Lloyd's Register Educational Trust

UNIVERSITY OF Southampton

Geotechnical Considerations in the Context of CCS

by

Dr Britta Bienen

The LRET Research Collegium
Southampton, 11 July – 2 September 2011

The University of Western Australia
Achieving International Excellence

Geotechnical considerations in the context of carbon storage in ocean spaces

Britta Bienen

Centre for Offshore Foundation Systems, University of Western Australia

Themes

THE UNIVERSITY OF WESTERN AUSTRALIA
Achieving International Excellence

- Examples of carbon sequestration in ocean spaces
  - –Sleipner West
  - –Gorgon
- Geotechnical considerations in the context of geo-sequestration of CO_2 in the offshore environment
- “Ship design”: Mobile jack-up drilling rigs
- Offshore wind energy installations

Geo-sequestration

THE UNIVERSITY OF WESTERN AUSTRALIA
Achieving International Excellence

Geological storage (aka geo-sequestration)

- Injection of carbon dioxide, generally in supercritical form, directly into underground geological formations
- Suggested as storage sites :

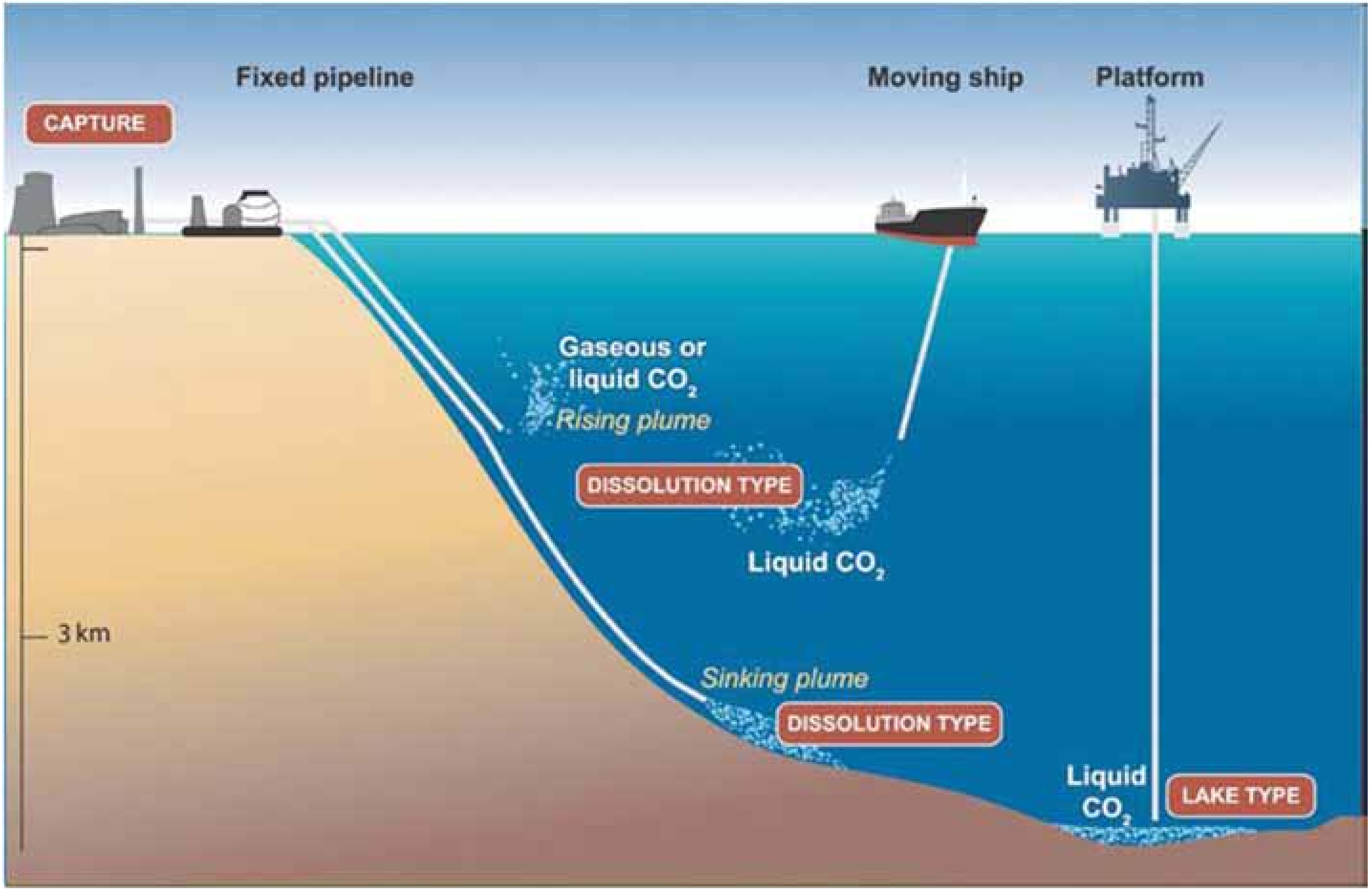
  Oil fields, gas fields, saline formations, unmineable coal seams, and saline-filled basalt formations
- Various trapping mechanisms prevent the CO_2 from escaping to the surface
  - physical (e.g., highly impermeable caprock)
  - geochemical

Other forms of CO_2 ocean storage

THE UNIVERSITY OF WESTERN AUSTRALIA
Achieving International Excellence

- **Dissolution**: depths of 1000 – 3000 m, upward-plume, CO_2 dissolves in seawater
- **Lake deposits**: depths > 3000 m, downward-plume, expected delay dissolution of CO_2, possibly for millennia
- **Bicarbonate(s)**: chemical reaction to combine CO_2 with carbonate mineral (such as limestone)

Other forms of CO_2 ocean storage



IPCC (2005)

Sleipner West, Norway

THE UNIVERSITY OF WESTERN AUSTRALIA
Achieving International Excellence

- Operator: Statoil, Norway
- International energy company presented in more than 30 countries around the world

- Sleipner gas field (after steed Sleipnir, Norse mythology)
- Sleipner West (proven in 1974), Sleipner East (1981)
- Central North Sea
- about 250 kilometres west of Stavanger

Source of information: Statoil, http://www.statoil.com

Sleipner West

Licensees:

Statoil (49.5%),

Esso Norge (32.2%),

Norsk Hydro (8.9%),

TotalFinaElf Exploration Norge (9.4%)

- Natural gas and light oil condensates from sandstone structures about 2,500 metres below sea level.

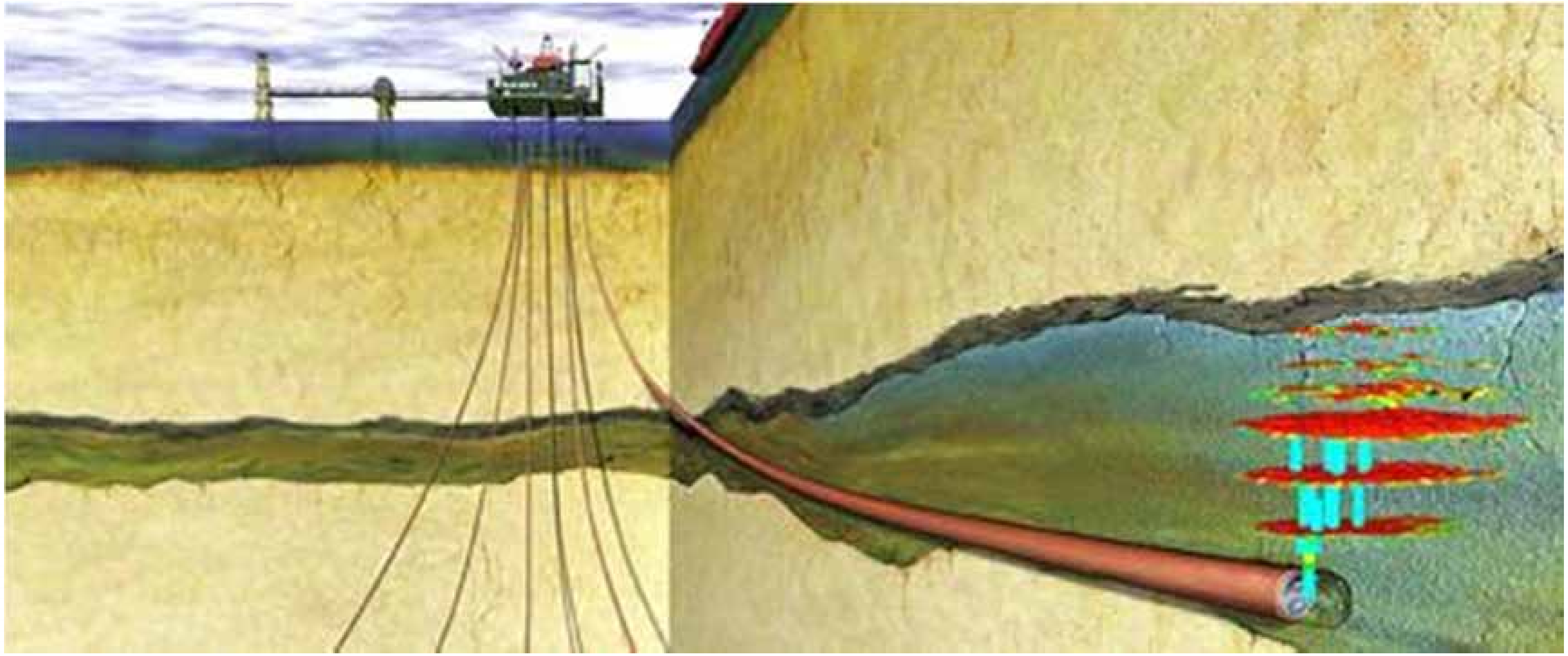
- Carbon capture and storage facility at Sleipner West
- World's first offshore CCS plant
- In operation since 1996

