Recent Advances in the Analysis of Offshore Foundation Systems
海洋基础工程的最新研究进展

Hsue-Shen Tsien Lecture
钱学森讲座

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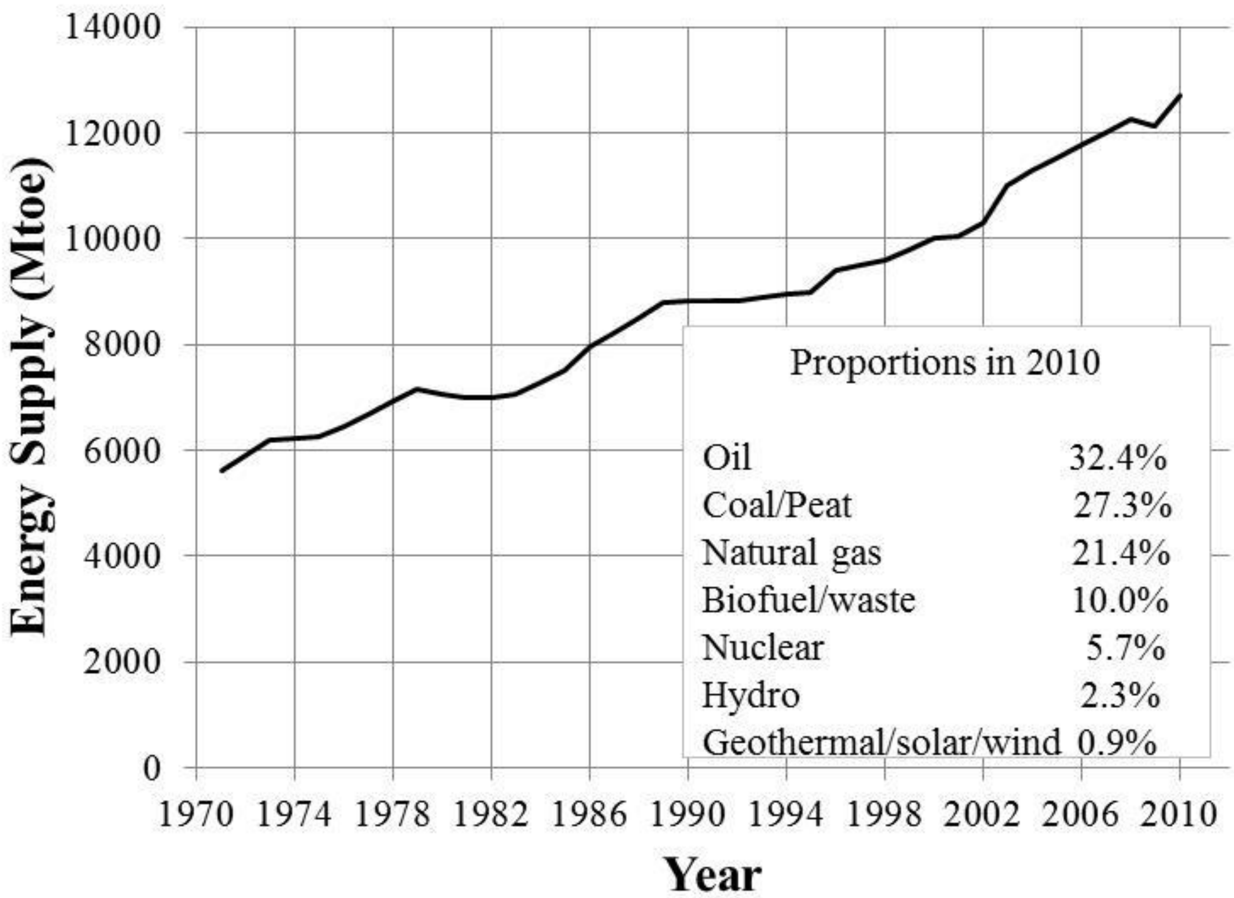
Hsue-Shen Tsien Lecture

Institute of Mechanics
Chinese Academy of Science

7 June 2016

An Era of Escalating Energy Demand
能源需求不断攀升的时代



Total primary energy supply
(from International Energy Agency, 2012[a])

An Era of Escalating Energy Demand
能源需求不断攀升的时代

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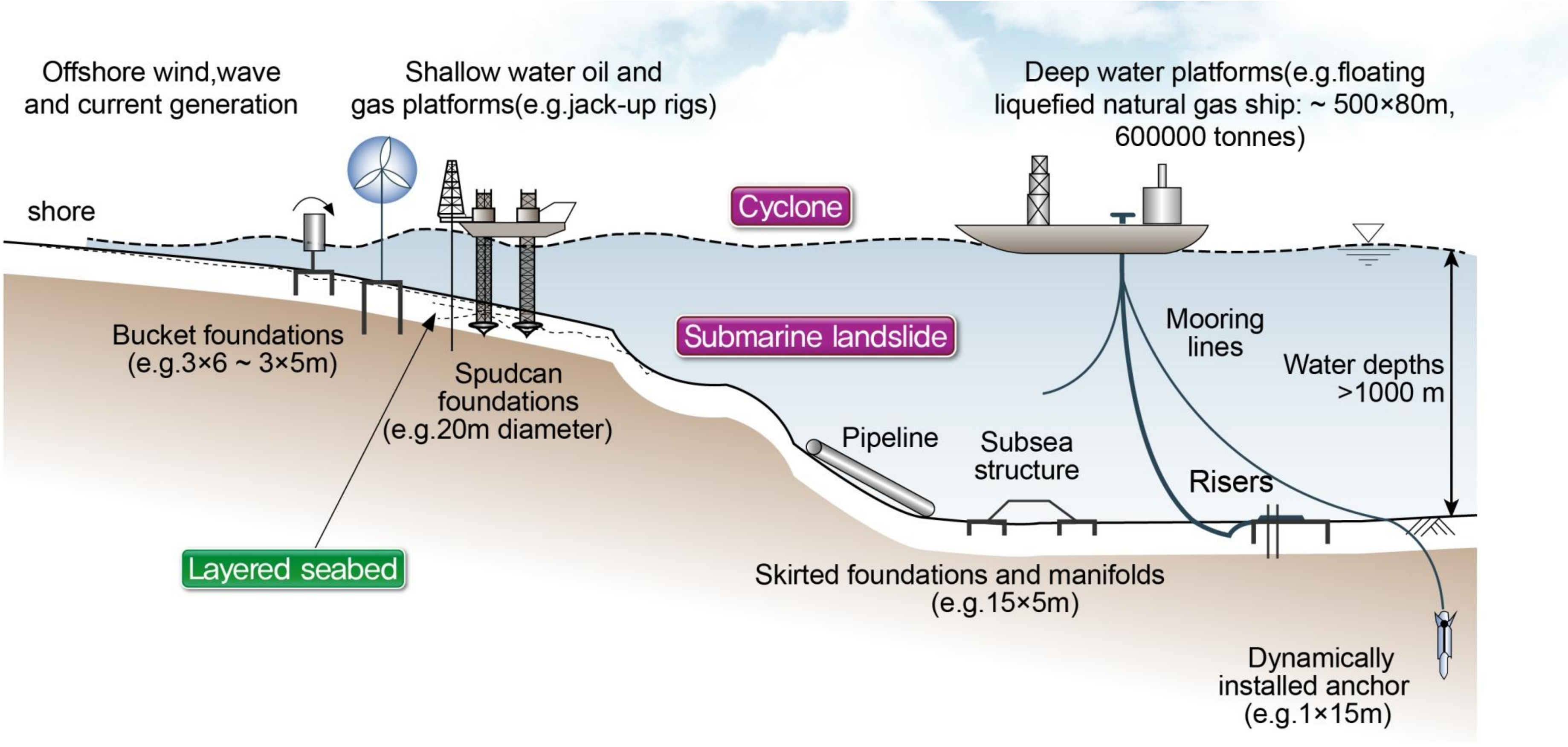
Renewables
可再生能源工程

