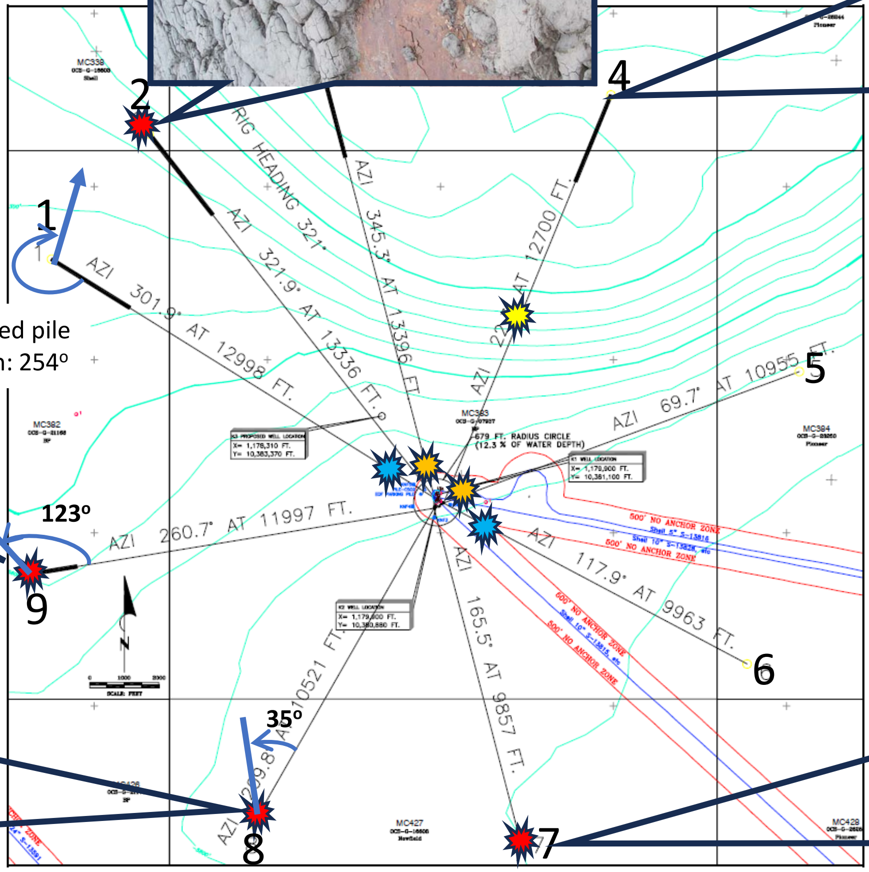


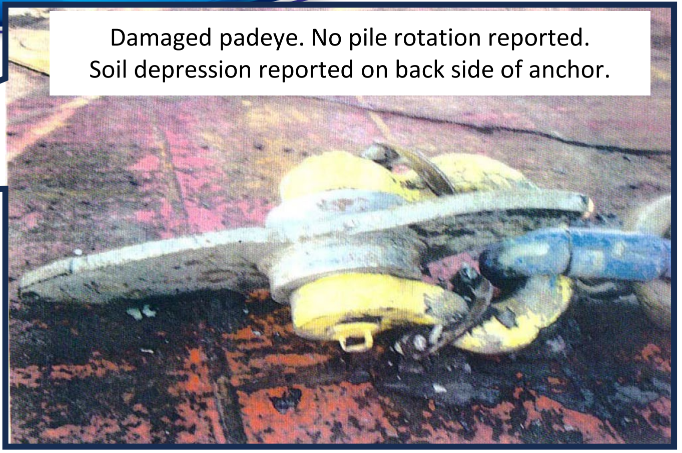
- Line failure sequence: 5, 4, 6, 7, 8, 3, 2, 9, 1

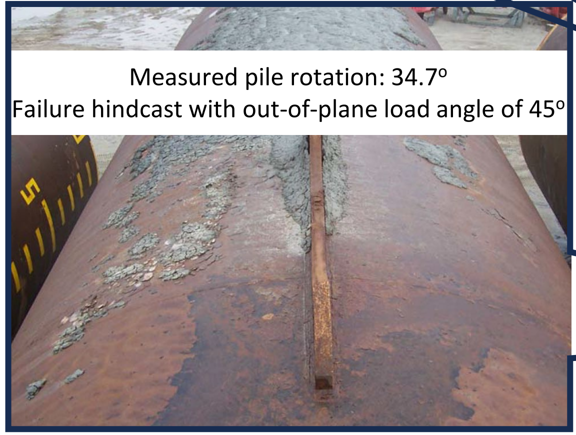


Suction piles failed structurally, not geotechnically





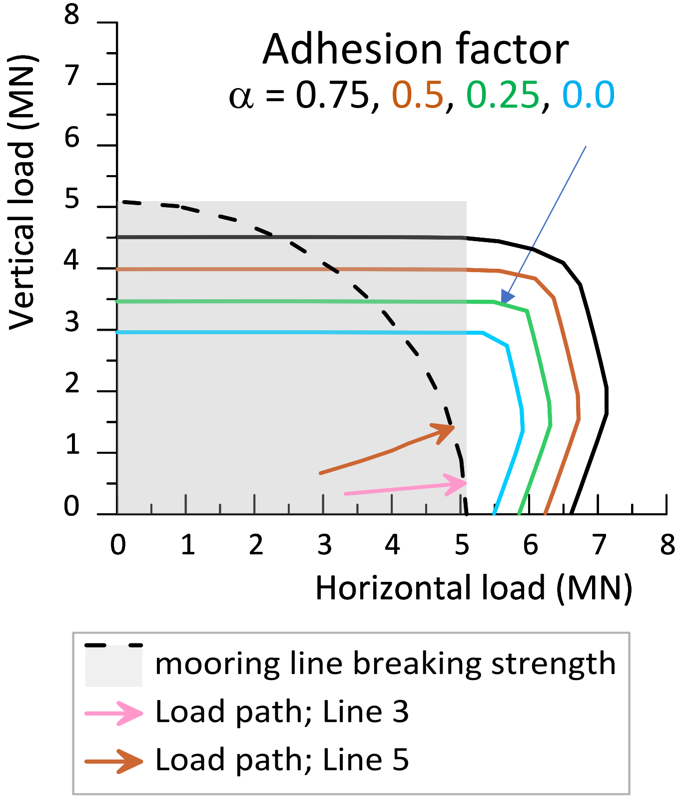




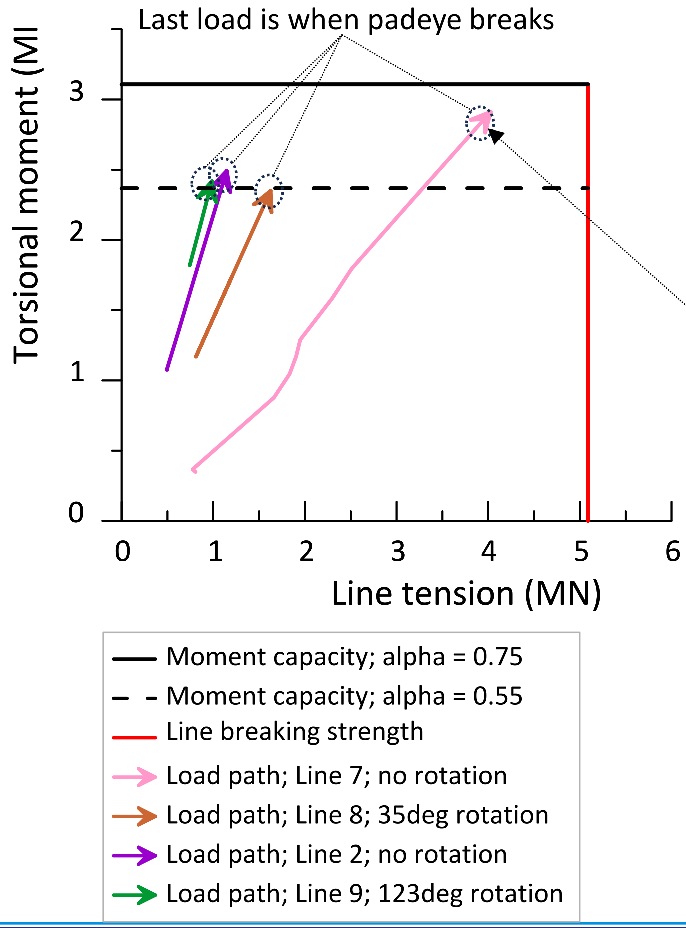
Line failure sequence: 5, 4, 6, 7, 8, 3, 2, 9, 1