=> Oldest plant that stores CO_2 on an industrial scale

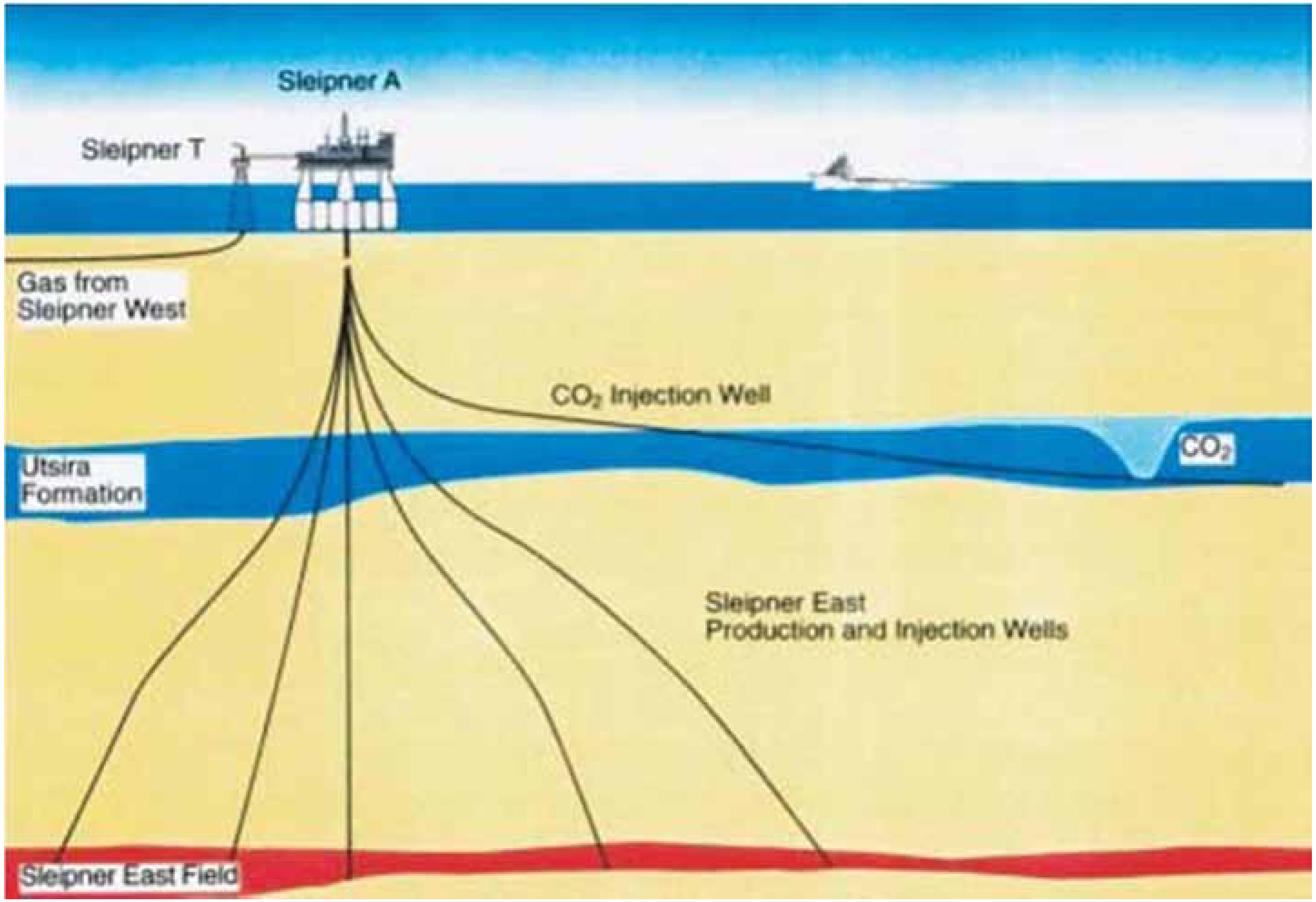
Sleipner West

Sleipner West

THE UNIVERSITY OF WESTERN AUSTRALIA
Achieving International Excellence

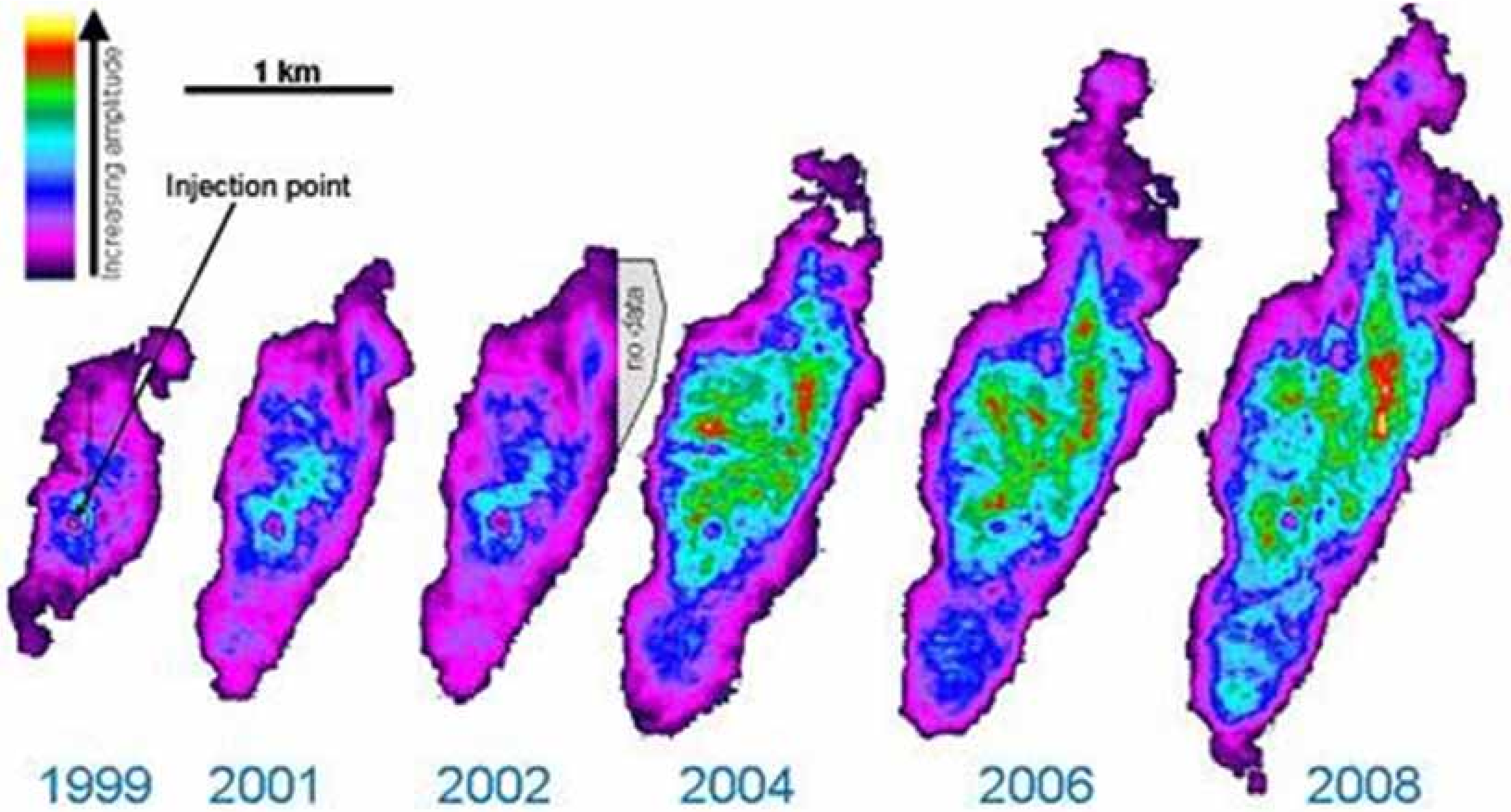


Sleipner West



IPCC (2005)

Sleipner West

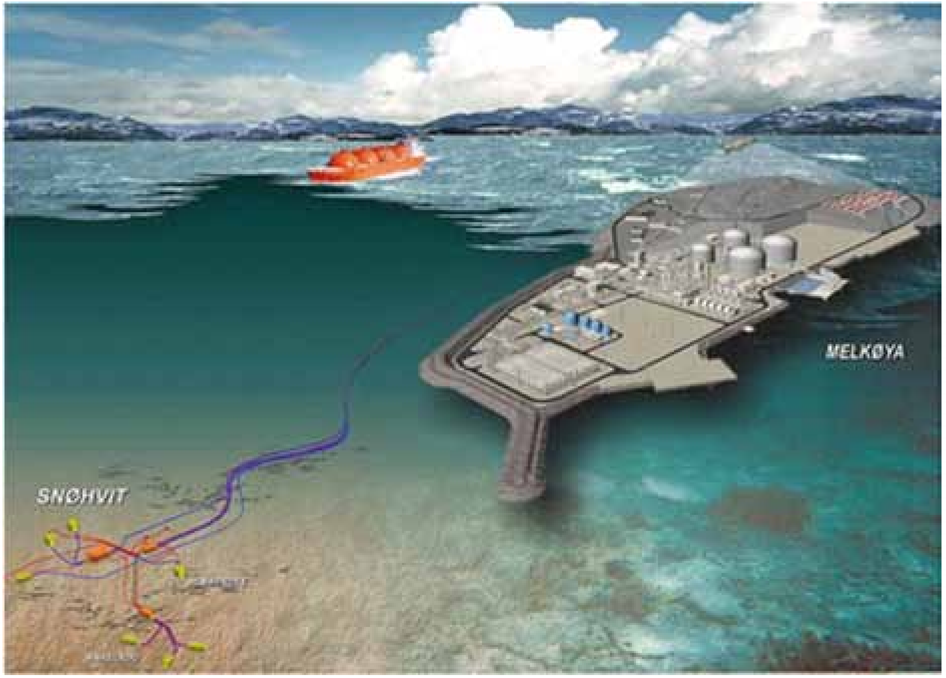


Images of the dispersal of stored carbon dioxide through the Utsira formation since injection began more than 12 years ago. The colour scale shows seismic amplitudes, which correspond approximately to vertically summed thicknesses of carbon dioxide in the sandstone.

Eiken et al. (2011)

Statoil, further projects

- In Salah (Algerian Sahara)
- Snøhvit (Barents Sea)



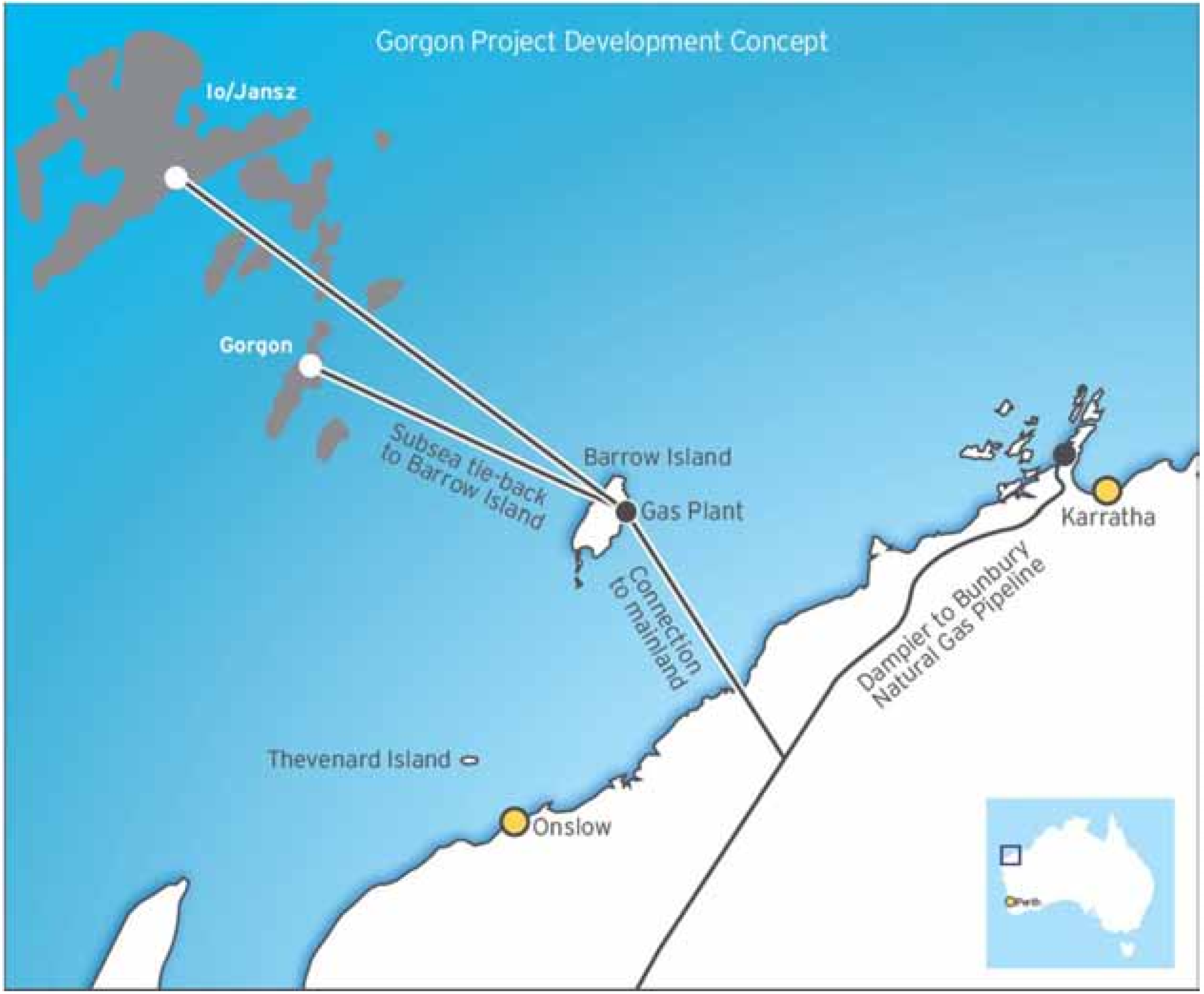
Source of information: Statoil, http://www.statoil.com

Gorgon, Australia

THE UNIVERSITY OF WESTERN AUSTRALIA
Achieving International Excellence

Gorgon

THE UNIVERSITY OF WESTERN AUSTRALIA
Achieving International Excellence



Source of information: Chevron, http://www.chevronaustralia.com

Gorgon

- Led by Chevron
- Greater Gorgon Area gas fields
- ~ 130 km off the north-west coast of Western Australia

- One of the world's largest natural gas projects
- The largest single resource natural gas project in Australia's history
- 15 million tonne per annum (MTPA) Liquefied Natural Gas (LNG) plant on Barrow Island
- domestic gas plant, capacity of 300 terajoules per day

Gorgon

- Important pillar of the Australian economy for > 40 years
- Projected AU$64 billion boost to Australia's Gross Domestic Product in first 30 years
- Direct and indirect employment of around 10,000 people at peak construction

- ~ 40 trillion cubic feet LNG

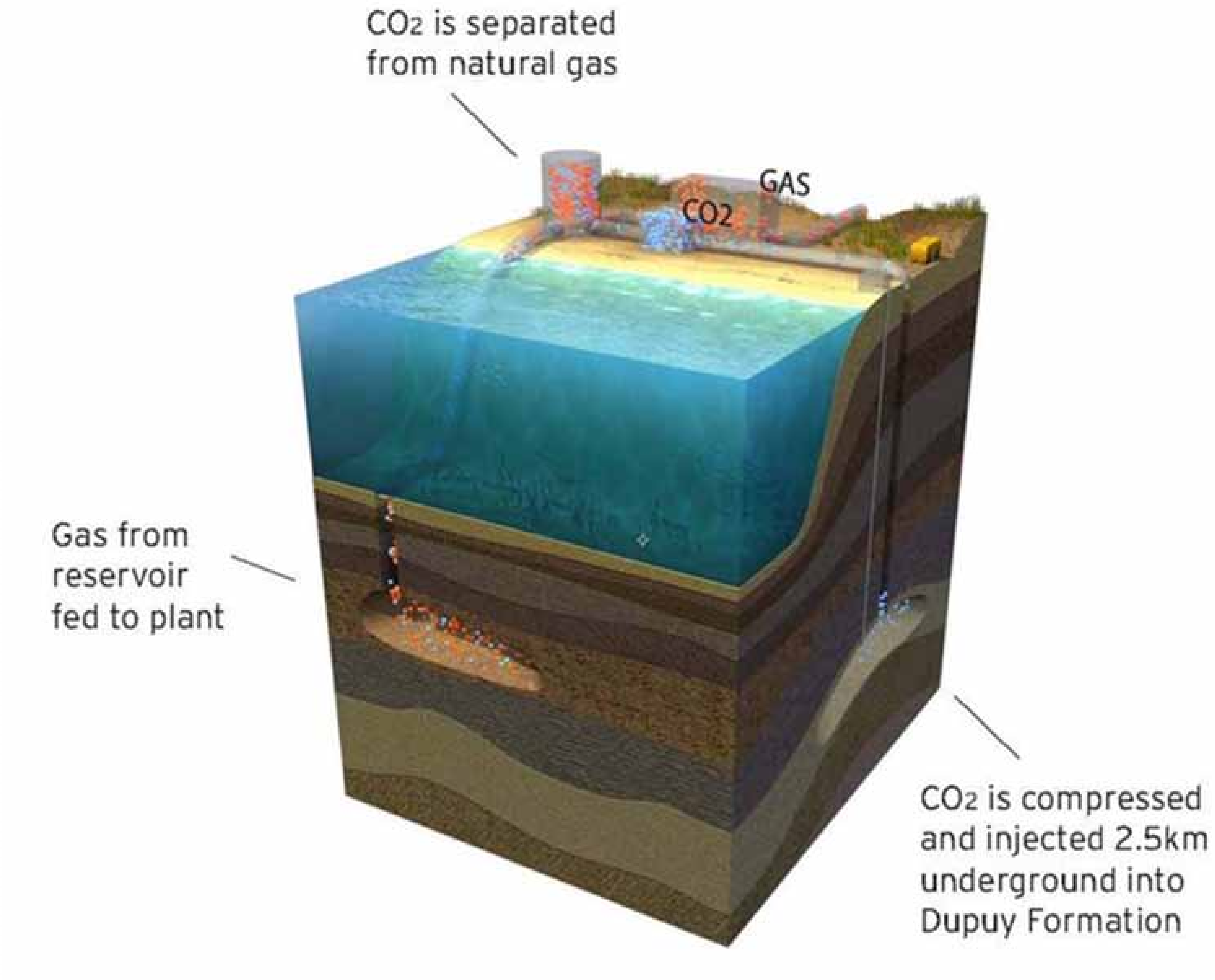
sufficient power for a city of 1 million people for 800 years