New regions
新水域

Deep water
深水工程

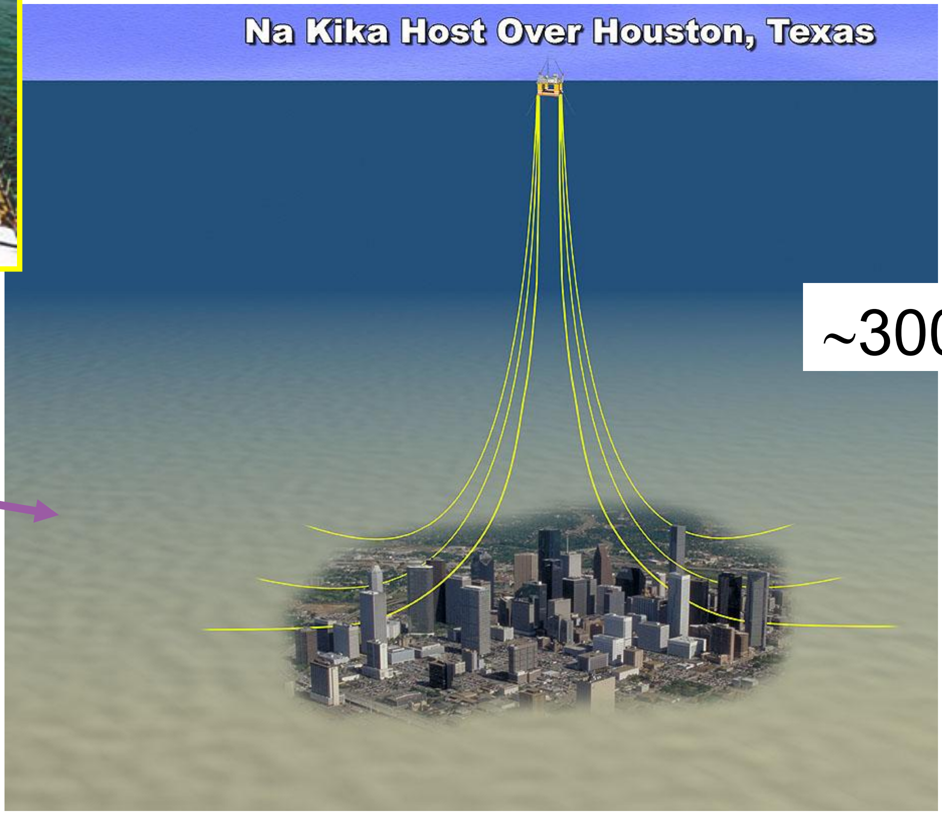


Challenge of Offshore Foundations

1. Large Foundations and Loads
大尺度的地基基础以及巨大负载

2. Enormous costs of site investigation and construction
现场勘探以及建设的巨额开销

3. Unknown soil conditions
海洋地基土的不确定性



Content 内容

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1. Deep Water	深水工程
- Plate anchors for mooring	平板锚系泊系统
2. New regions	新水域
- Installation of mobile drilling “jack-up” platforms	自升式钻井平台的安装
- Use of probabilistic methods	非确定性分析方法
3. Renewable Energy Infrastructure	可再生能源工程
- Wave devices with shared moorings	波浪电机和共享性系泊
4. Conclusions	结论

Content 内容

1. Deep Water 深水工程
   - Plate anchors for mooring 平板锚系泊系统
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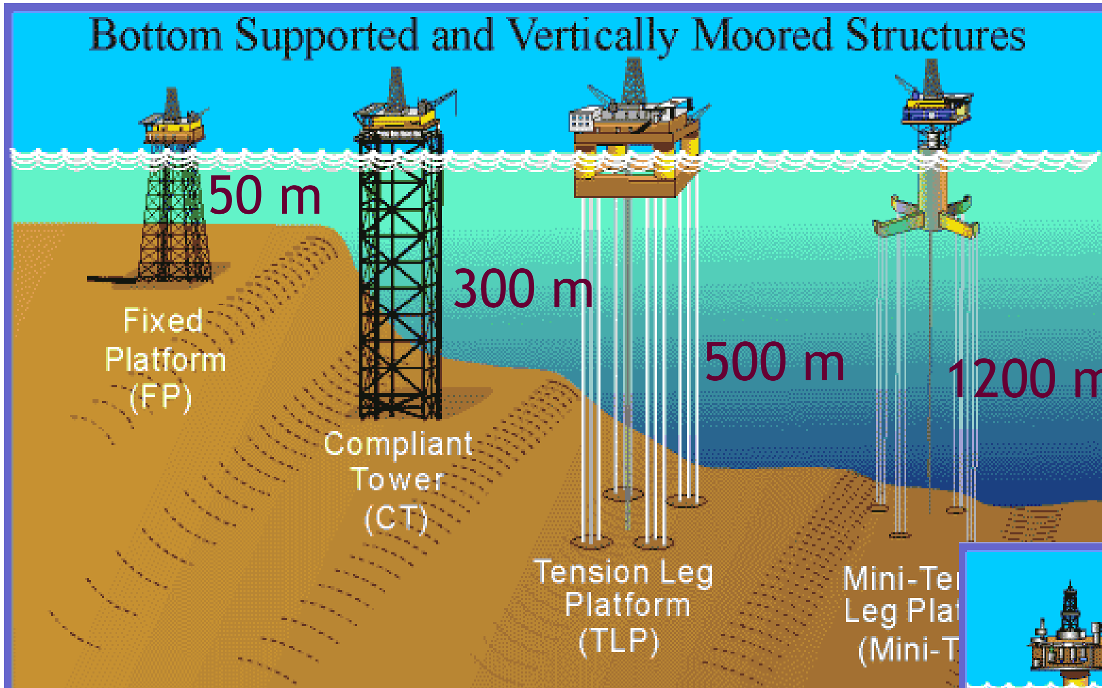
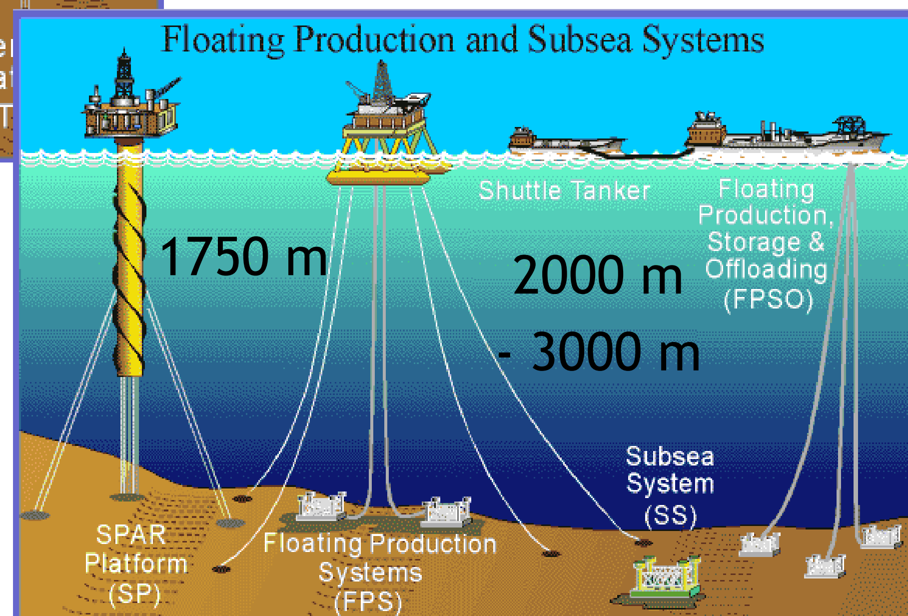
Off the slippery slope …
随着水深的巨增…



Fixed platforms
固定性平台

Floating facilities
浮动式平台



Courtesy
Minerals Management Services

plus mudmats and pipelines …
防沉垫和海底管道...