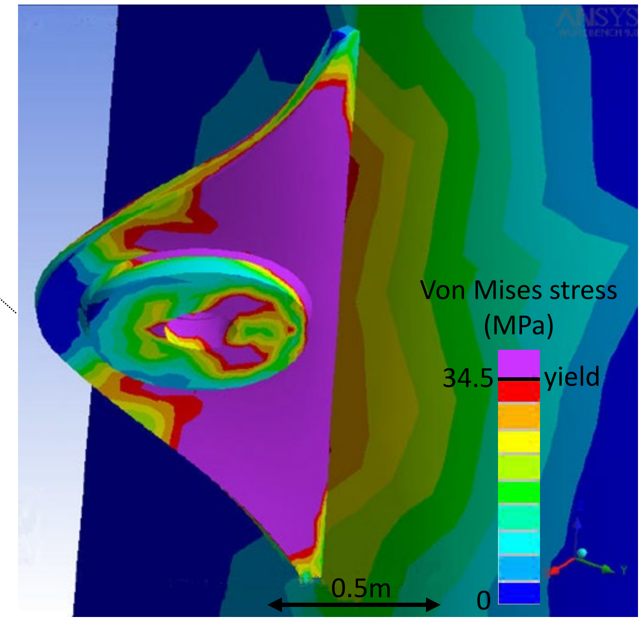
LINE FAILURE VS ANCHOR FAILURE VS PADEYE FAILURE

V-H failure interaction diagram
In-line loading



Moment-Line tension failure interaction diagram

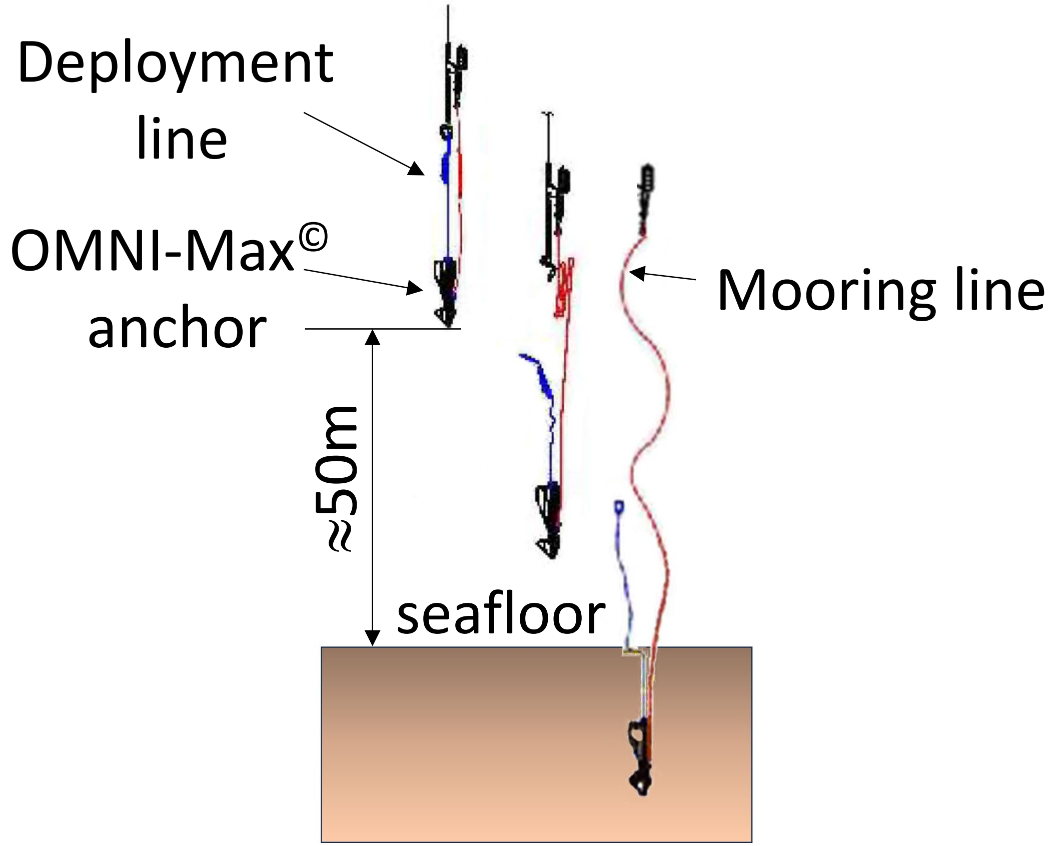




Stresses in padeye for Line 7 at failure (modified from Delmar, 2005).

PERFORMANCE OF OMNI-MAX© ANCHORS

GRAVITY-INSTALLED ANCHORS WITH OMNI DIRECTIONAL LOADING CAPABILITY



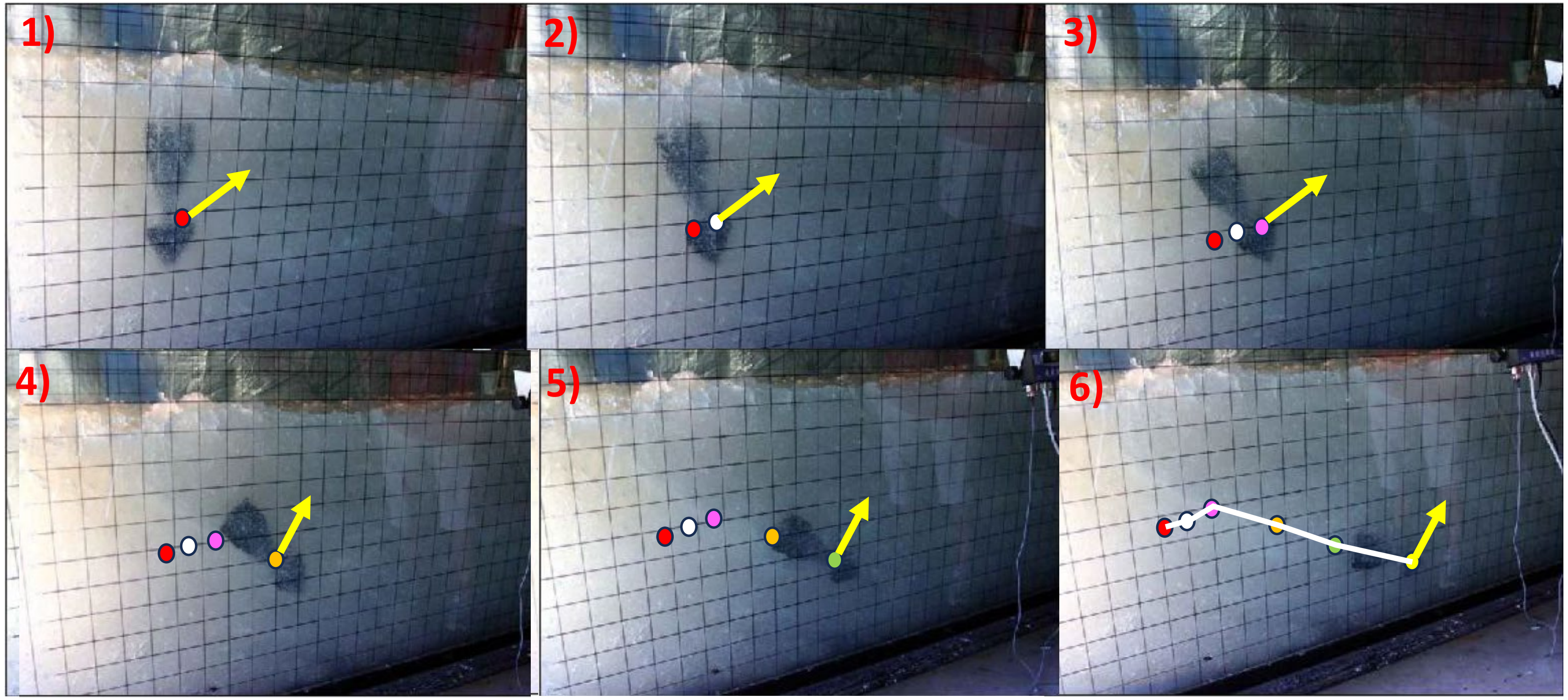
Modified from Shelton (2007)