Gorgon

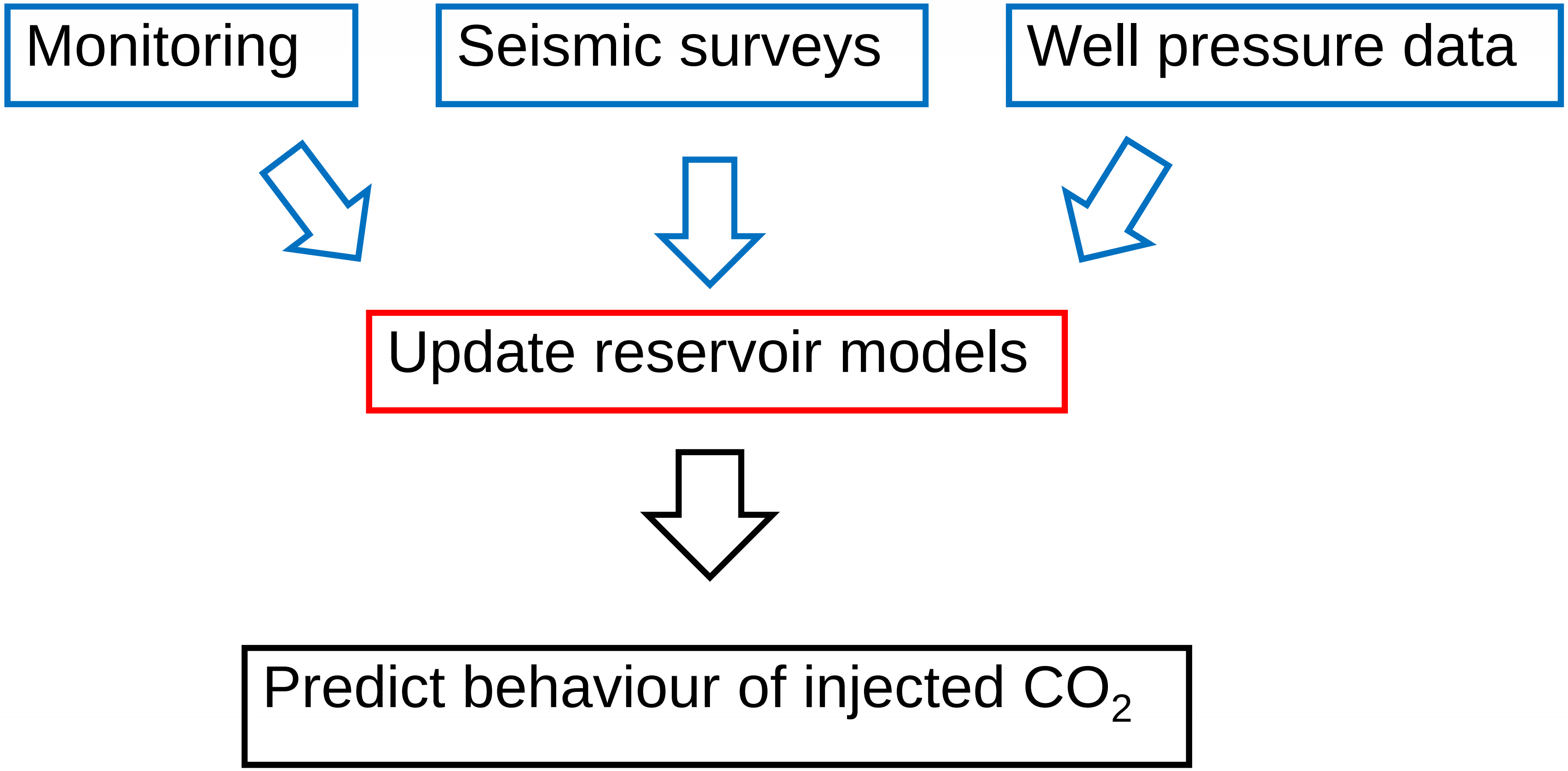
- Largest proposed carbon dioxide sequestration operation in the world
- Designed to capture 3.5 Mt of CO_2 per annum
- CO_2 injection location: central eastern coast of Barrow Island near the gas processing plant
- Site selection, aims: maximise distance from major geological faults and limit ground disturbance
- Injection wells: directionally drilled from surface locations
- Minimise the area of land required for the well sites, surface facilities, pipelines and access roads
- Monitoring wells: sample points within injection area

Gorgon

THE UNIVERSITY OF WESTERN AUSTRALIA
Achieving International Excellence



Gorgon


Monitoring
Seismic surveys
Well pressure data
Update reservoir models
Predict behaviour of injected CO_2

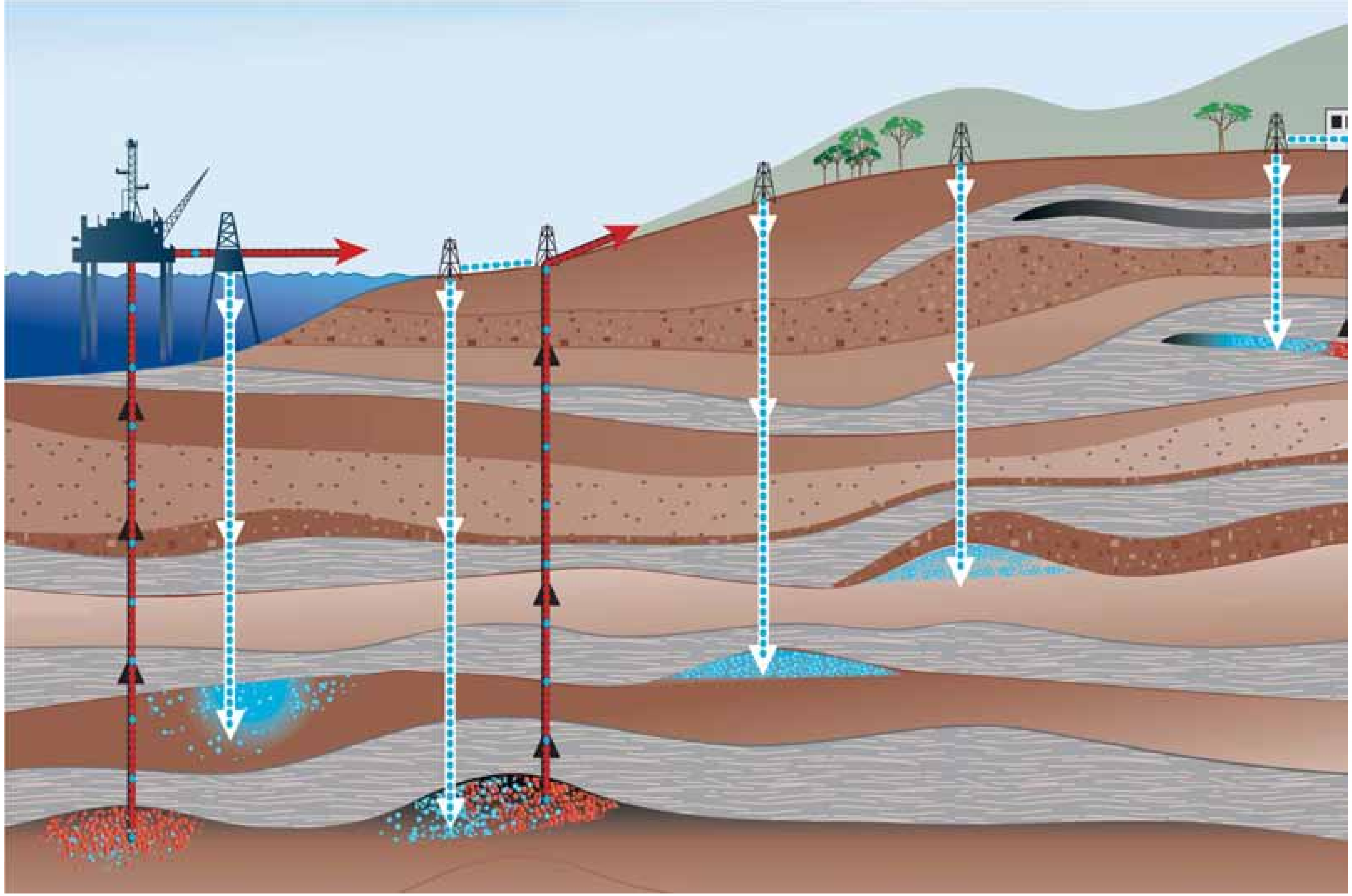
Themes

THE UNIVERSITY OF WESTERN AUSTRALIA
Achieving International Excellence

- Examples of carbon sequestration in ocean spaces
  - –Sleipner West
  - –Gorgon
- Geotechnical considerations in the context of geo-sequestration of CO_2 in the offshore environment
- “Ship design”: Mobile jack-up drilling rigs
- Offshore wind energy installation

Geotechnical considerations

THE UNIVERSITY OF WESTERN AUSTRALIA
Achieving International Excellence



IPCC (2005)

Geotechnical considerations

THE UNIVERSITY OF WESTERN AUSTRALIA
Achieving International Excellence

- Geohazards (tectonic activity)
- Soil permeability
- Subsea installations
- Pipeline-soil interaction
- Movements of the seabed due to carbon sequestration

$\Rightarrow$ Potential impact on soil-structure interaction of existing or proposed infrastructure

General considerations

- Major concern: effectiveness as climate change mitigation option due to leakage of stored CO_2
- IPCC estimate: risks comparable to those associated with current hydrocarbon activity for well-selected, designed and managed geological storage sites
- CO_2 could be trapped for millions of years
- Well selected storage sites likely to retain over 99% of injected CO_2 over 1000 years
- Greater risk: Leakage through the injection pipe

Themes

THE UNIVERSITY OF WESTERN AUSTRALIA
Achieving International Excellence

- Examples of carbon sequestration in ocean spaces
  - –Sleipner West
  - –Gorgon
- Geotechnical considerations in the context of geo-sequestration of CO_2 in the offshore environment
- “Ship design”: Mobile jack-up drilling rigs
- Offshore wind energy installation

“Design”, context of jack-ups

THE UNIVERSITY OF WESTERN AUSTRALIA
Achieving International Excellence

Site ✓

?

⇒ Site-specific assessment

Why?

- Self-elevating
- MOBILE

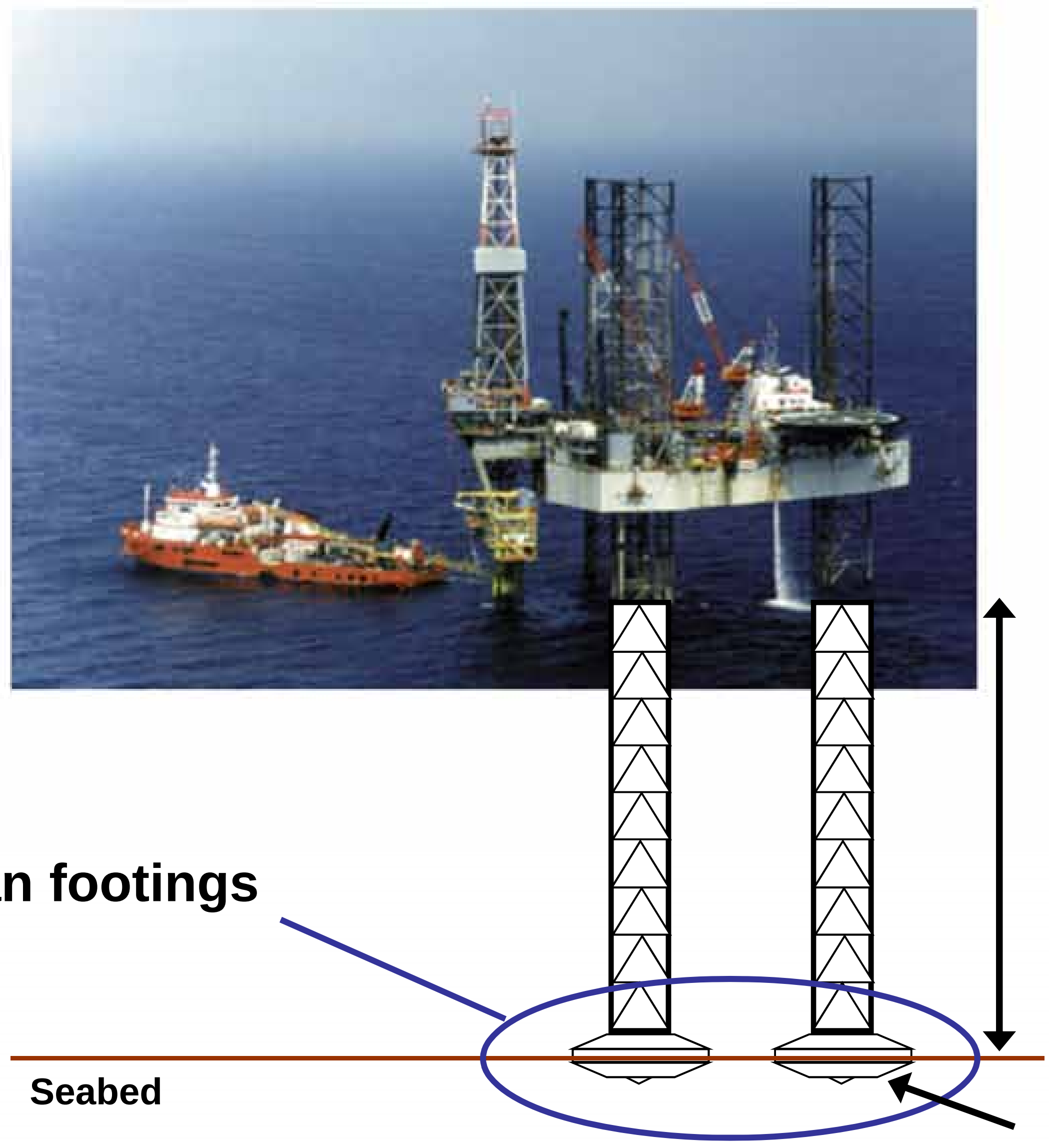
  i.e.re-useable
- Time spent on location

  ~ 2 weeks to 3 months

Goldeneye, North Sea (artist's impression)

What's beneath the water?

THE UNIVERSITY OF WESTERN AUSTRALIA
Achieving International Excellence



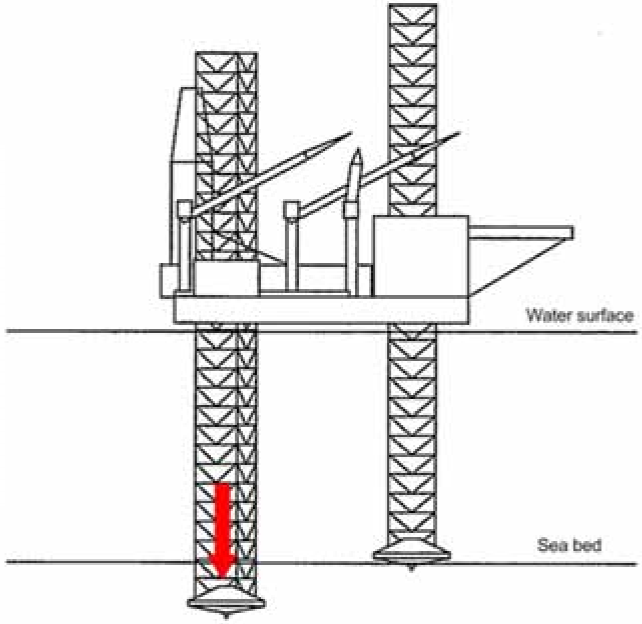
Risks associated with jack-ups

- In **transit**
  - Ship impact, towline failure, flooding, capsize (legs 500 ft above the water line)
- During **installation**
  - High leg impact loads at touchdown, contact with other structures (pipeline, WHP), punch-through, …
- During **operation**
  - Punch-through (not necessarily in the clear after installation!), leg sliding, excessive platform movement, ship impact, wave impact on hull, loss of foundation stability due to scour, rack/pinion failure

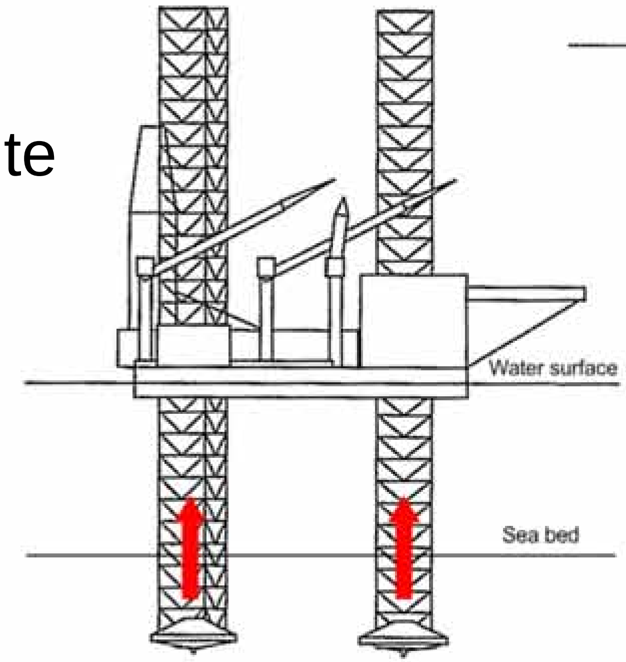
Jack-ups tend to be used to their operational and design limits

Considerations, examples

- "Simple" installation
- Punch-through
- Rack Phase difference (RPD)



- Removal from site



Modified after Dean (2010)

Installation on a sandy site

Bearing capacity problem, but…

•Context of offshore jack-up platforms

•Footing penetration

•SI?