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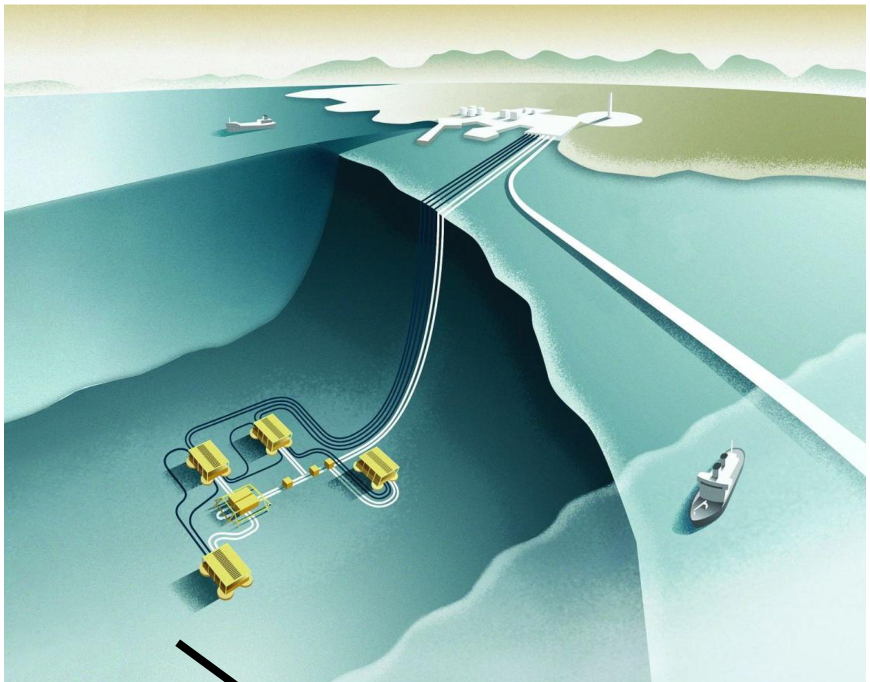
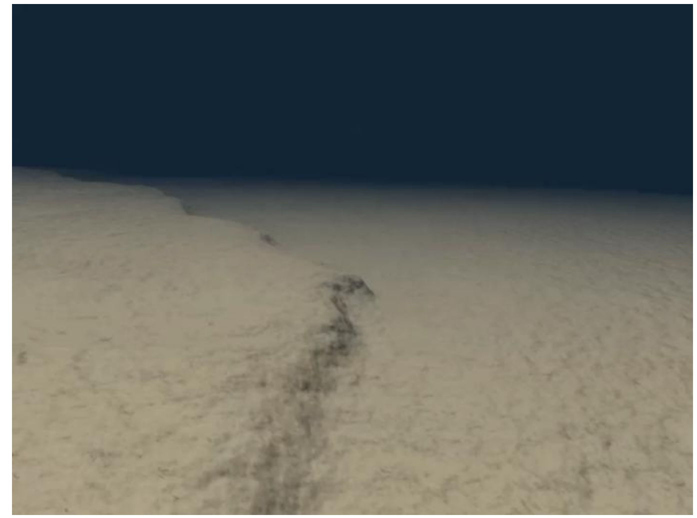
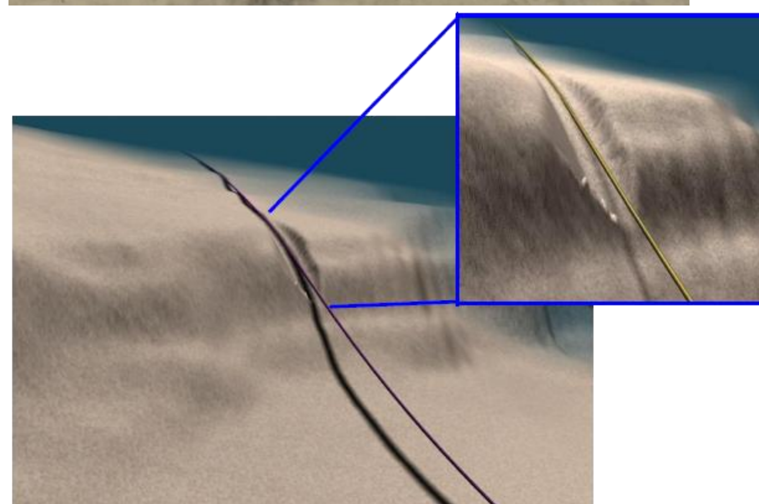


mudmat

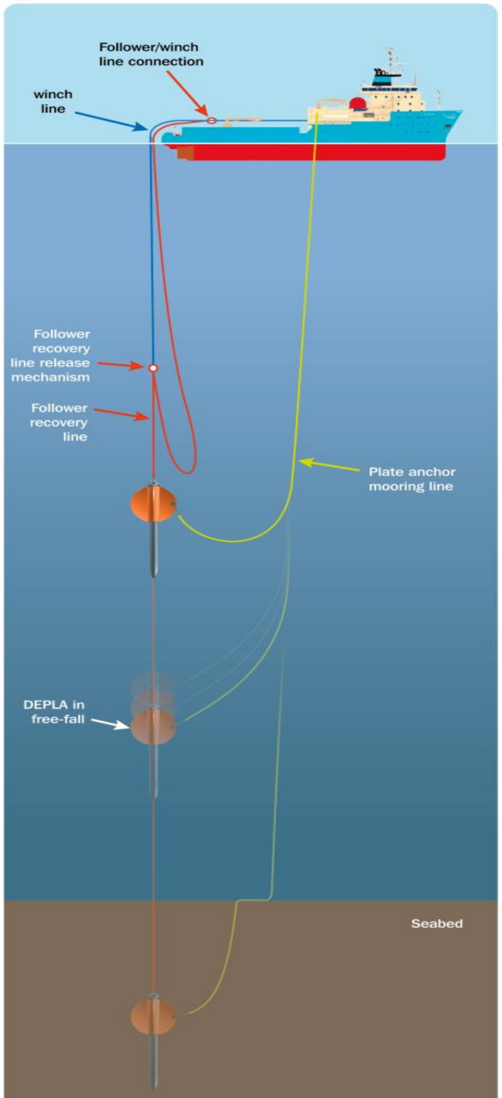
jumper

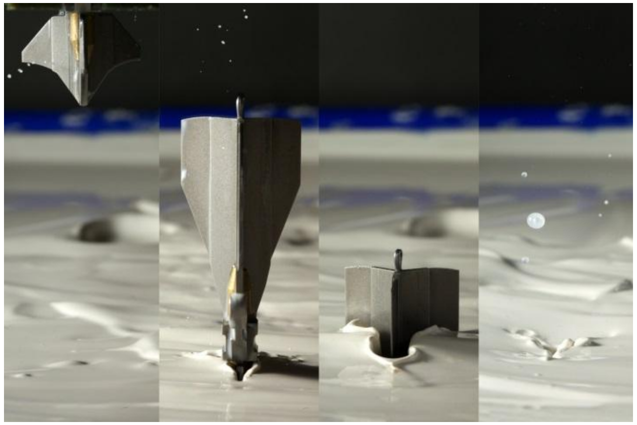
pipeline

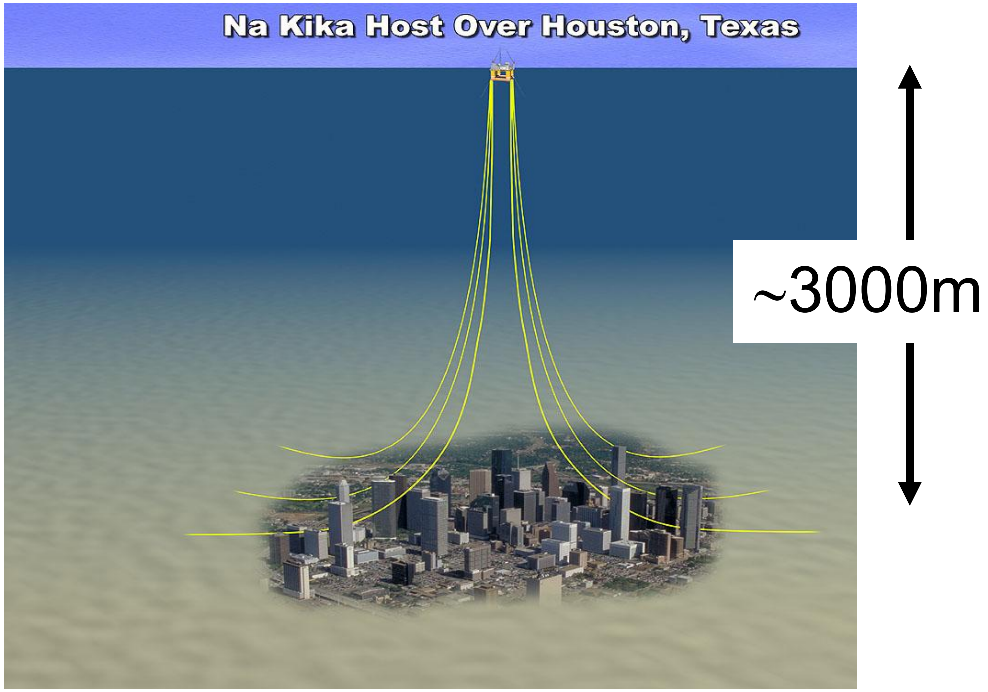




Deepwater Anchors 深水锚







Geotechnical Challenges in Deep Water
深水工程中的岩土力学挑战

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- **Characteristic environment 环境特征**
  - > 1000 m: Soft, lightly over consolidated fine-grained sediments
    大于1000米水深：轻微超固结的细颗粒软土
- **Example geotechnical challenges**
  - Enormous costs of site investigation 现场测试的巨额开销
    - Strength determination: cyclic degradation, sampling challenge
    - Increasing focus on upper layers (in-situ methods)
  - Mobility of infrastructure 可移动性的基础设施
    - Large deformations, incl. changes in seabed topography
    - Fluid-structure-soil interactions (e.g scouring of anchor chains)
  - Capacities under repetitive cyclic loading 往复加载下的承载能力
    - Possible transformations in soil properties (disturbance/healing)
  - Focus now both on capacity and stiffness 承载能力和刚度