Typical length overall: ≈ 9.1m; Weight (dry): ≈ 39t

From https://delmarsystems.com/products/anchors/omni-max/

OMNI-MAX© ANCHORS KEYING BEHAVIOR: MODEL TESTS IN LAPONITE

LAPONITE: TRANSLUCENT SMECTITE

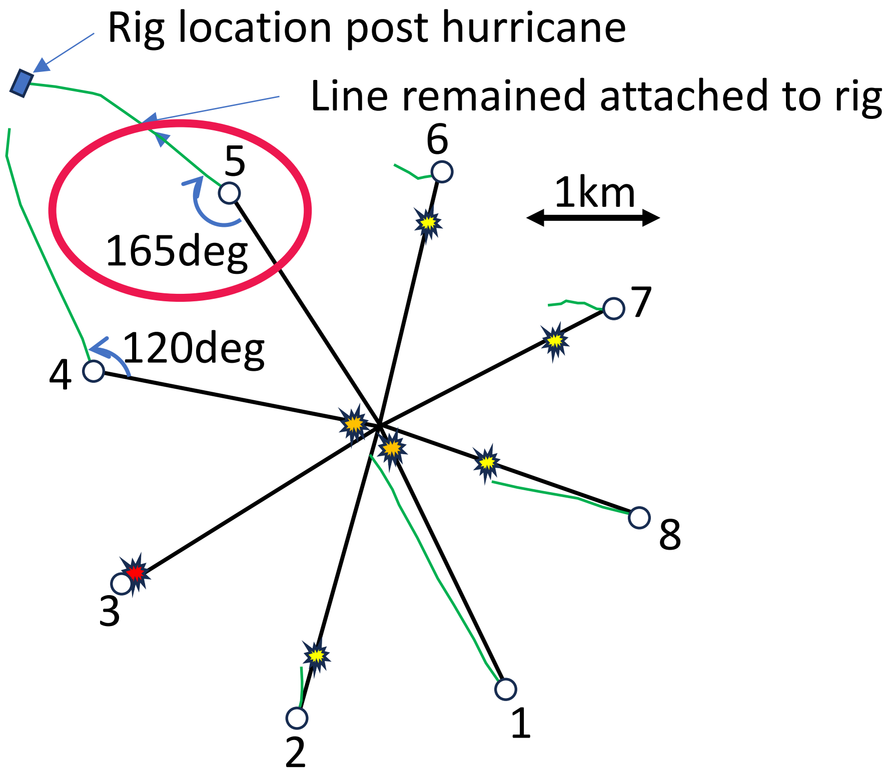


Trajectory of load attachment point with load sequence 1 to 6

Modified from Shelton (2007)

Performance during hurricane Gustav (2008)

Transocean Amirante rig – All mooring lines broke, except one



Failure sequence: 8, 1, 7, 6, 2, 3, 4

- Parted at fairlead
- Parted in intermediate wire
- Anchor structural failure

Anchor	Installed penetration (m)	Post hurricane penetration (m)	Estimated capacity (MN)	Estimated maximum anchor load (MN)	Ratio maximum Load/Capacity	Additional embedment during hurricane (m)
1	16.5	23.5	2.5	3.6	144%	7.0
2	16.5	32.9	3.4	4.9	144%	16.4
3	15.9	35.1	3.9	5.5	141%	19.2
4	17.7	36.6	3.4	4.8	141%	18.9
5	16.5	19.2	2.2	3.0	136%	2.7
6	16.8	26.5	2.7	3.9	144%	9.7
7	18.3	31.1	2.8	4.0	143%	12.8
8	16.8	29.0	3.0	4.2	140%	12.2

Modified from Zimmerman et al. (2009)

Summary of anchor performance lessons learned

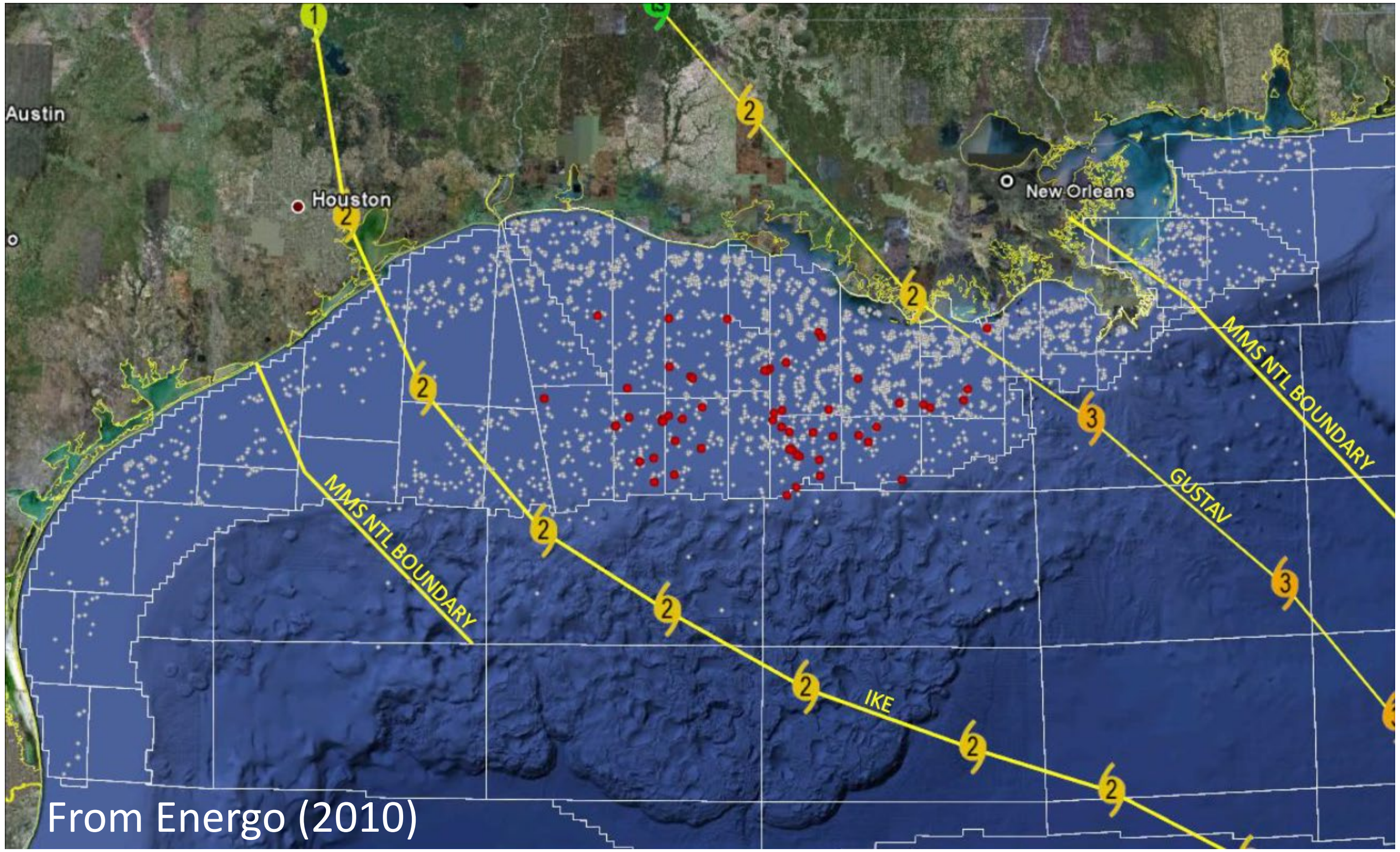
Design methods not proved wrong!