ϕ??

(density, stresses, compressibility)

BC???

Guidelines

THE UNIVERSITY OF WESTERN AUSTRALIA
Achieving International Excellence

- SNAME (2008)
- ISO19905-1

Primarily aimed at site-specific assessment during operation

- InSafeJIP: guideline available for download (free)

http://insafe.woking.rpsplc.co.uk/download.asp

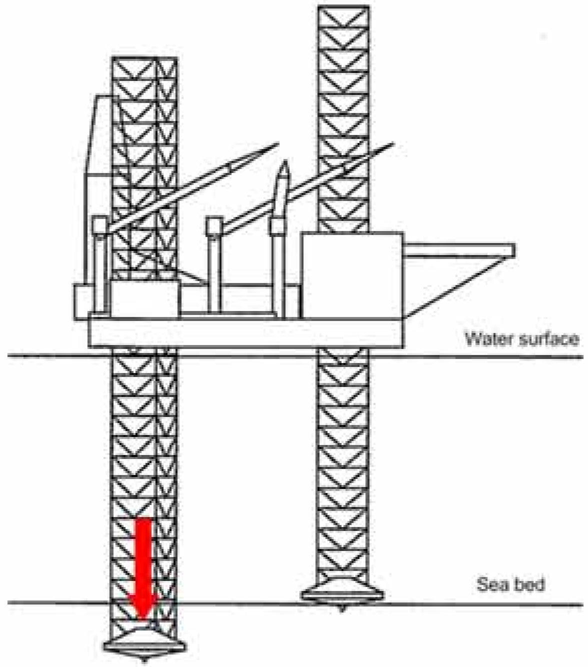
→ Focus on SI workscope and procedures, jack-up installation

Use realistic ϕ, account for mobilisation in BC

Spudcan

Motivation

- Accurate, not conservative prediction required
- Prediction of vertical load-penetration curve
- Footing penetration, not placement
- Large diameter foundations
- Conical foundation profile
- SI data



Modified after Dean (2010)

Ultimate aim: direct correlation with piezocone

Bearing capacity

- Soil characteristics
- Dense sand -> little penetration
- Soft clay -> larger penetration

  (of the order of 20-30 m)

  -> soil backflow?

Where is the uncertainty?...

“Simple” installation

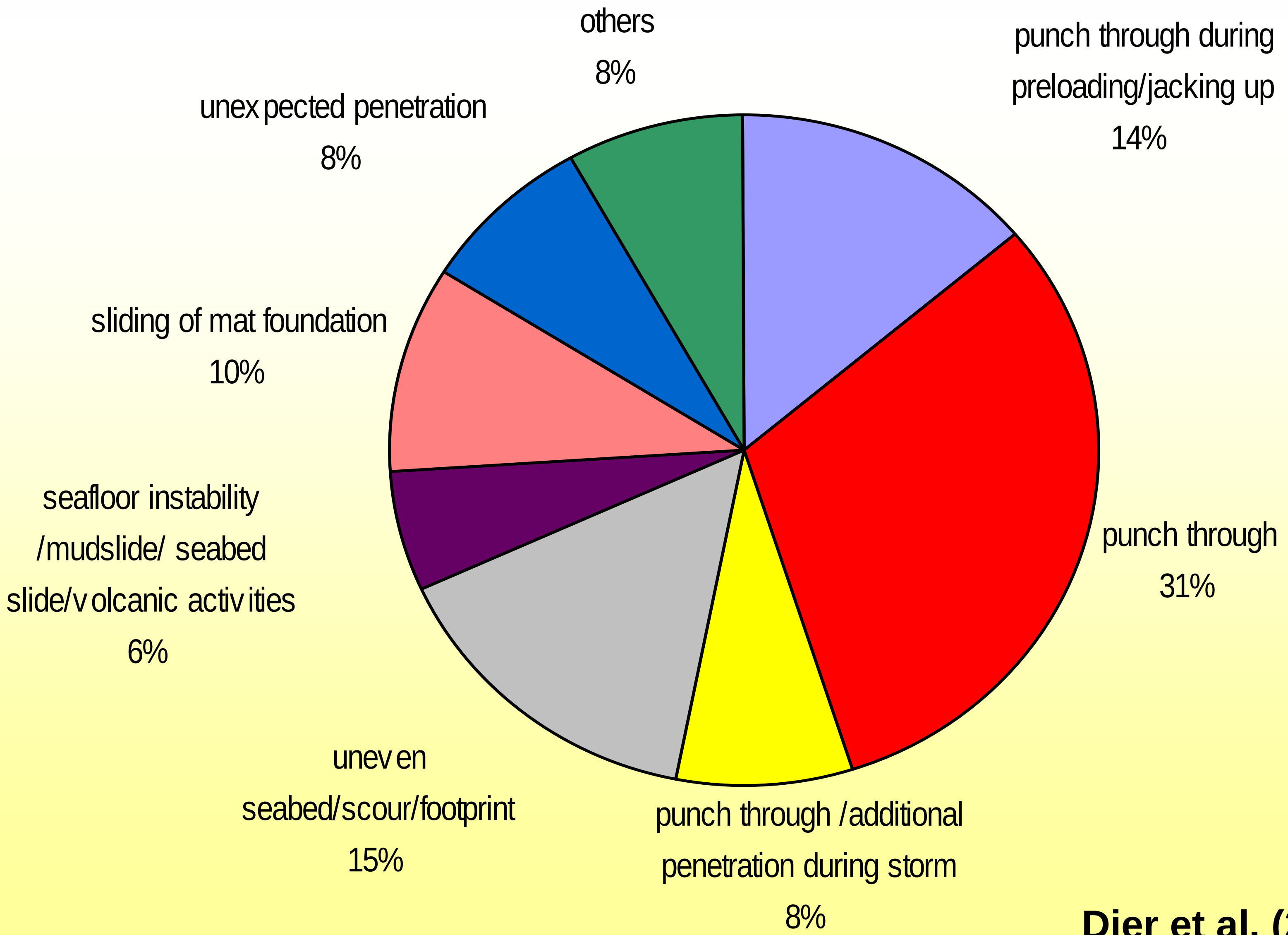
Where is the uncertainty?

Real life scenario:

- Neither single sand nor single clay
- Carbonate soils
- Silts
- …

Jack-up foundation failure

THE UNIVERSITY OF WESTERN AUSTRALIA
Achieving International Excellence

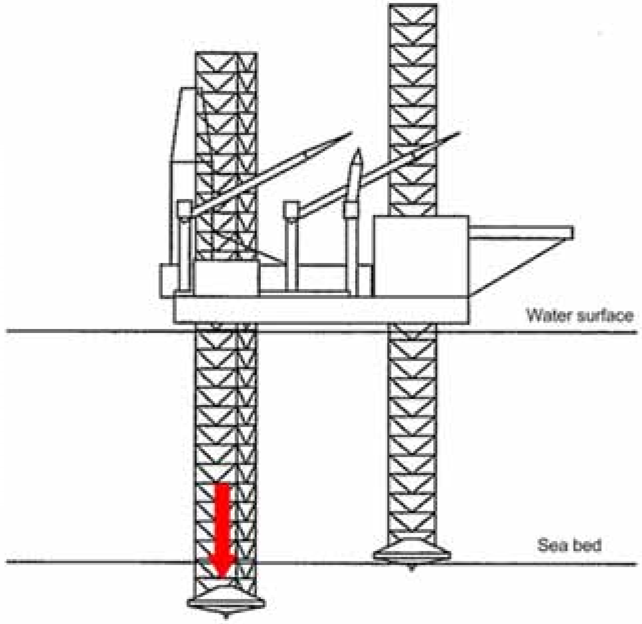


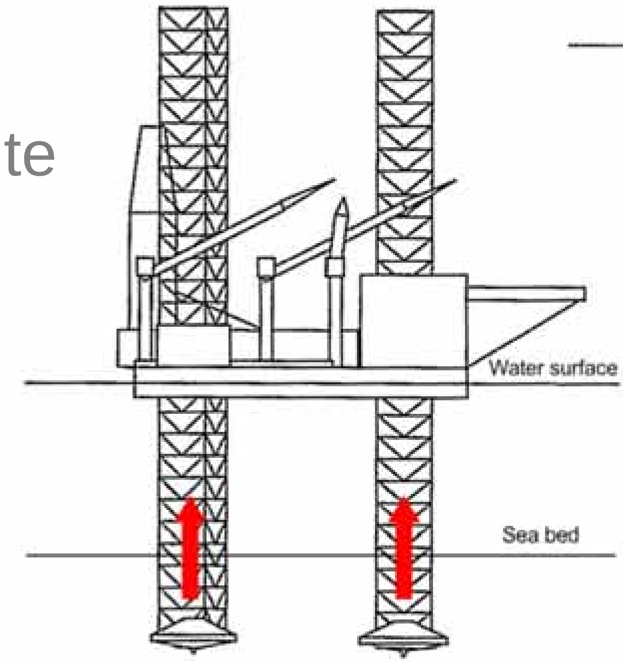
Dier et al. (2004)

Considerations, examples

THE UNIVERSITY OF WESTERN AUSTRALIA
Achieving International Excellence

- "Simple" installation
- Punch-through
- Rack Phase difference (RPD)
- Removal from site





Modified after Dean (2010)

Punch-through failure

THE UNIVERSITY OF WESTERN AUSTRALIA
Achieving International Excellence

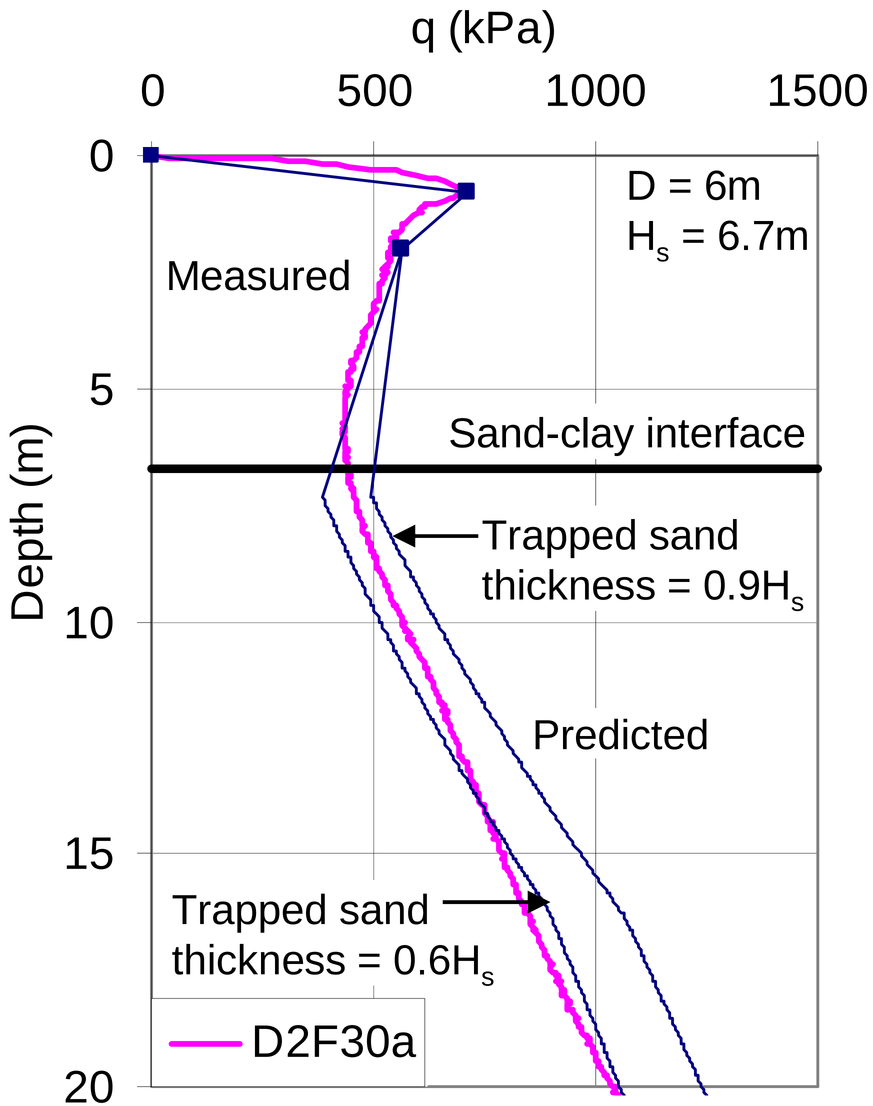
AD19, September 2002,

Saudi Arabia

Punch-through

Maersk Victory, November 1996, South Australia

Punch-through



(Lee 2009)