Geotechnical Challenges in Deep Water
深水工程中的岩土力学挑战

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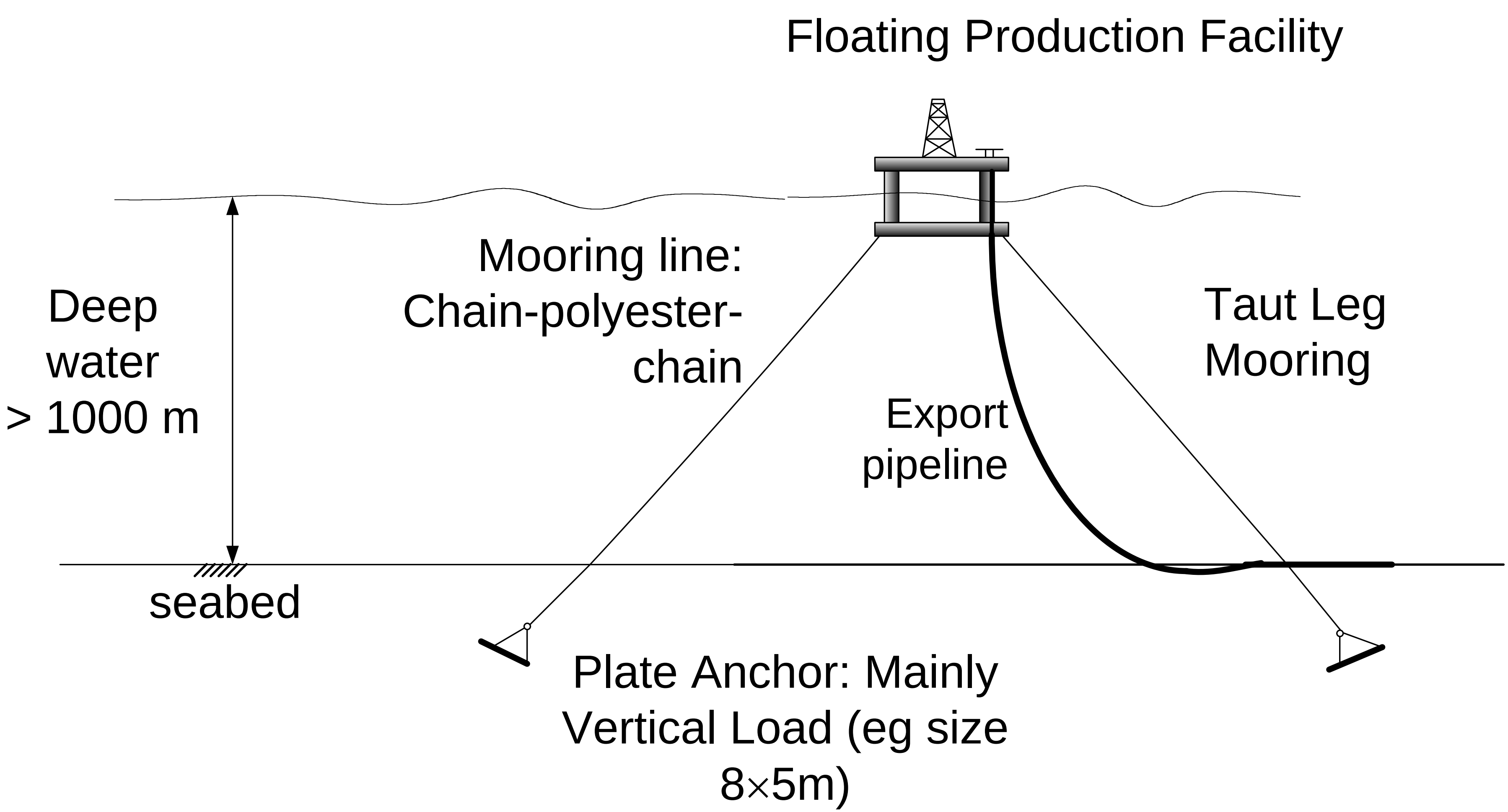
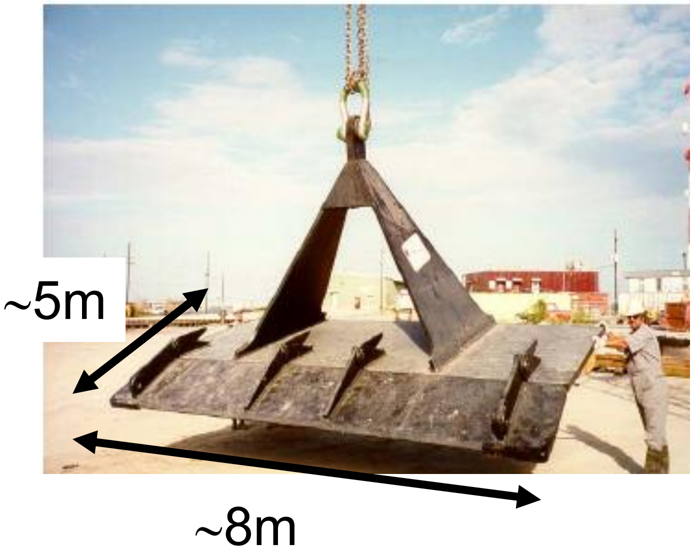
- **Some example solutions**
  - Improved in-situ technology 现场测试技术的进展
    - Large-diameter piston coring
    - Continuous T-bar and ball penetrometers (with pore pressures)
    - Automation
  - **New Anchor configurations: 新型锚的设计**
    - Such as **SEPLA,** Torpedo anchors, OMNI-max

    Discussing today
  - Hybrid foundations 组合型基础
    - Mudmats with piles in corners
  - Improved numerical methods: 数值方法的进展
    - Failure envelopes written directly in combined loading space
    - Large deformation finite element analysis techniques

Example Solution: SEPLAs
方案举例：吸力贯入式板锚

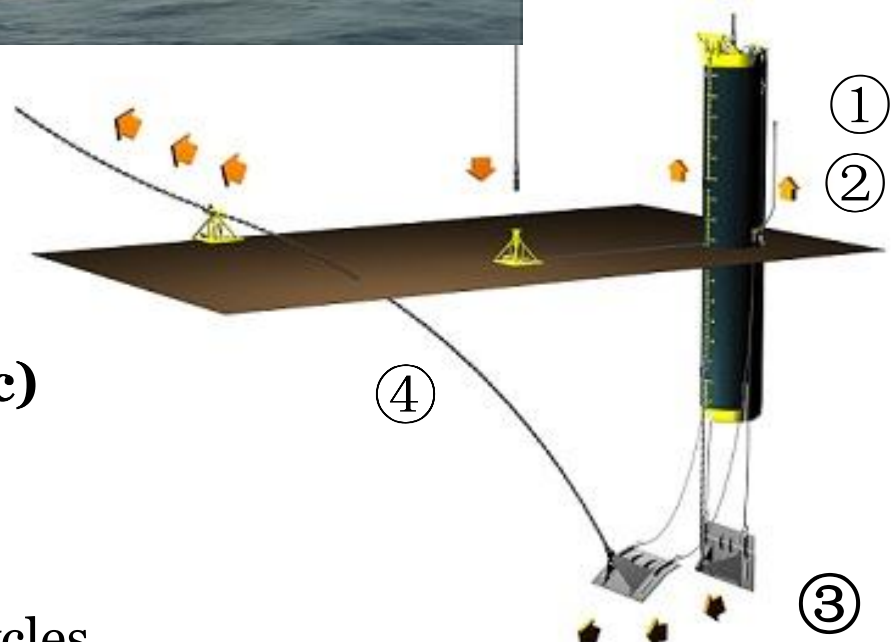


Example Solution: SEPLAs
方案举例：吸力贯入式板锚



① suction installation
② caisson retrieval
③ anchor keying
④ operational (sustained/cyclic)