- Most mooring failures occur in the wire line, as predicted and intended
- Behavior of suction anchors is as predicted:
  - Line failure vs anchor structural failure vs anchor geotech failure
- Omni-Max© anchor behavior as predicted:
  - Anchor diving behavior under overloads
  - Anchor retaining capacity after large rotations
- Out-of-plane loading can cause structural failure
- Key improvement of performance includes increasing the geotechnical and structural capacity under out-of-plane loading

Performance of fixed structures during hurricanes

300 platforms destroyed since 1948!

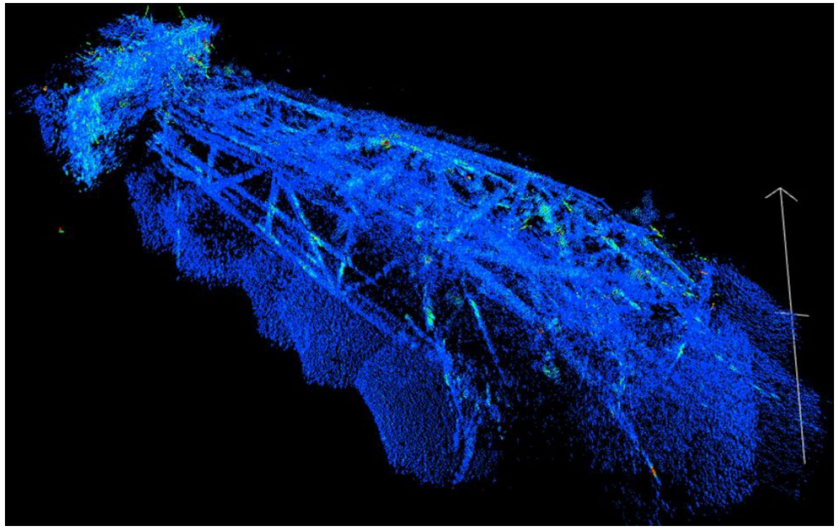
60 fixed platforms destroyed in 2008 (59 in Ike, 1 in Gustav)



Destroyed platforms

DESTROYED PLATFORMS:

EITHER TOPPLED, DAMAGED, OR LEANING BEYOND REPAIR



Echoscope survey of toppled platform on seafloor in Ewing Banks area

Platform damaged beyond repair in Eugene Island area

Platform leaning beyond repair in East Cameron area

From Energo (2010)

PERFORMANCE OF FREE-STANDING CAISSON, HURRICANE ANDREW (1992)

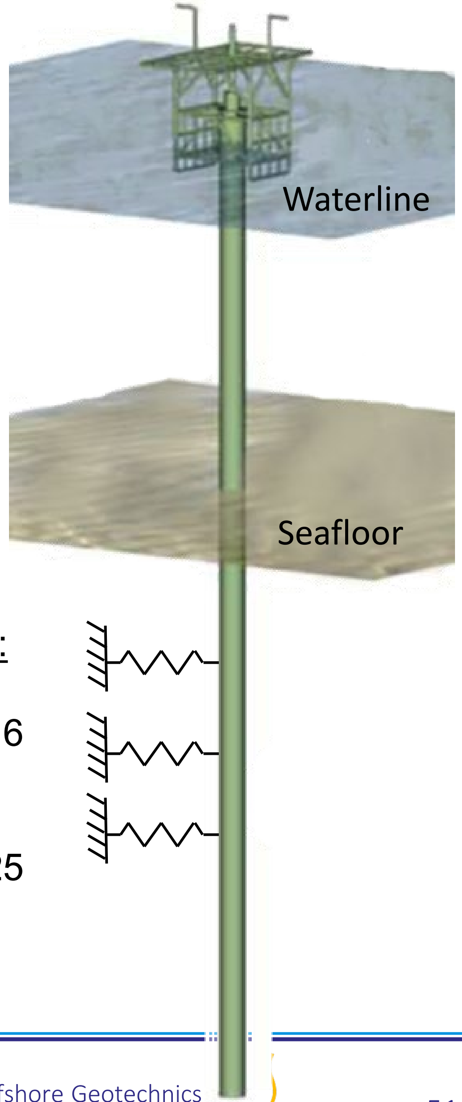
API STUDY (WU ET AL. 2020)

- Water depth: 16.2m
- Pile: 1.2m diameter, 29m penetration in soft clay
- Caisson damaged during Hurricane Andrew in August 1992, found leaning 15 degrees at waterline

Illustrative caisson damage after hurricane
(these caissons are not the one for this case record)

<u>Lateral support p-y springs:</u>

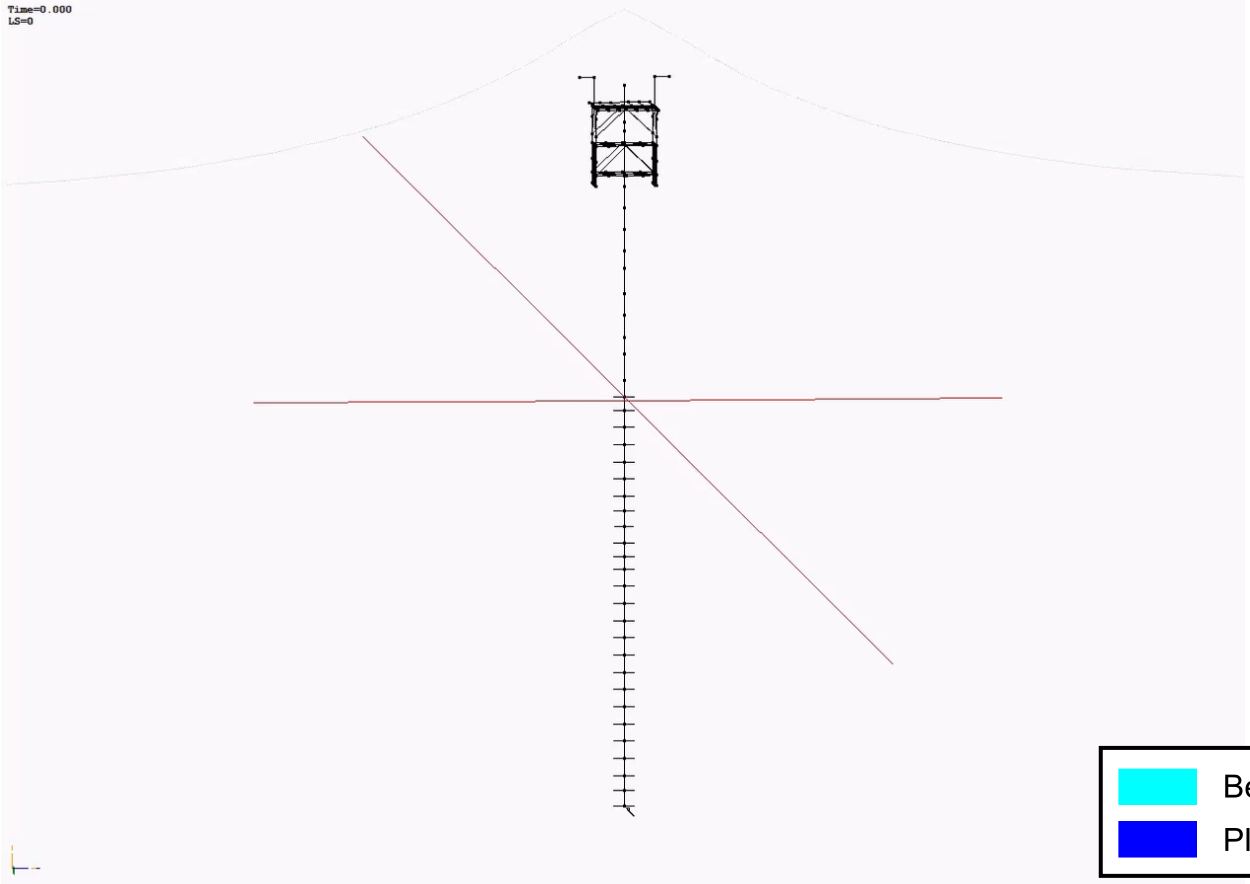
- Model 1: ISO 19901-4:2016 **<u>monotonic</u>** curves
- Model 2: ISO 19901-4:2025 **<u>cyclic</u>** curves