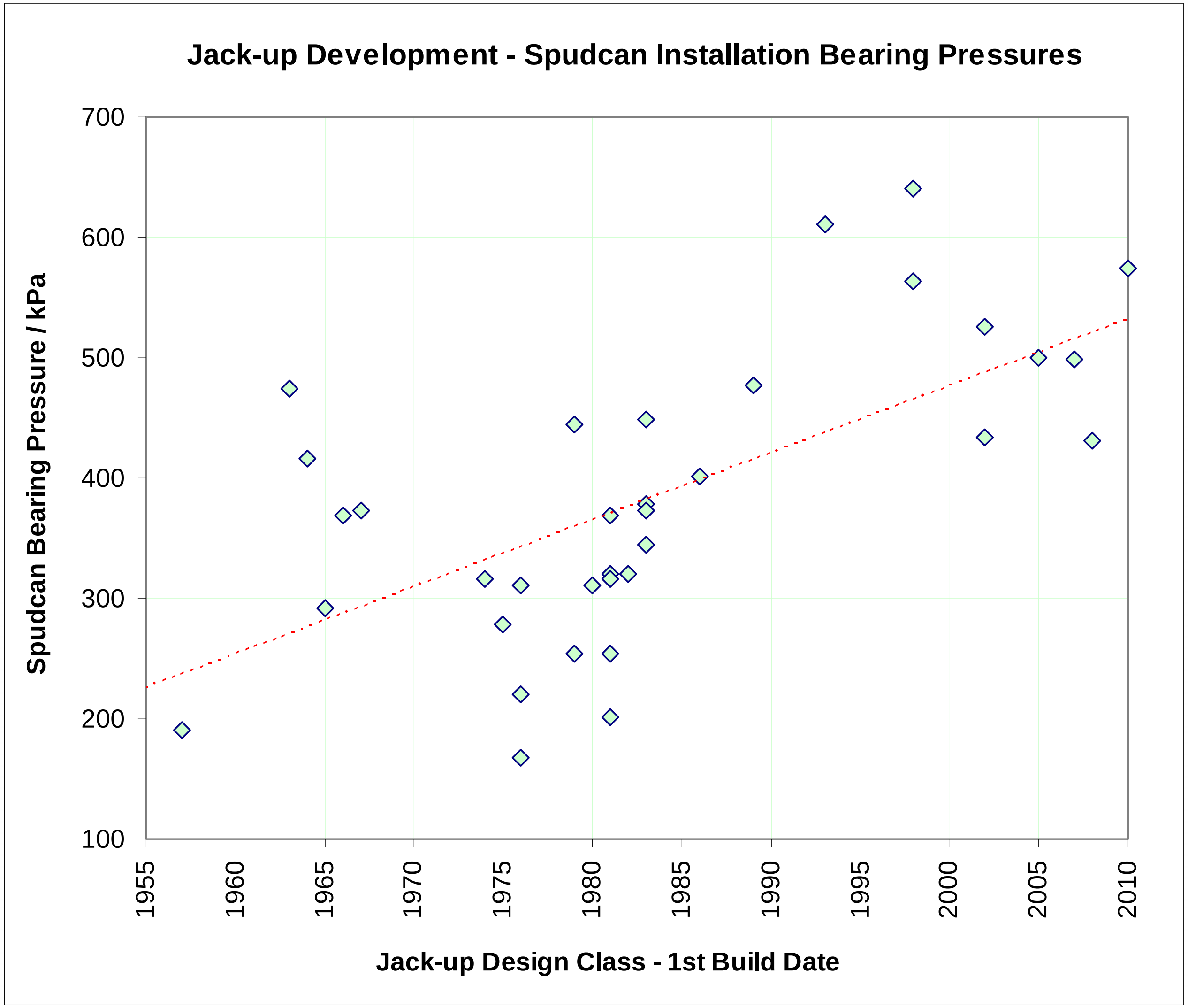
Punch-through

- Uncontrolled
- Structural problems
  - Leg bending,
- Damage to leg-hull connection,
  - Failure of leg element(s),
  - Lost time, lost revenue, repairs,
  - Excessive penetration -> legs not long enough
  - …
  - Collapse of rig

Punch-through

The University of Western Australia
Achieving International Excellence

Added risk: Increasing bearing pressure

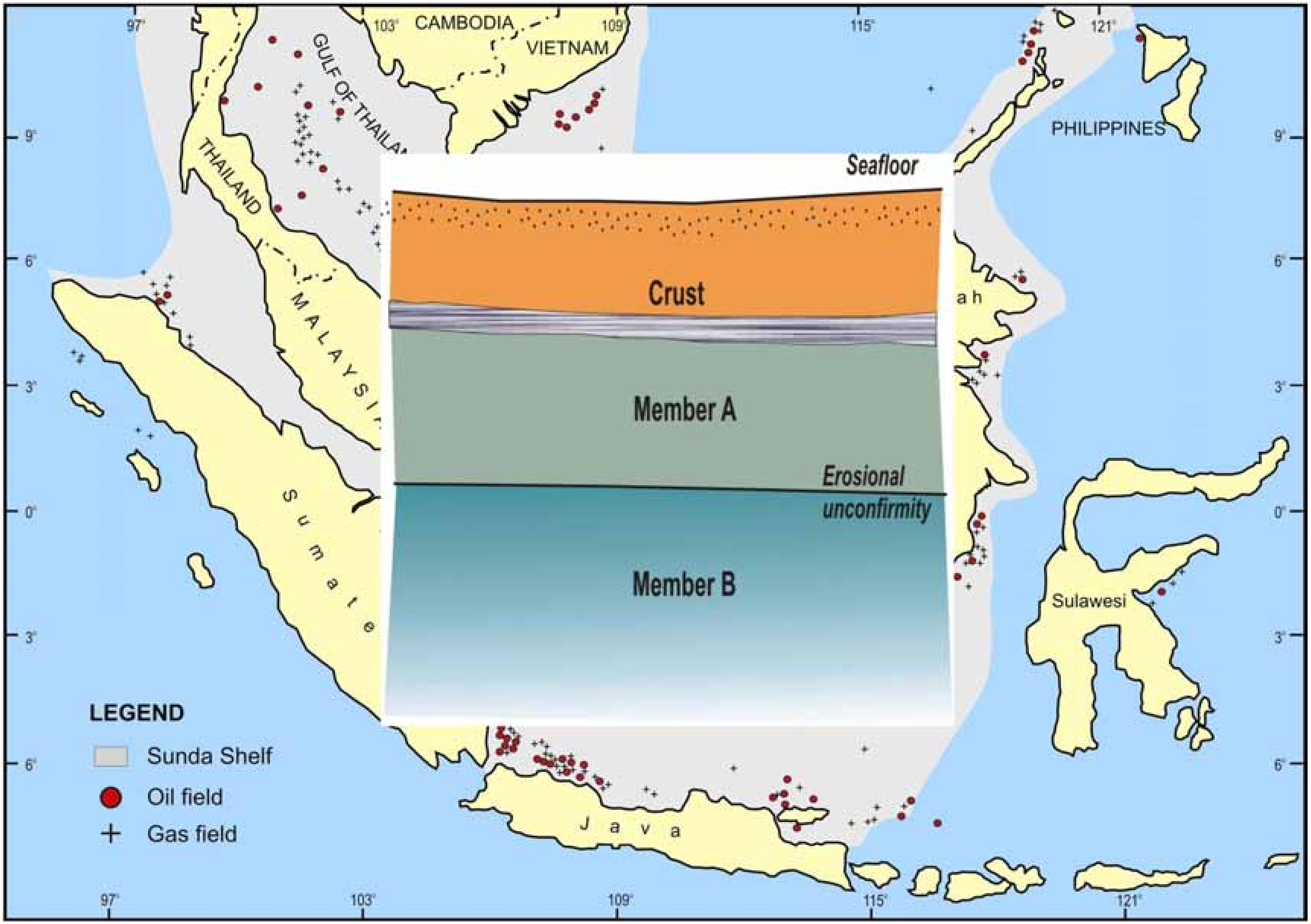


Osborne et al. (2006)

Clay over clay, Sunda Shelf

Castleberry & Prebaharan (1985)

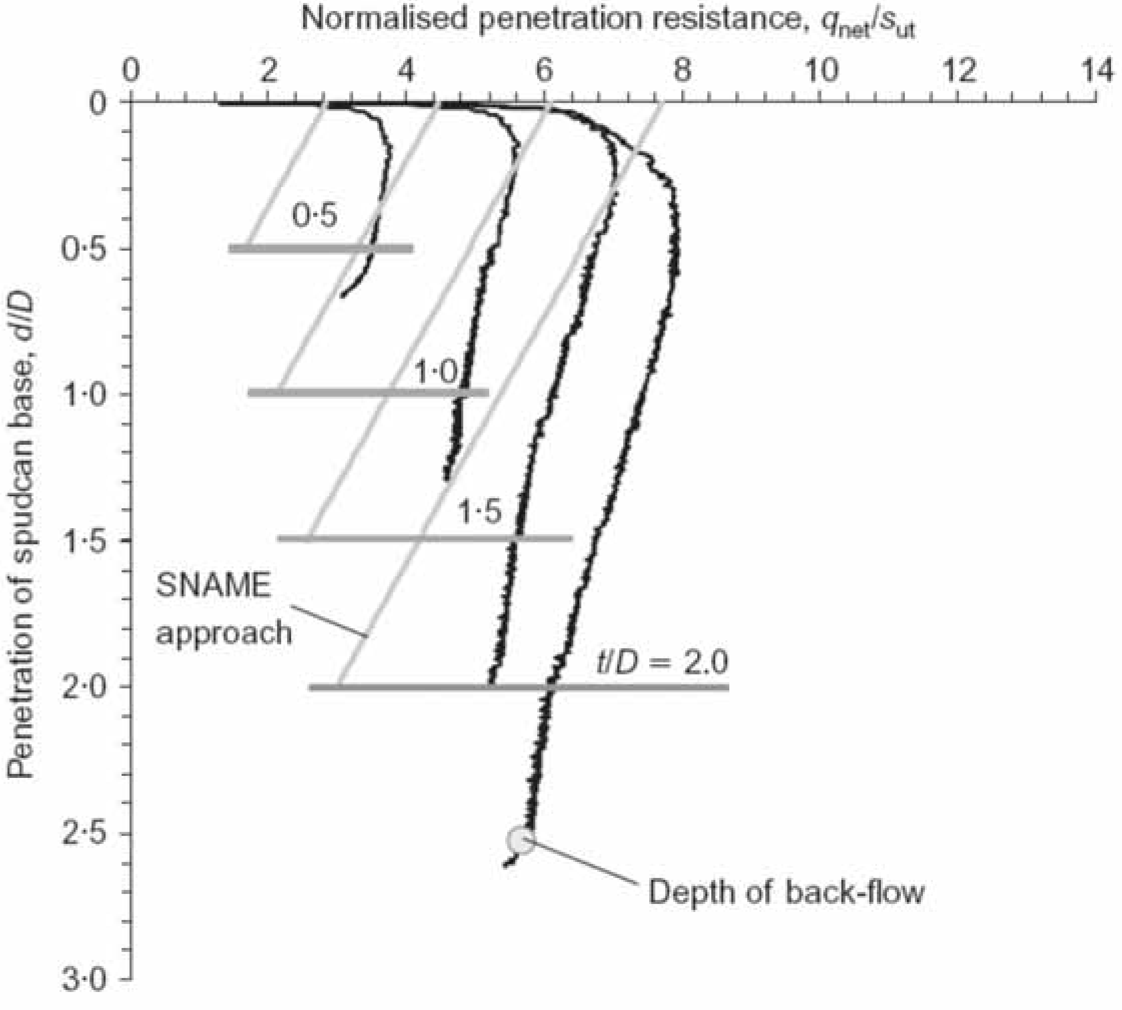
THE UNIVERSITY OF WESTERN AUSTRALIA
Achieving International Excellence



Punch-through: Clay over clay

THE UNIVERSITY OF WESTERN AUSTRALIA
Achieving International Excellence

Comparison of finite element results with SNAME (2008)



Hossain & Randolph (2010)

Punch-through: Sand over clay

SNAME (2008):

Two recommended methods

- Punching shear method
- Projected area method

  "although this method can provide reasonable quantitative estimates on leg penetration, it may not be based on a physically correct model"

Input: best estimate of soil strength parameters

-> Bearing resistance at every prescribed embedment using either one of the two methods with a safety factor of unity

-> Assess punch-through potential based on predicted bearing resistance-depth profile and target preload

Punch-through, sand over clay

Existing methods (incl. those in SNAME 2008)

are based on

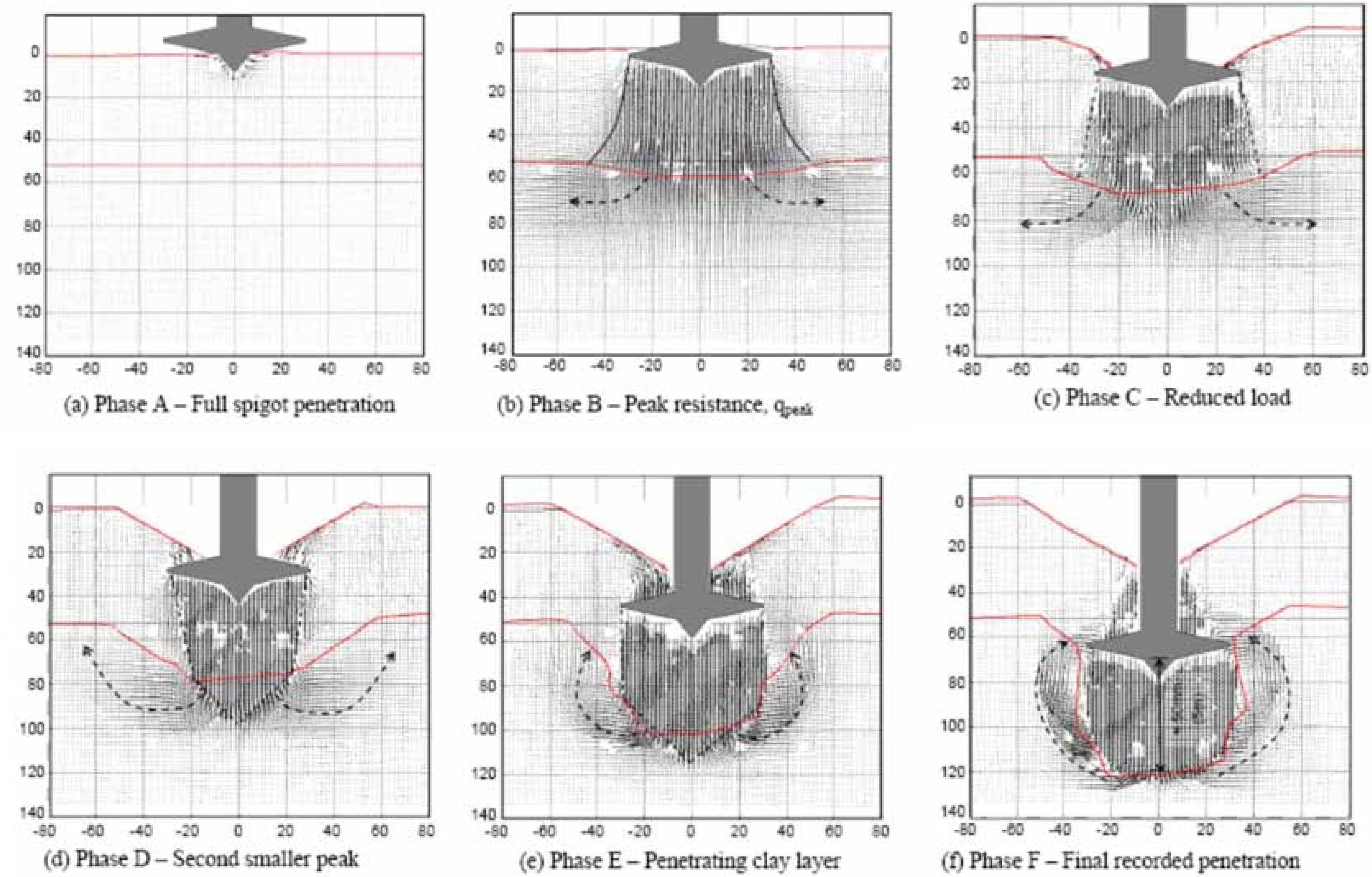
- wished in place footing and
- one failure mechanism

- is that correct?