Industry requirement:
- Keying model
- Bearing capacity factors under cycles



(modified after www.intermoor.com)

Predicting the keying trajectory
预测就位运动轨迹

(Lowmass, O'Loughlin, 2006)

Predicting the keying trajectory
预测就位运动轨迹

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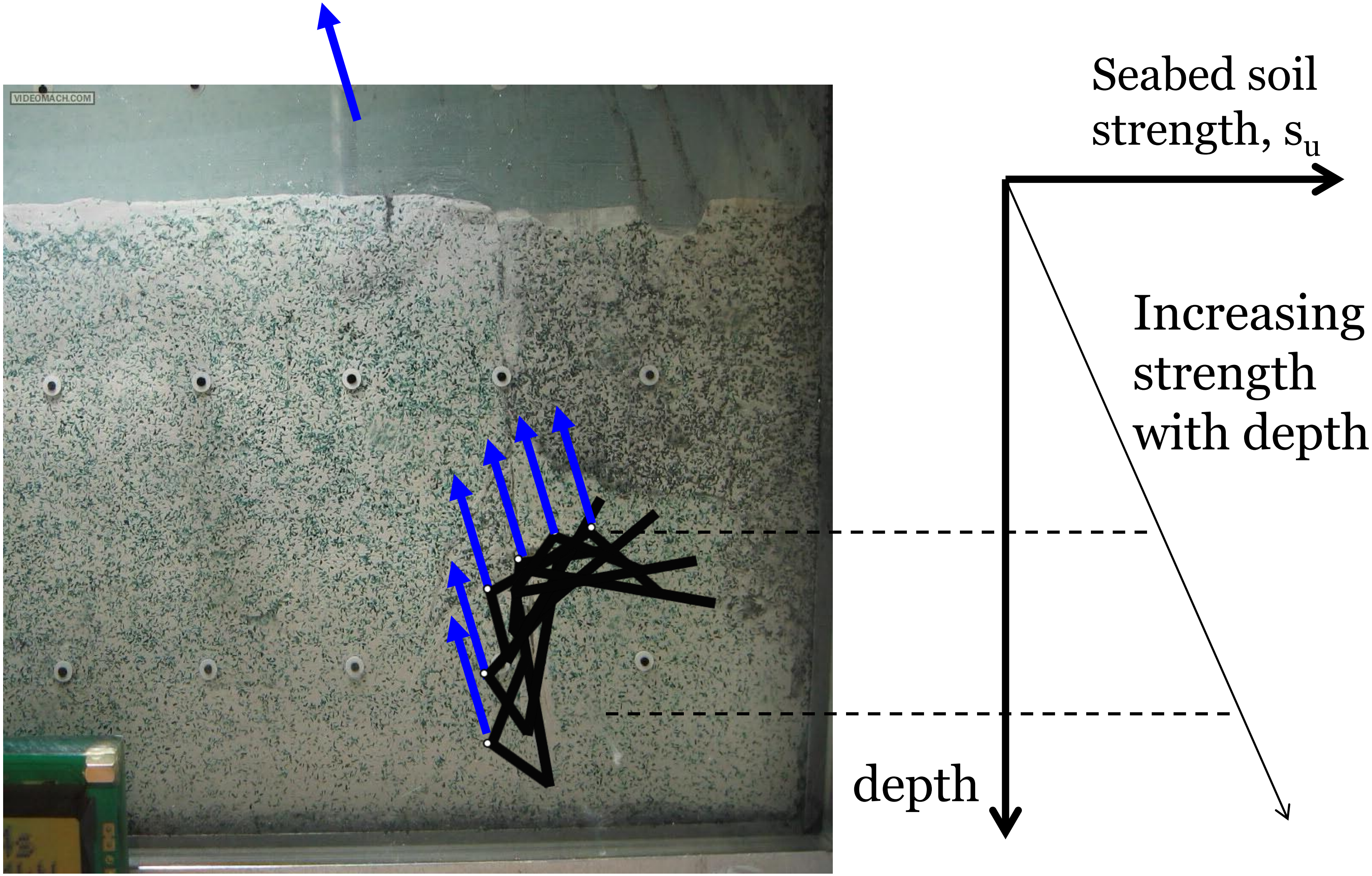


Keying Model: Plasticity Approach
就位运动模型：塑性分析方法

Perfect plasticity assumed, therefore 3 components:

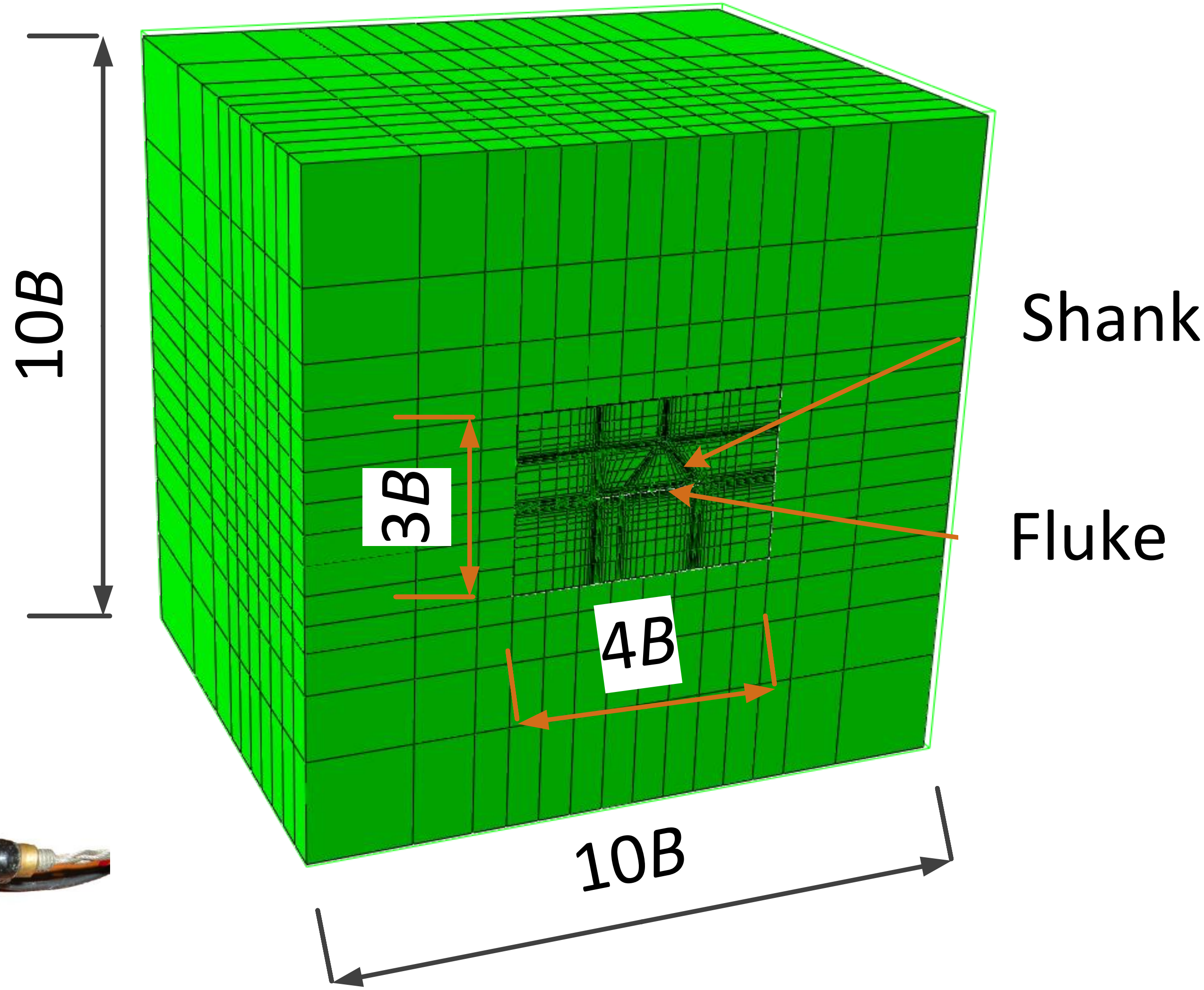
- Yield surface written directly in combined VHM on fluke
- Associate flow rule assumed
- Hardening law (i.e. increase size of Yield Surface with depth)

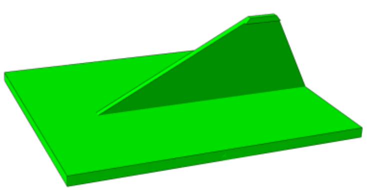
Advantages:

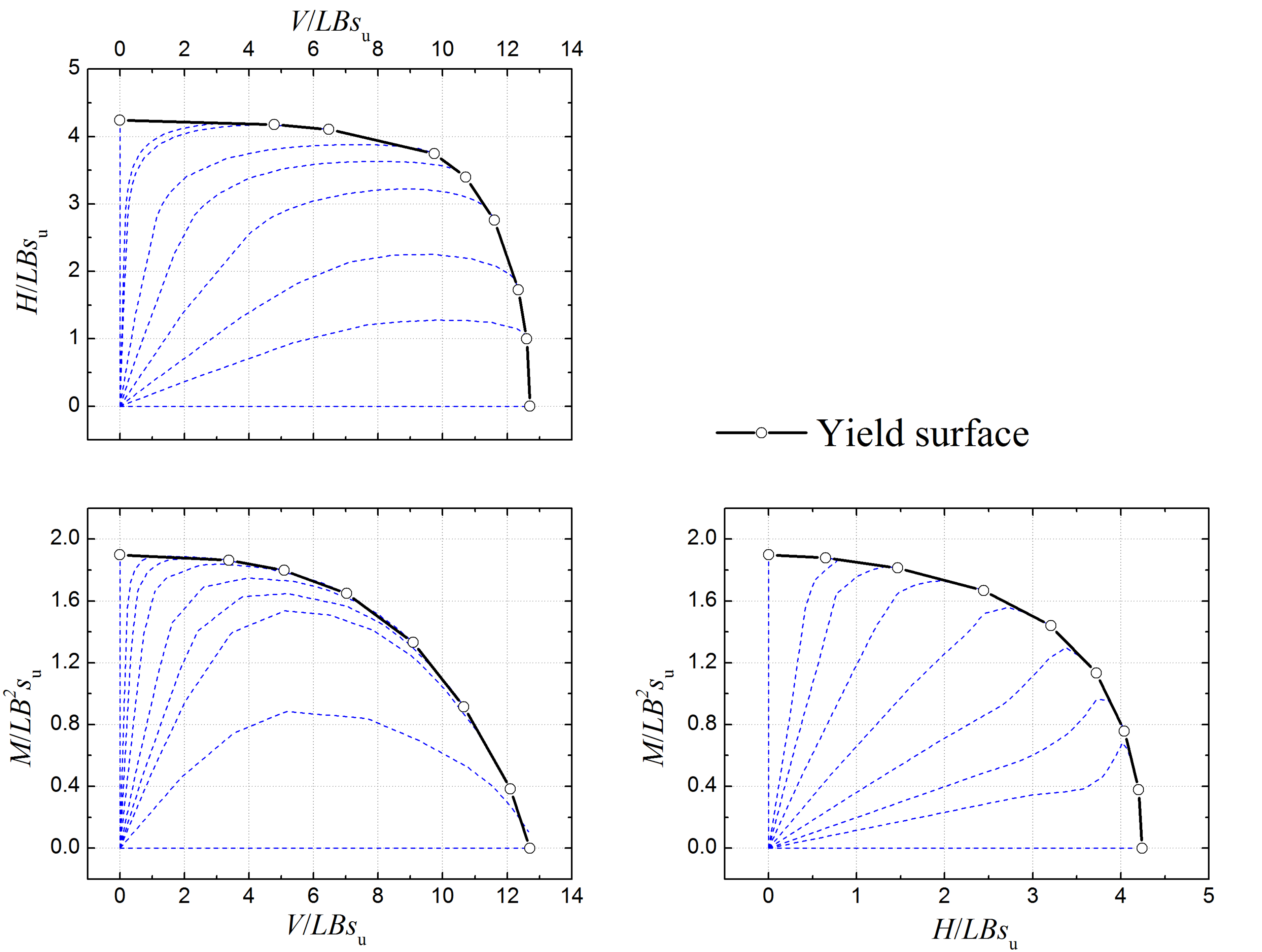
- Easy to implement
- Quick to run
- Parameters can be easily adjusted.

Based on similar approach to analytical modelling of drag-anchors (O'Neill, Elkhatib: PhDs at UWA)