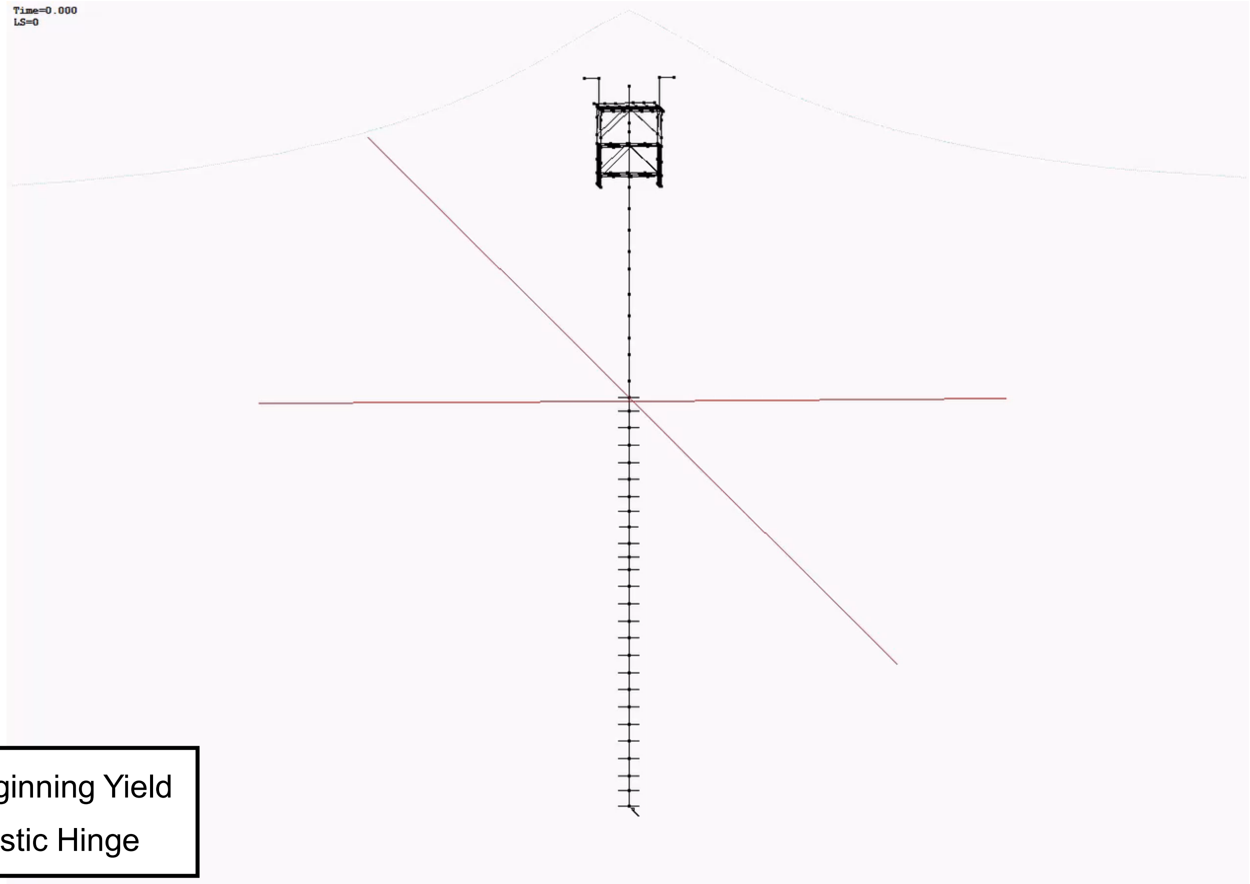
HINDCAST OF PERFORMANCE

DYNAMIC PUSH-OVER ANALYSIS. BOTH MODELS USE DSS (DIRECT SIMPLE SHEAR) SHEAR STRENGTH

Using ISO 19901-4:2025 **cyclic** p-y curves



Using ISO 19901-4:2016 **monotonic** p-y curves

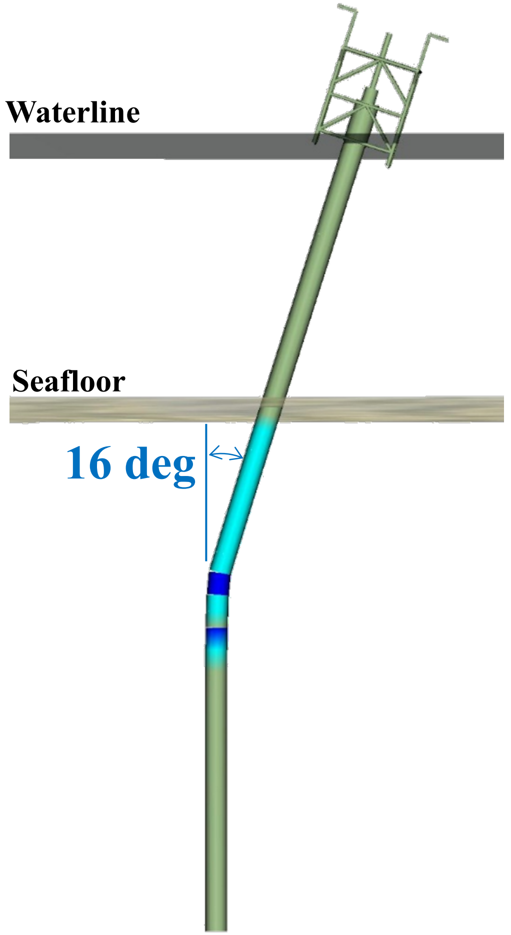


(cyan)	Beginning Yield
(blue)	Plastic Hinge

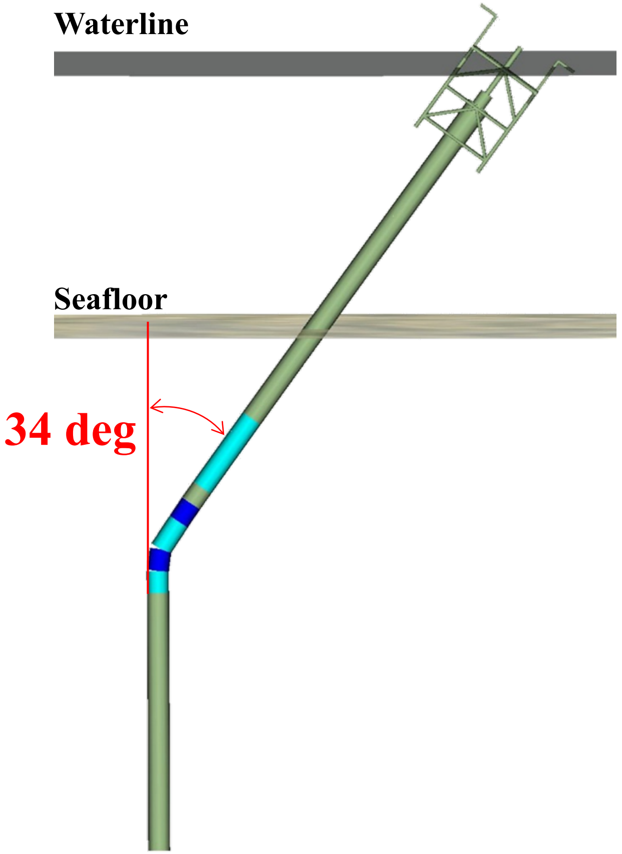
Caisson Hindcast vs Measured Performance

ISO 19901-4:2025 method for laterally loaded piles in clays not proved wrong!

Using ISO 19901-4:2025 API/ISO cyclic p-y curves



Using ISO 19901-4:2016 monotonic p-y curves



Field observation: 15 deg.