Punch-through, sand over clay

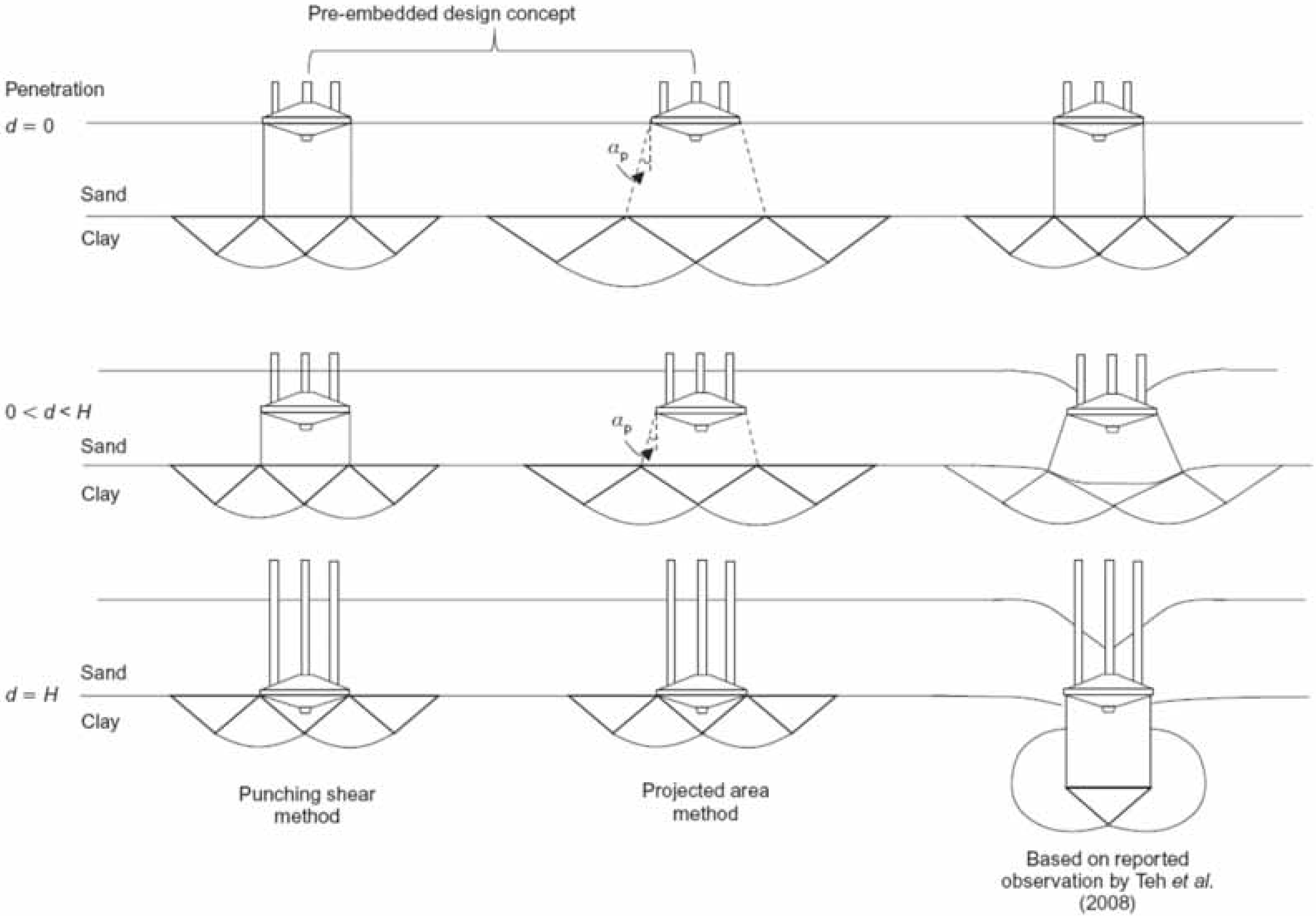
Punch-through

Sand over clay (Teh et al. 2008)

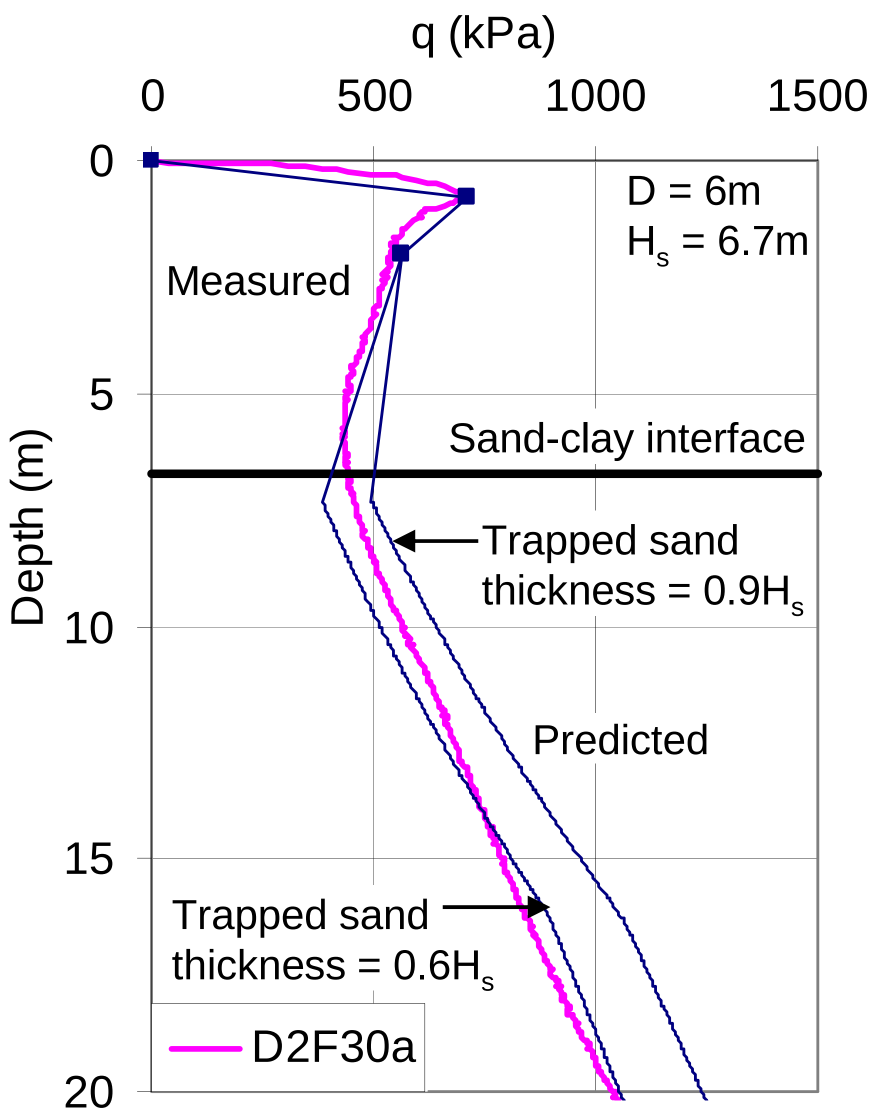


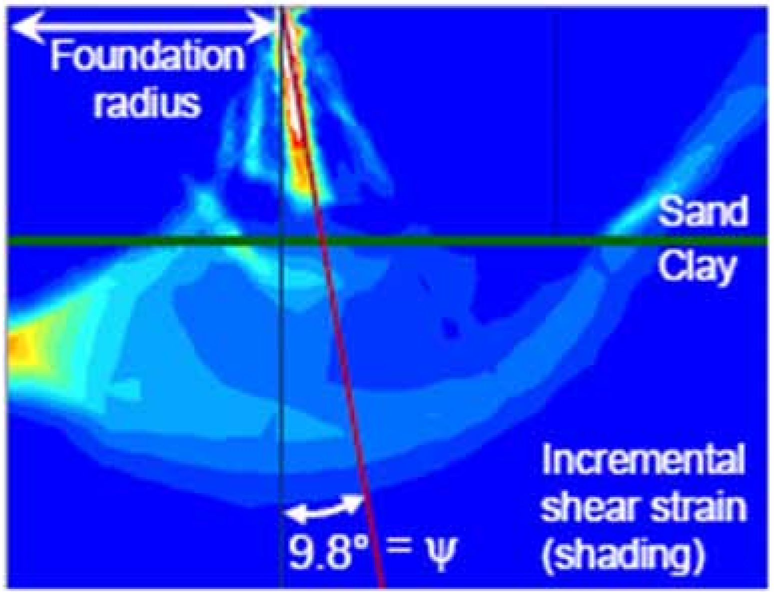
Punch-through, sand over clay

Comparison of failure mechanisms (Teh et al. 2010)



Punch-through





(Lee 2009)

Recent developments

THE UNIVERSITY OF WESTERN AUSTRALIA
Achieving International Excellence

Punch-through sand over clay

Teh, K.L., Cassidy, M.J., Leung, C.F., Chow, Y.K., Randolph, M.F., Quah, C.K. (2008). Revealing the bearing failure mechanisms of a penetrating spudcan through sand overlaying clay. *Géotechnique*. Vol. 58, No. 10, pp. 793-804.

Lee, K.K., Randolph, M.F., Cassidy, M.J. (2009). New simplified conceptual model for spudcan foundations on sand overlying clay soils. *Proc. 41st Offshore Technology Conference*, Houston, OTC-20012.

Teh, K.L., Leung, C.F., Chow, Y.K., Cassidy, M.J. (2010). Centrifuge model study of spudcan penetration in sand overlying clay. *Géotechnique*, Vol. 60, No. 11, pp. 825-842.

Punch-through clay over clay

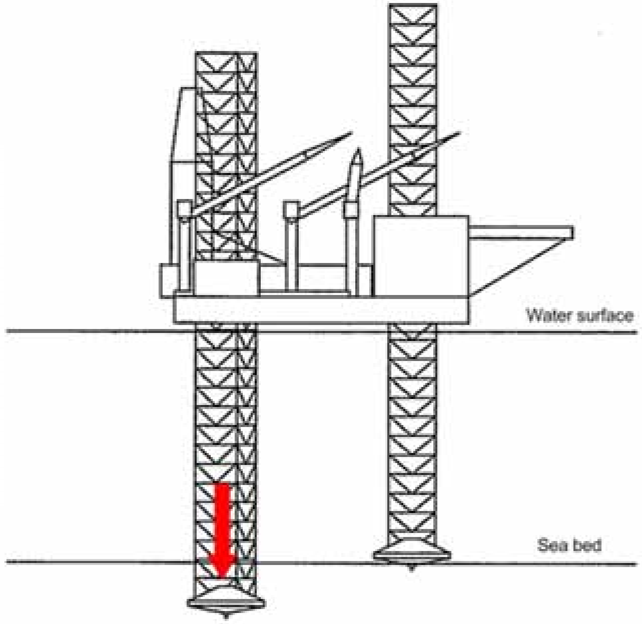
Hossain, M.S. and Randolph, M.F. (2010). Deep-penetrating spudcan foundations on layered clays: centrifuge tests. *Géotechnique*, Vol. 60, No. 3, pp. 157-170.

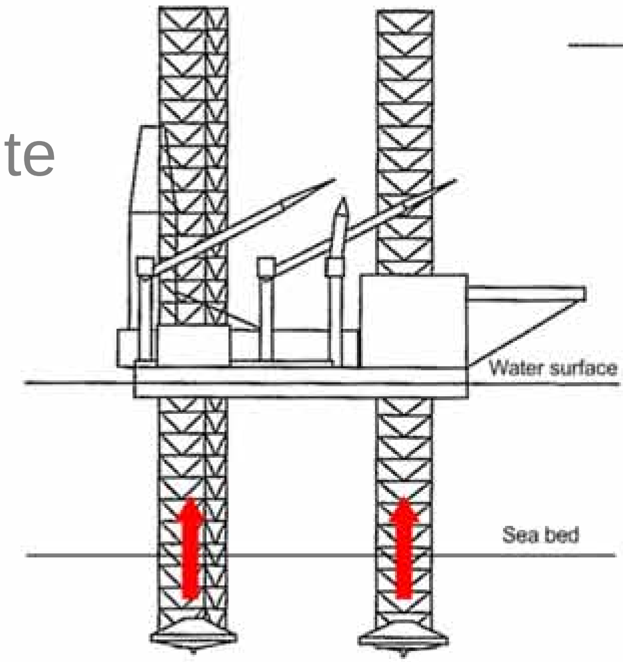
Hossain, M.S. and Randolph, M.F. (2010). Deep-penetrating spudcan foundations on layered clays: numerical analysis. *Géotechnique*, Vol. 60, No. 3, pp. 171-184.

Considerations, examples

- “Simple” installation
- Punch-through
- **Rack Phase difference (RPD)**

- Removal from site





Modified after Dean (2010)

Rack phase difference (RPD)

THE UNIVERSITY OF WESTERN AUSTRALIA
Achieving International Excellence

- **What is RPD?**
  - **"Measurable difference in the vertical position of the chords relative to each other within an individual leg"**

    Nowak & Lawson (2005)

  - **Alerts to potential problems!**

Rack phase difference (RPD)

Why is it important?