Keying Model: Plasticity Approach
就位运动模型：塑性分析方法





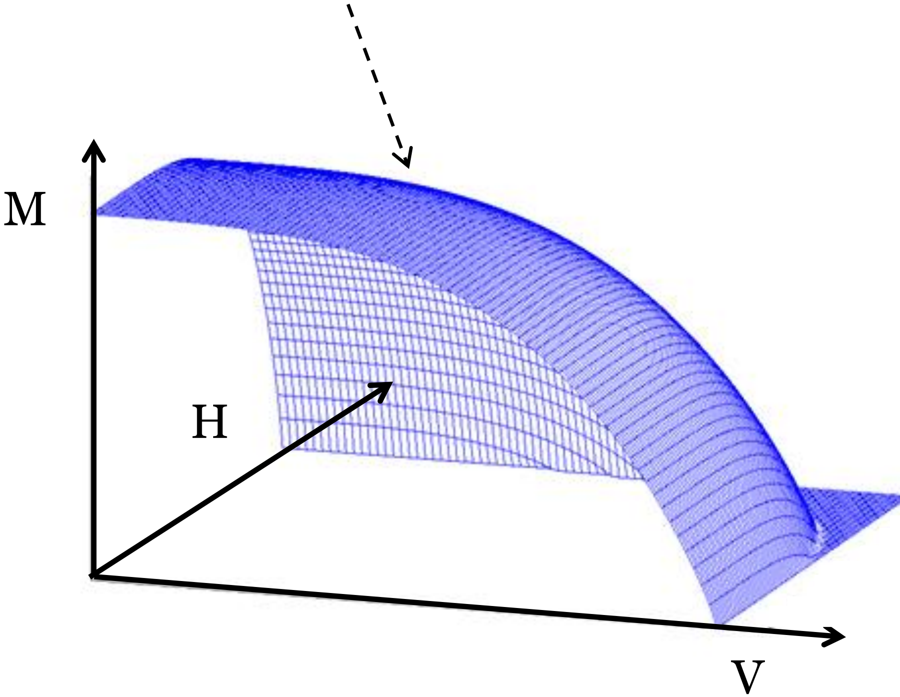


V/LBsu
H/LBsu
M/LB2su
V/LBsu
M/LB2su
H/LBsu
Yield surface

Keying Model: Plasticity Approach
就位运动模型：塑性分析方法

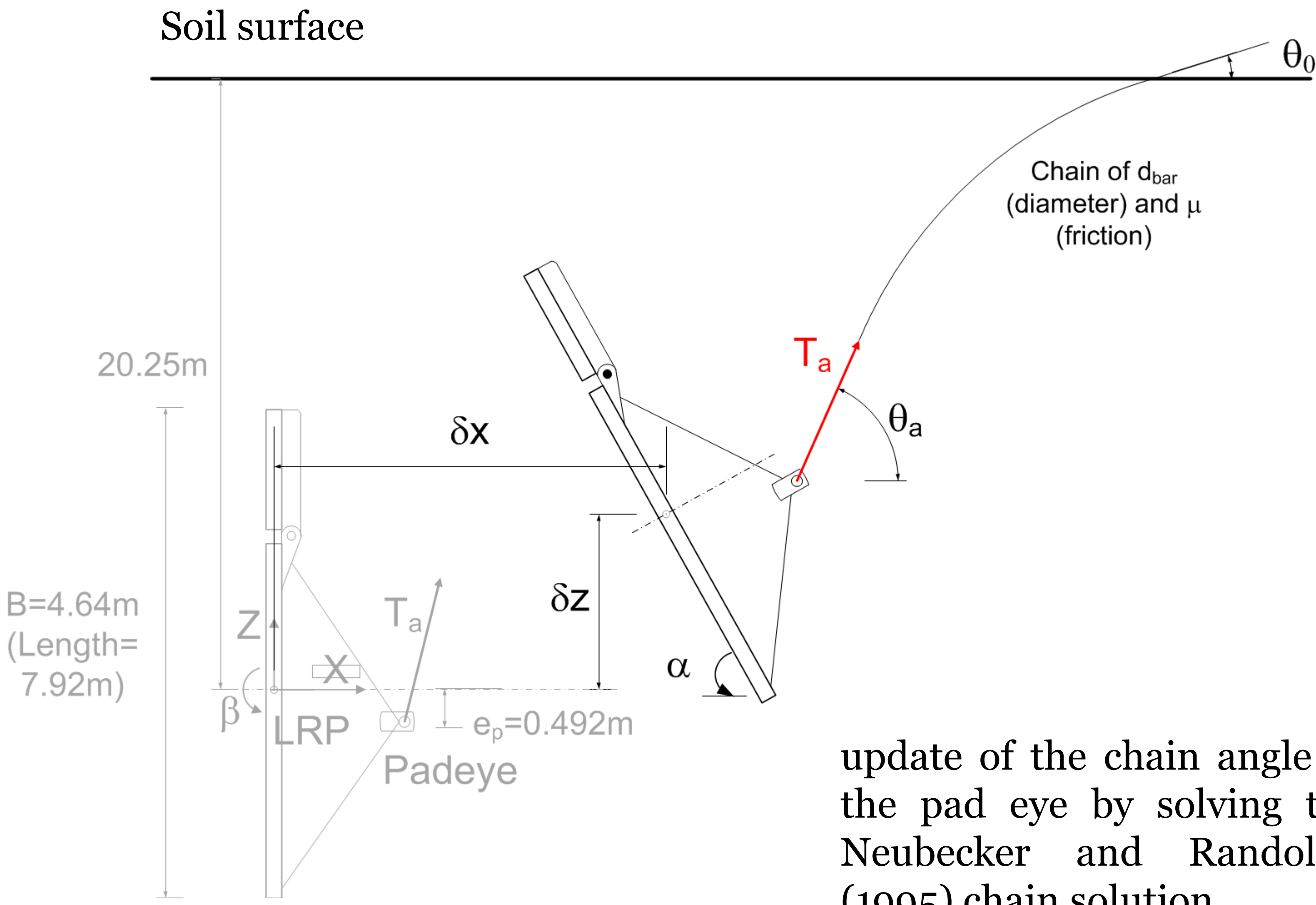
$$f=\left(\frac{V}{V_{max}}\right)^{q}-1+\left[\left(\frac{M}{M_{max}}\right)^{m}+\left(\frac{H}{H_{max}}\right)^{n}\right]^{\frac{1}{p}}=0$$

	Fluke only	SEPLA
V_{max}/LBs_u	12.6	12.7
H_{max}/LBs_u	2.9	4.2
M_{max}/LB^2s_u	1.9	1.9
m	1.01	1.02
n	4.05	4.01
p	1.01	1.01
q	4.01	4.01



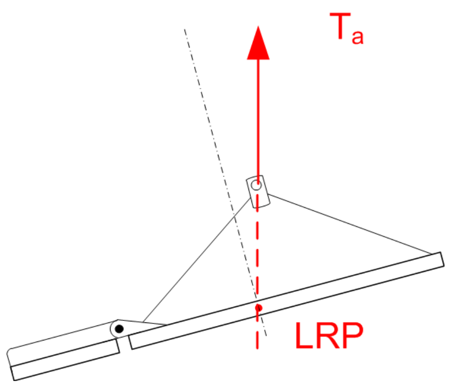
Yield Surface proposd by Bransby and O'Neill (1999) and Elkhatib and Randolph (2005) for drag anchor application

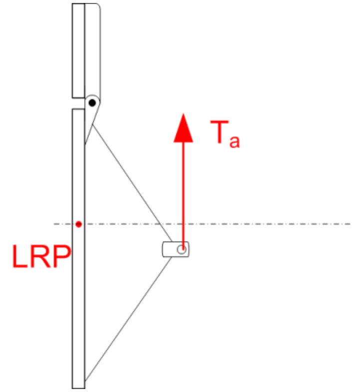
SELPA Keying Example 就位分析算例



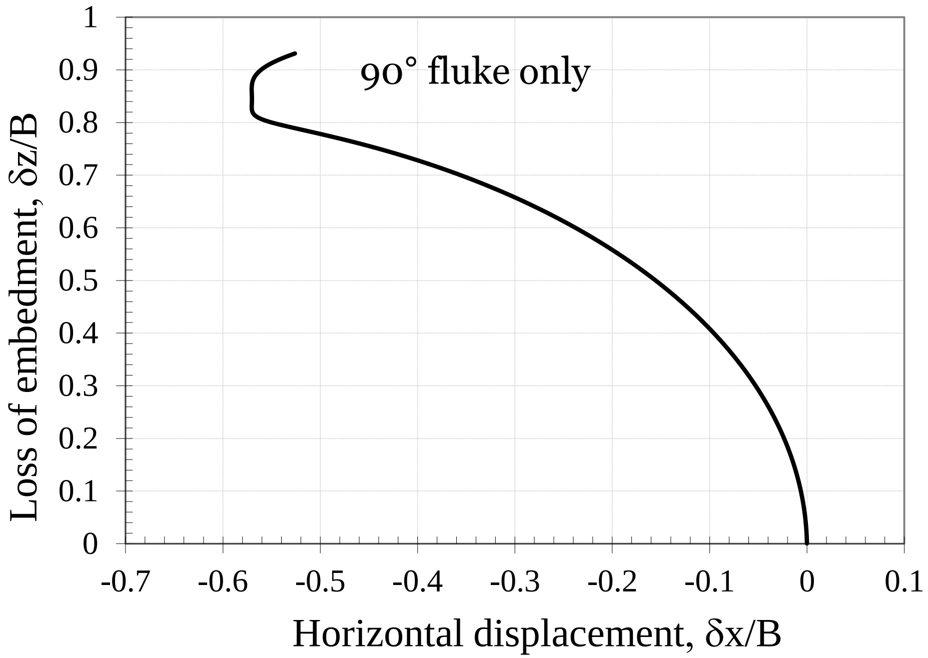
update of the chain angle at the pad eye by solving the Neubecker and Randolph (1995) chain solution