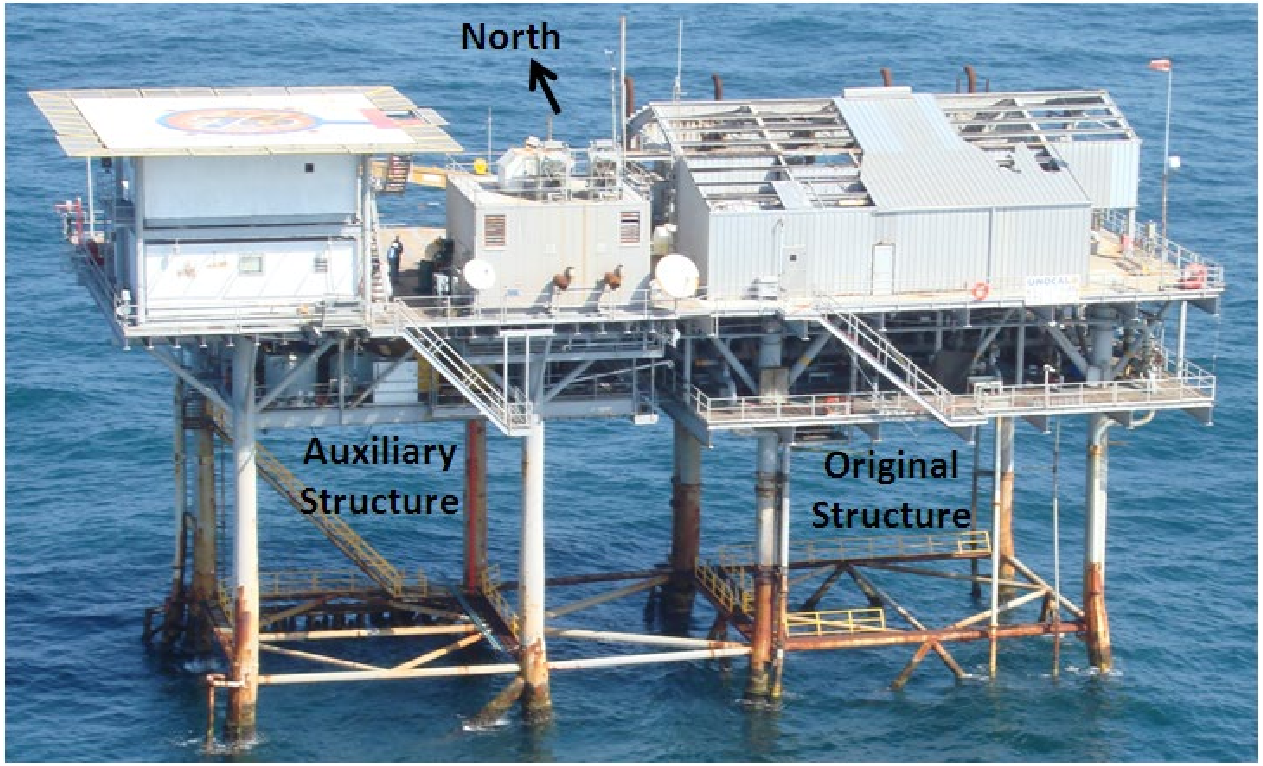
(cyan)	Beginning Yield
(blue)	Plastic Hinge

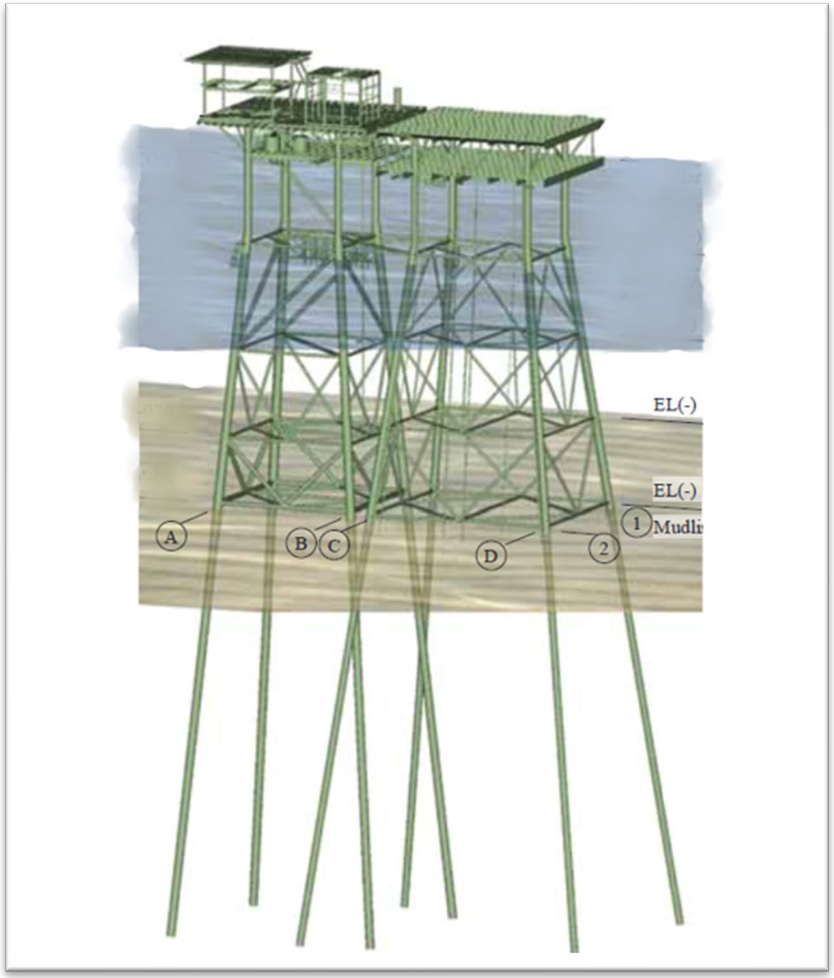
See Wu et al. (2020) for details

PERFORMANCE OF SS JACKET, HURRICANE IKE (2008)

API STUDY (WU ET AL. 2020)

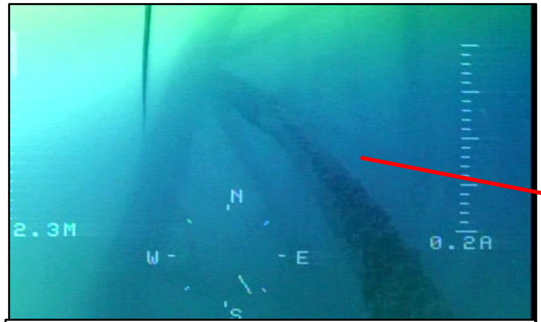
- Two 4-pile jacket platforms
- Pile penetration: 54.8m into soft to stiff clay
- Platform damaged during Hurricanes Gustav & Ike (2008)