Sharples (2008)

Rack phase difference (RPD)

GSF High Island III

after Hurricane Rita

Sharples (2008)

Rack Phase difference

THE UNIVERSITY OF WESTERN AUSTRALIA
Achieving International Excellence

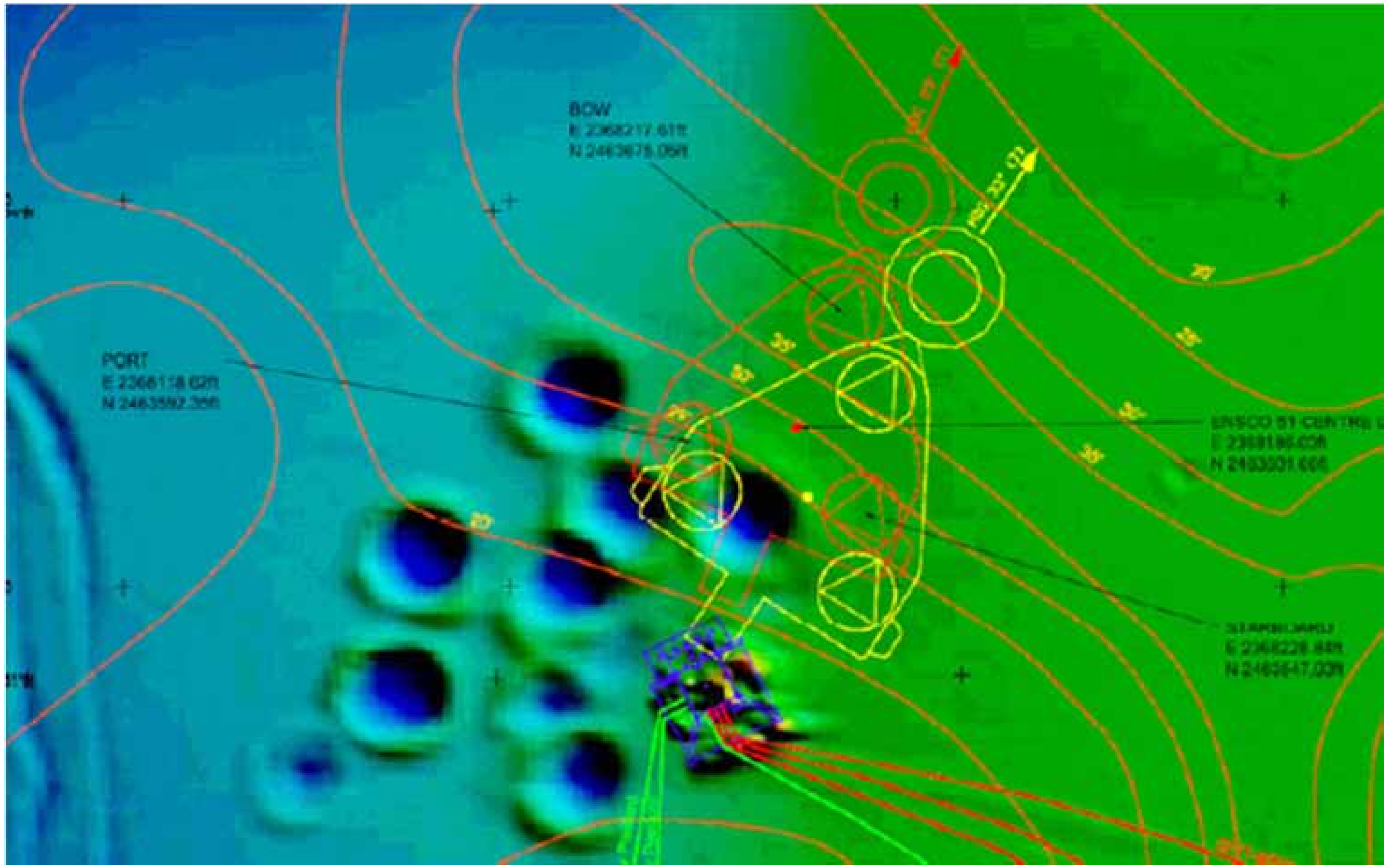
… a measure of how "unhappy" the rig is

Typical situations where RPD occurs:

- Existing footprints
- Sloping or uneven seabed (hard spots)
- Scour (leading to uneven seabed)
- Rapid penetration / punch-through

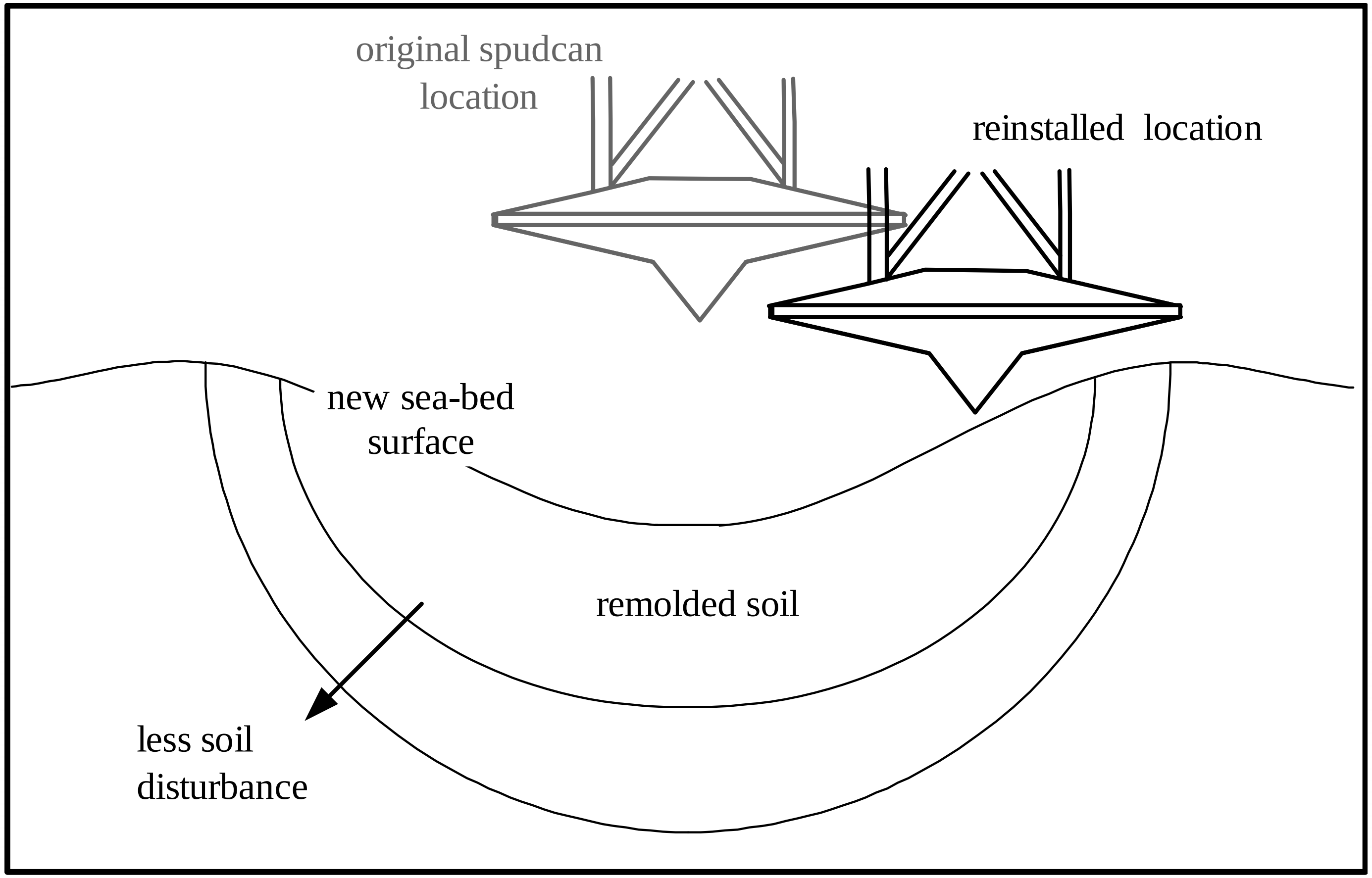
Nowak & Lawson (2005)

Existing footprints



Nowak et al. (2008)

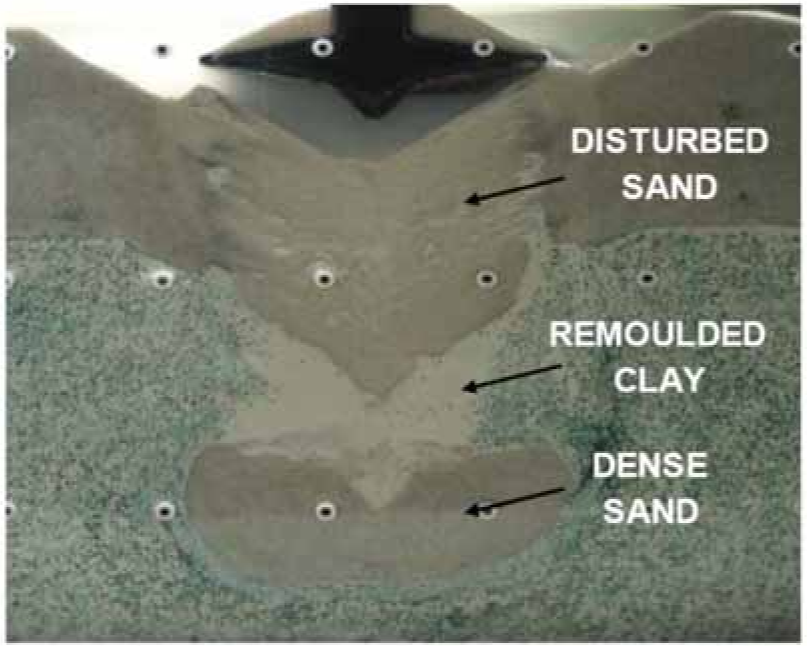
Soil characteristics at existing footprints



Soil characteristics at existing footprints

Change in sand over clay soil profile (Teh 2006)

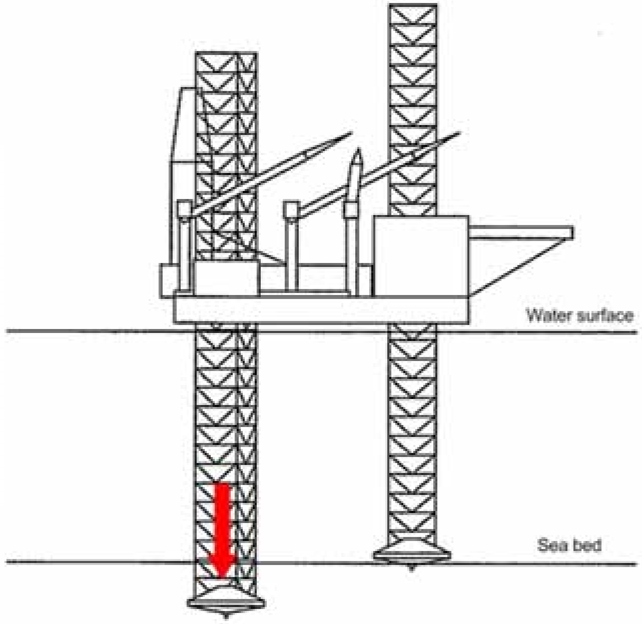
(a) Prior to spudcan installation



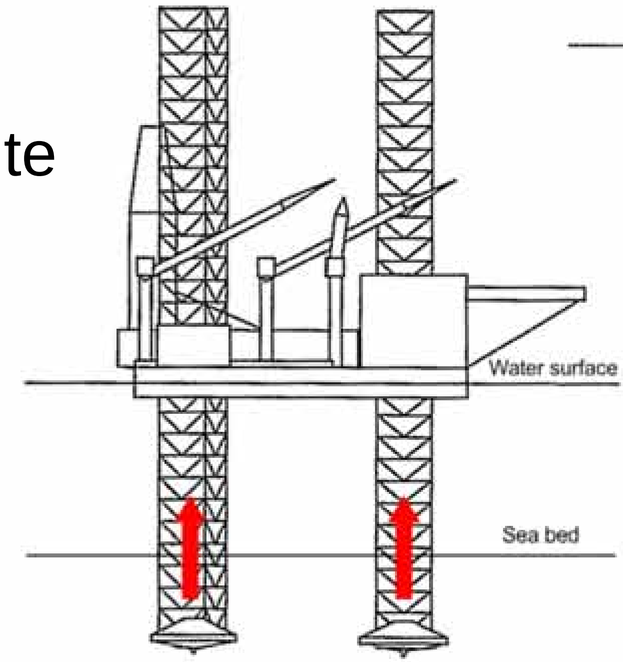
(b) After spudcan extraction

Considerations, examples

- “Simple” installation
- Punch-through
- Rack Phase difference (RPD)

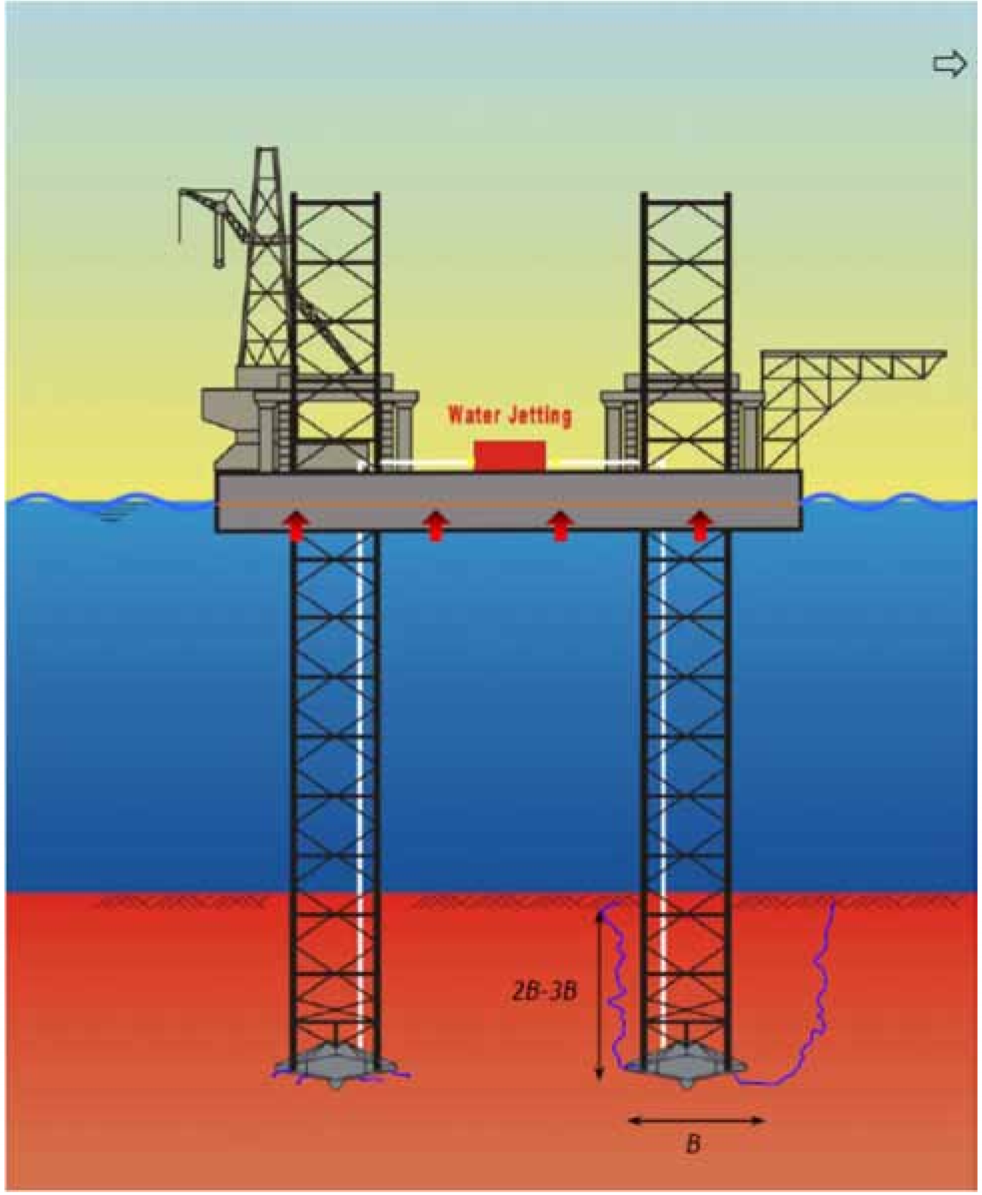


- Removal from site



Modified after Dean (2010)

Spudcan extraction with jetting



Purwana et al. (2008)