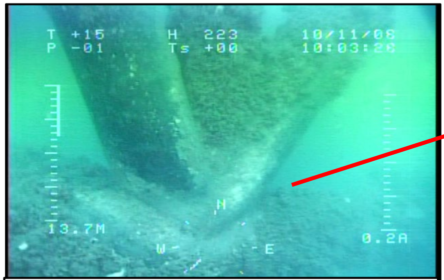


Platform Damage Post Hurricane Ike

Joint failure and separated members

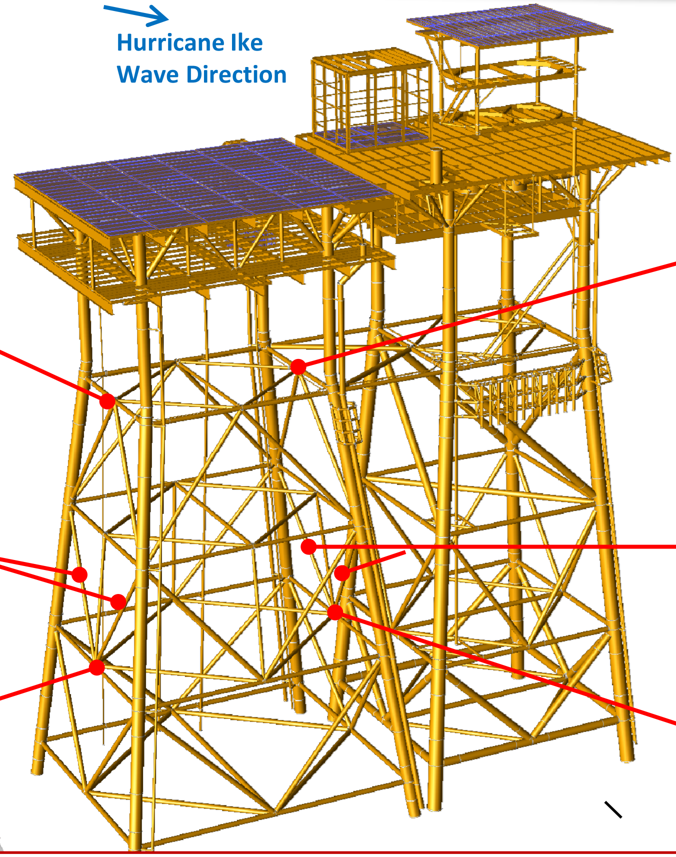


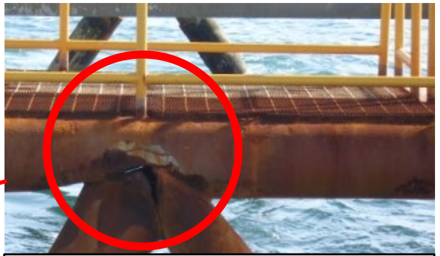
Buckled braces



Cracked and damaged joint

Hurricane Ike
Wave Direction





Joint failure and separated members

Buckled braces

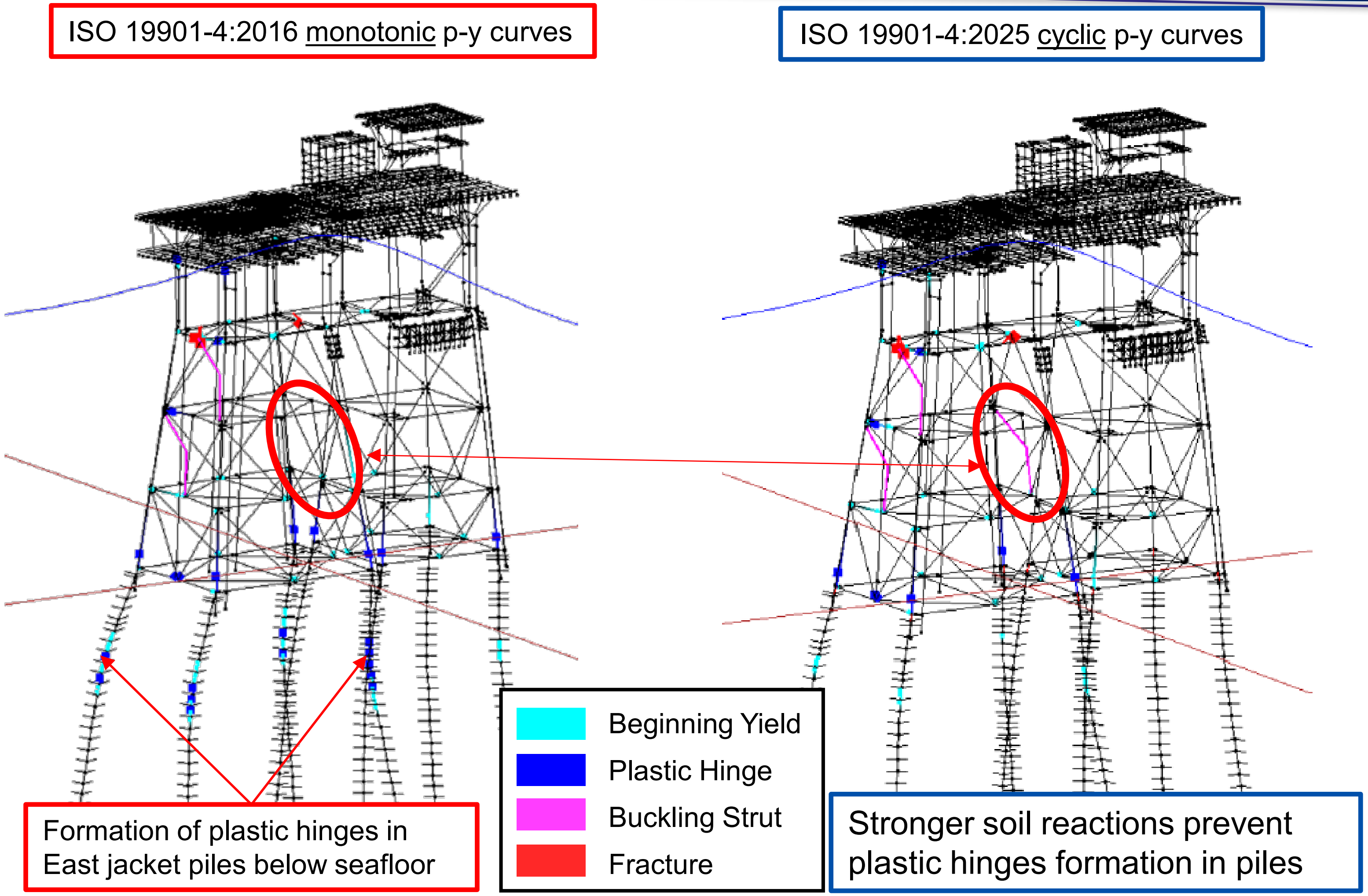
Cracked and damaged joint

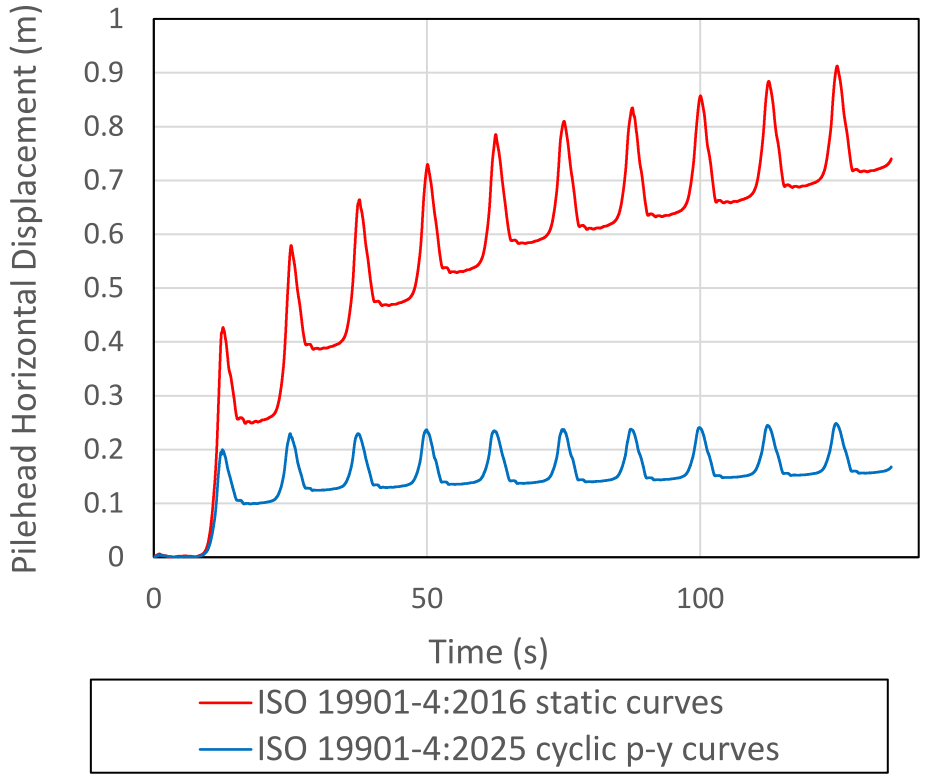
PILE FOUNDATION

NO INDICATION OF PILE FOUNDATION FAILURE OR LATERAL DISPLACEMENTS IN UNDERWATER INSPECTIONS

Hindcast of Platform Performance during Hurricane Ike

After 2 cycles of maximum wave



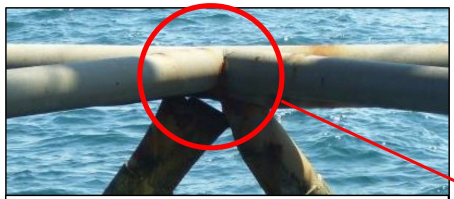


The hindcast with the ISO 19901-4:2025 cyclic p-y curves is more consistent with the fact that no noticeable pile lateral displacement was reported (0.4 m displacement vs 0.1 m)

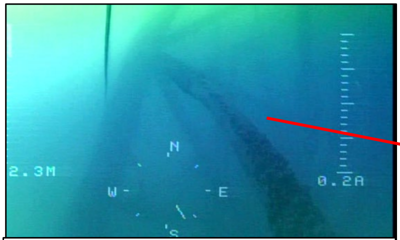
SS PLATFORM PREDICTED VS OBSERVED DAMAGE

USING ISO 19901-4:2025 CYCLIC P-Y CURVES WITH DSS SHEAR STRENGTH

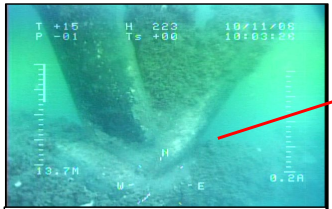
ISO 19901-4:2025 framework for lateral pile-soil interaction in clays not proved wrong!



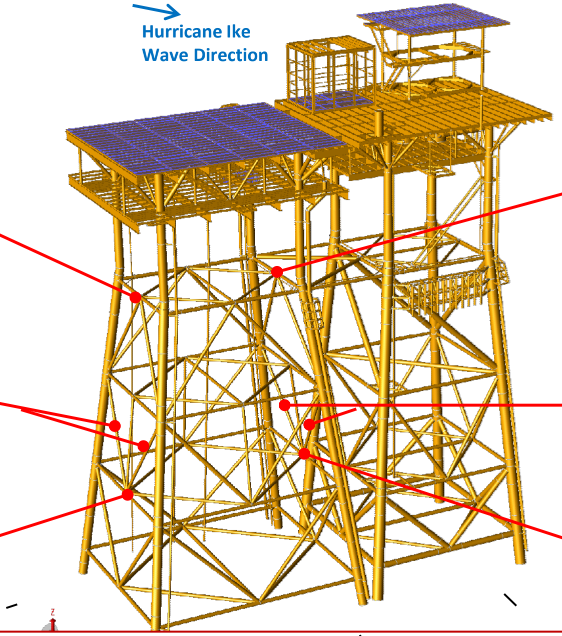
Joint failure and separated members



Buckled braces

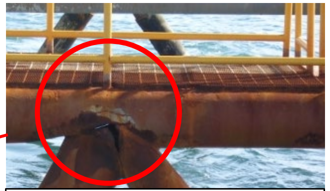


Cracked and damaged joint

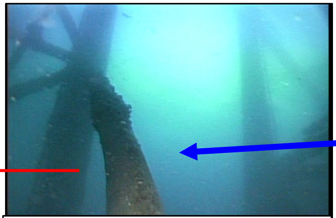


PILE FOUNDATION

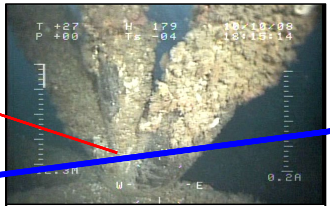
NO INDICATION OF PILE FOUNDATION FAILURE OR LATERAL DISPLACEMENTS IN UNDERWATER INSPECTIONS



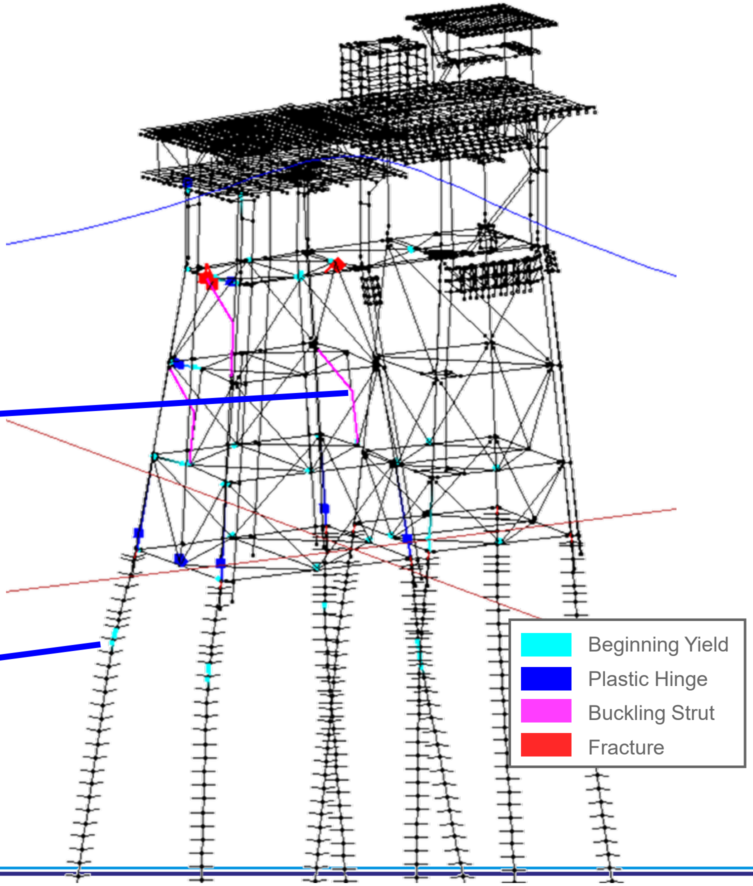
Joint failure and separated members



Buckled braces



Cracked and damaged joint



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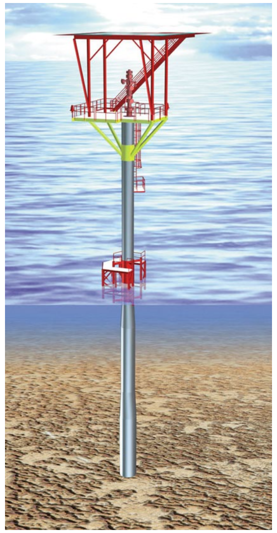
THE IMPORTANCE OF IDENTIFYING RIGHT FAILURE MECHANISM

RELEVANCE OF HYDROCARBONS LESSONS LEARNED TO NEW ENERGY PROJECTS

SIMILAR STRUCTURES, DIFFERENT SCALE!

Hydrocarbons

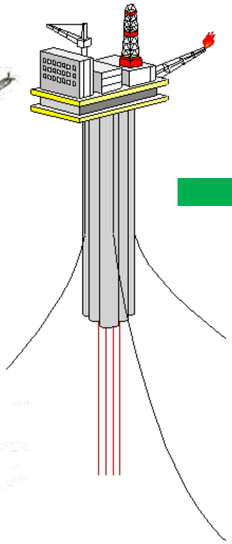
Offshore Wind



Caisson

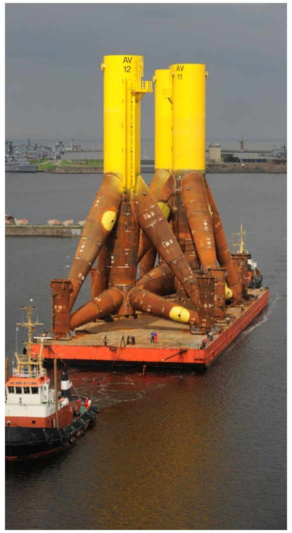
Multi-pod

Jacket



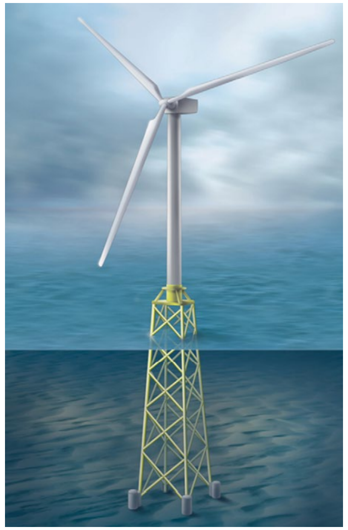
Spar

Monopile



Credit: Mandelsloh

Multi-pod



Credit: Bjarne Stenberg

Jacket

Credit: DNV

Spar

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