Spudcan extraction with jetting

Experiments carried out in the UWA geotechnical centrifuge

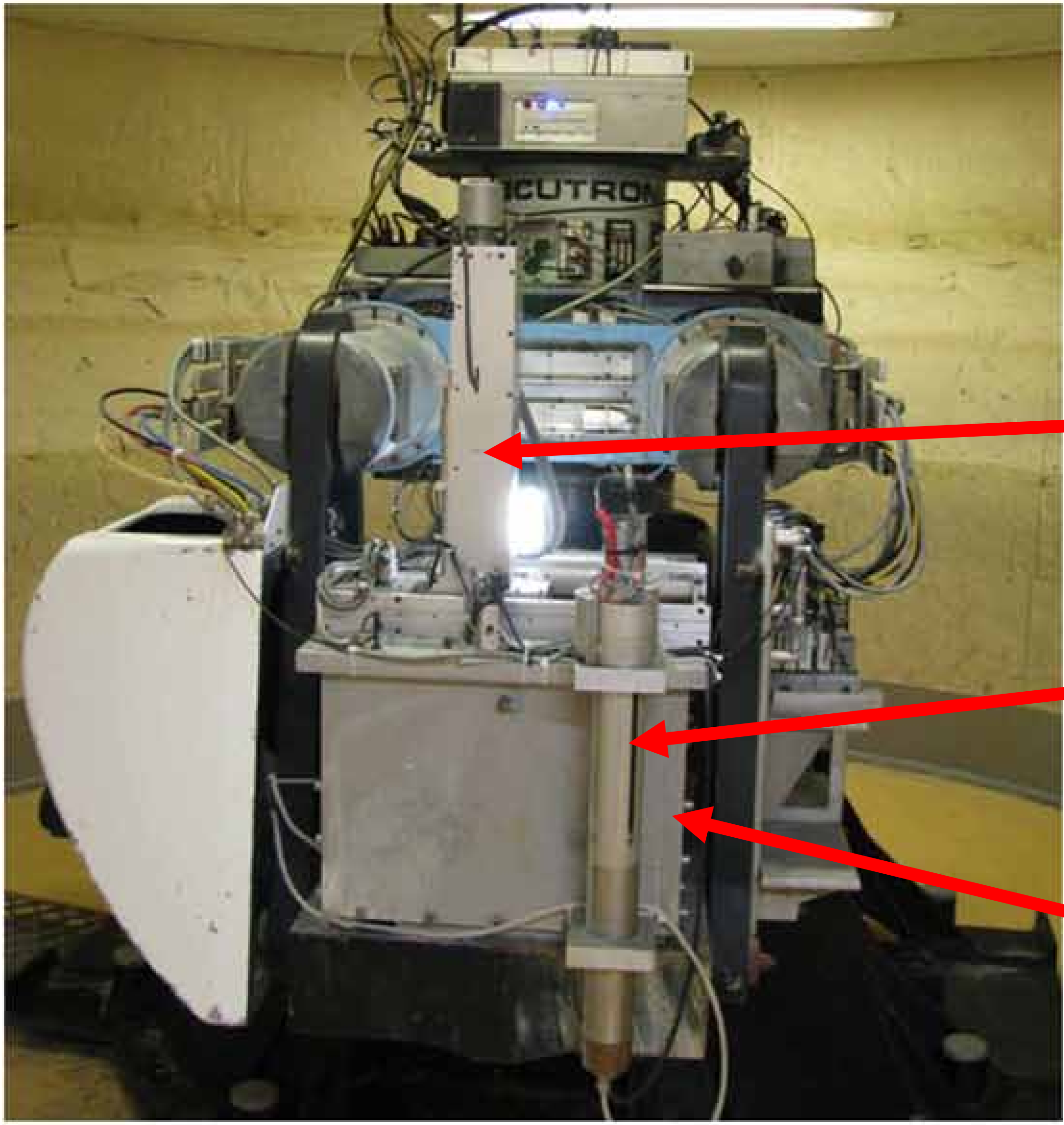
Gaudin et al. (2011)

Centrifuge experiments

The University of Western Australia
Achieving International Excellence

- Numerous field experiments offshore not feasible
- True scale model
- Similitude to prototype
- Carefully controlled conditions
- Enhanced g level

Centrifuge experiments

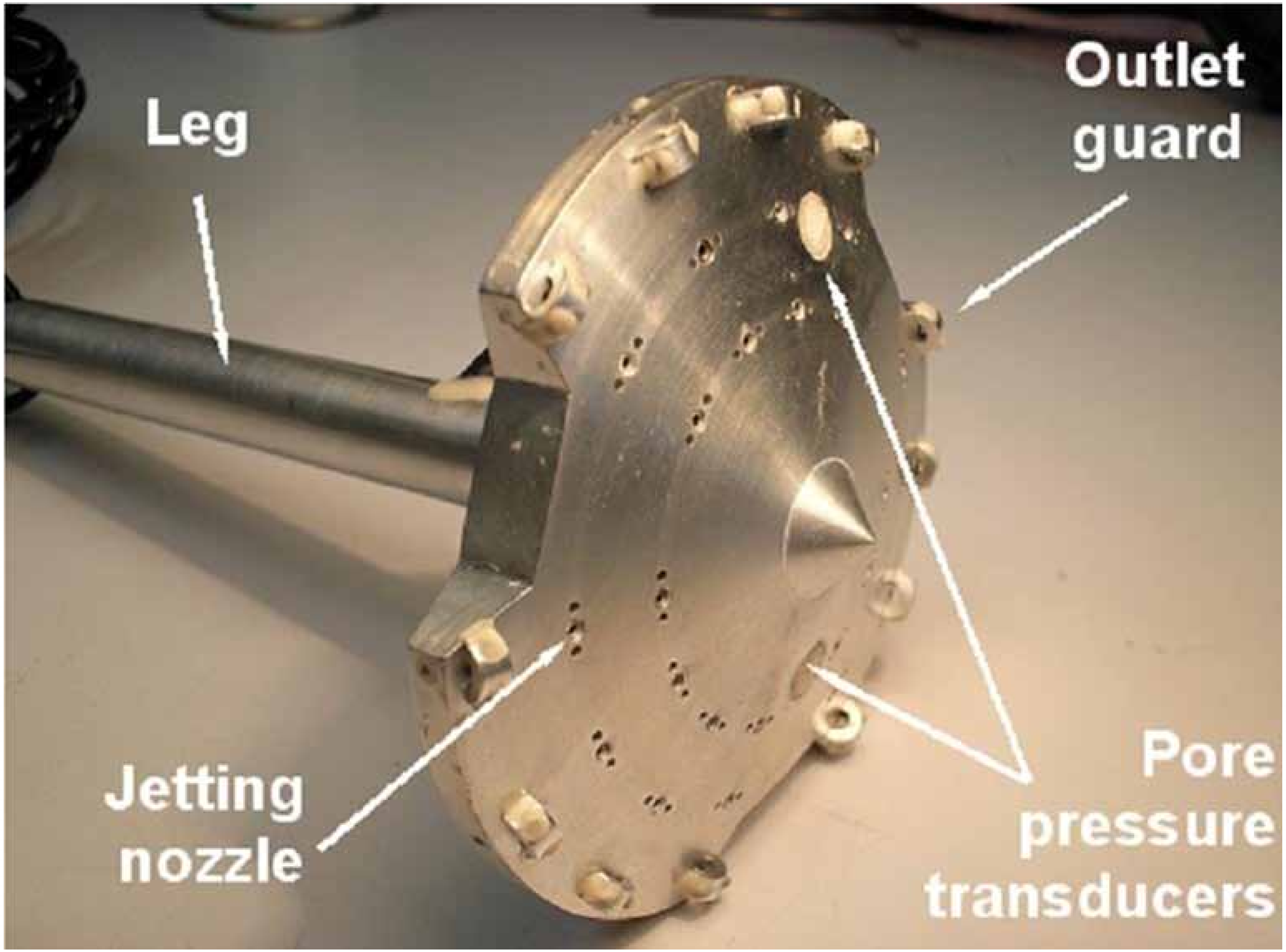


2D actuator

Syringe pump

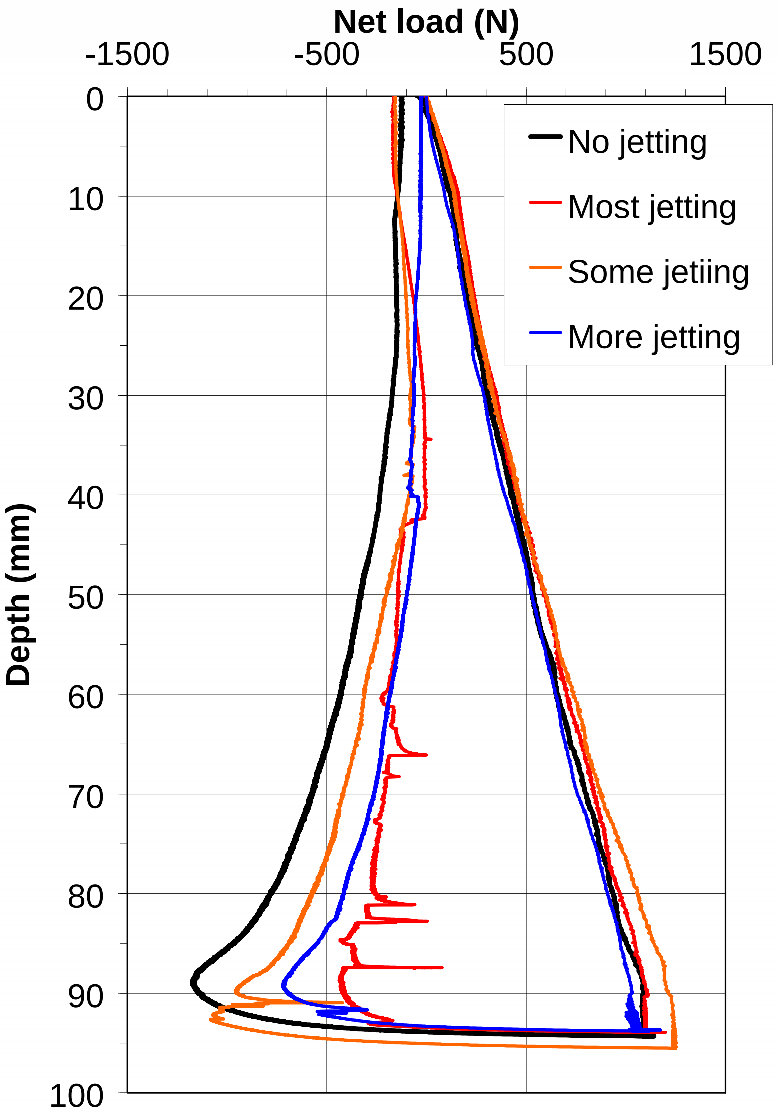
Strongbox

Centrifuge model



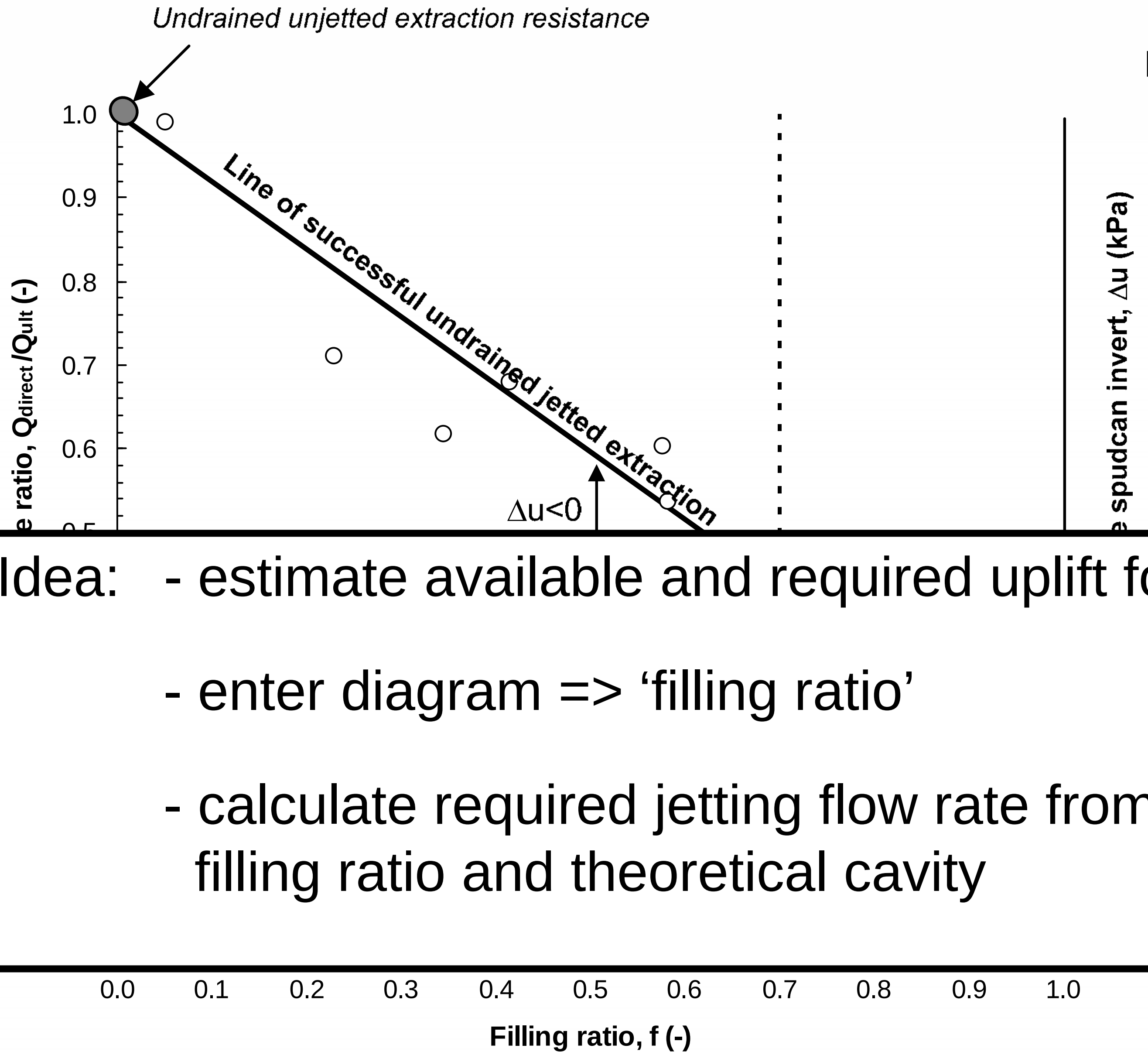
Spudcan extraction with jetting

Experiments carried out in the UWA geotechnical centrifuge



Conceptual framework

Bienen et al. (2009)



Idea: - estimate available and required uplift force

- enter diagram => 'filling ratio'

- calculate required jetting flow rate from required filling ratio and theoretical cavity

Themes

- Examples of carbon sequestration in ocean spaces
  - –Sleipner West
  - –Gorgon
- Geotechnical considerations in the context of geo-sequestration of CO_2 in the offshore environment
- “Ship design”: Mobile jack-up drilling rigs
- Offshore wind energy installation

Offshore wind energy

- Foundation concepts
  "exported" from
  onshore experience
- Differences in scale
- Differences in logistics

Offshore wind turbine under construction

Offshore wind energy

THE UNIVERSITY OF WESTERN AUSTRALIA
Achieving International Excellence

- Differences in loading

? Applicability of methods?

⇒ Development of appropriate design methods

⇒ Development of novel foundation concepts

Alpha Ventus

Thank you

-

Questions?