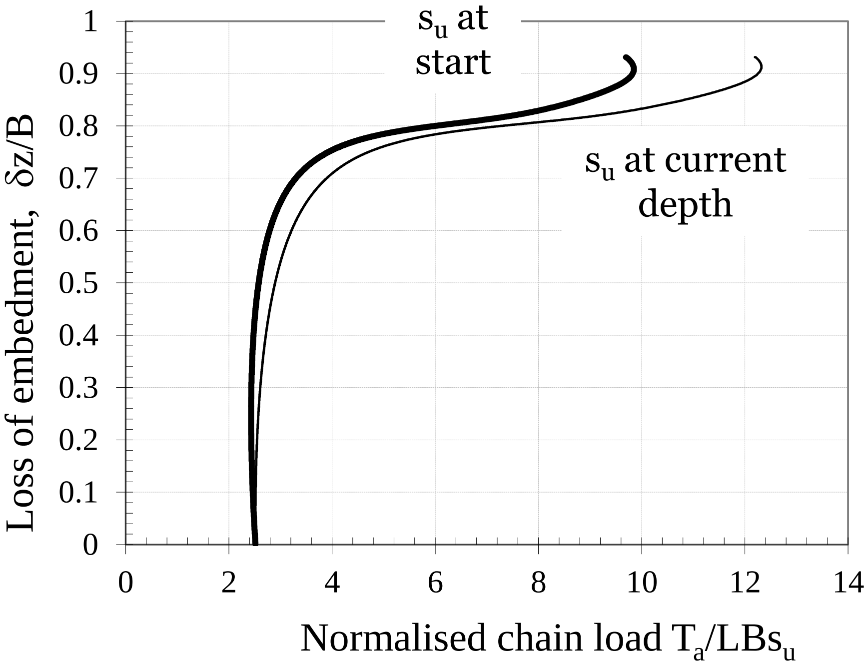
SELPA Keying Example　就位分析算例



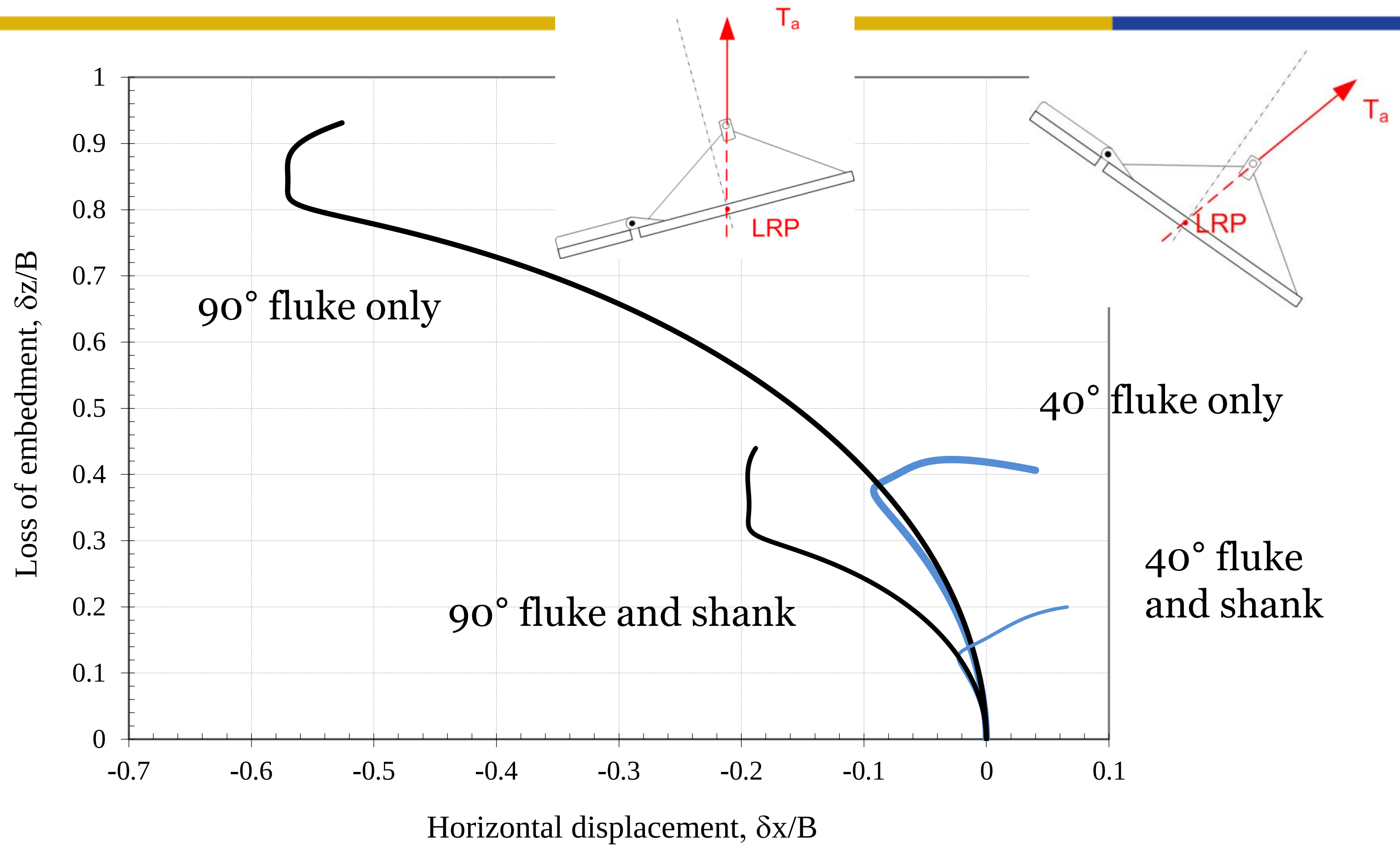


- Loss of ~20% in capacity



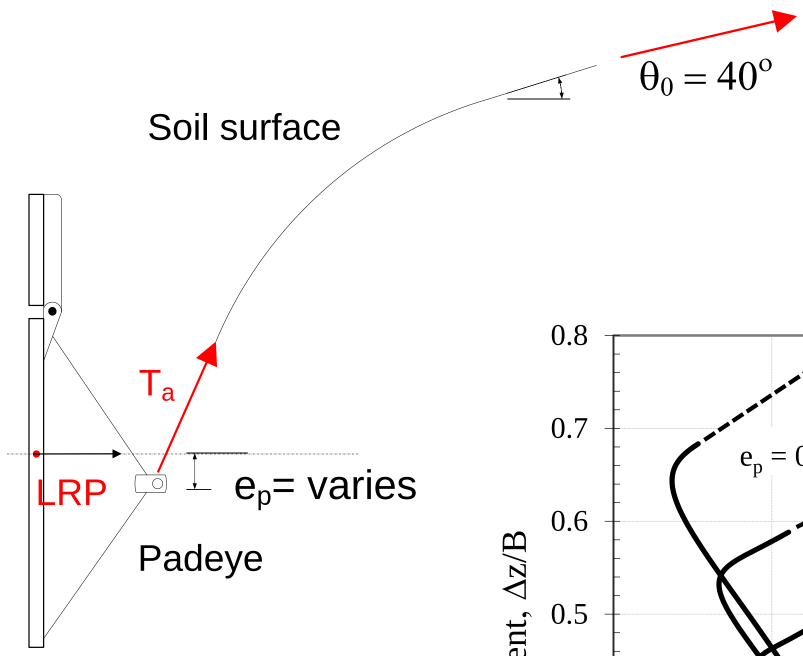


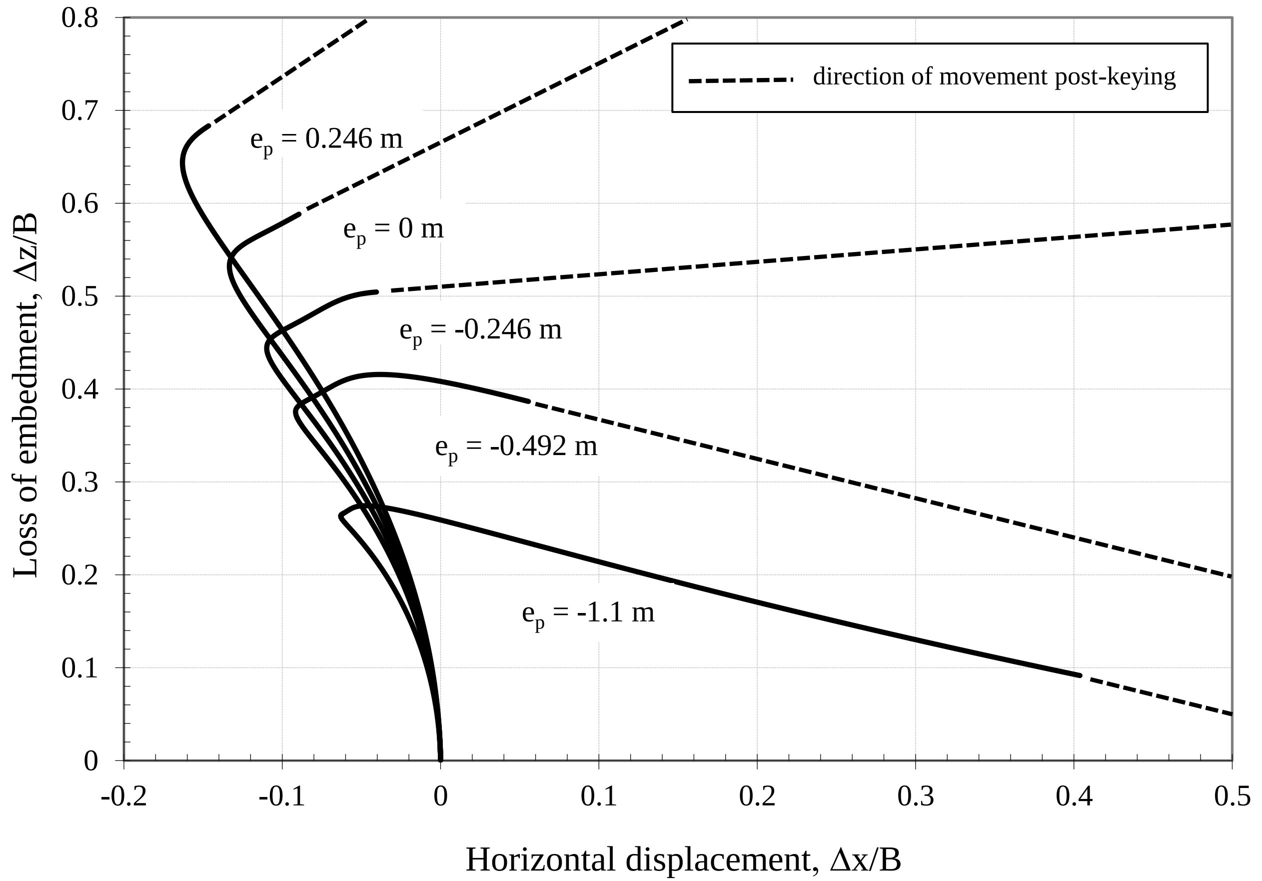
SELPA Keying Example　就位分析算例



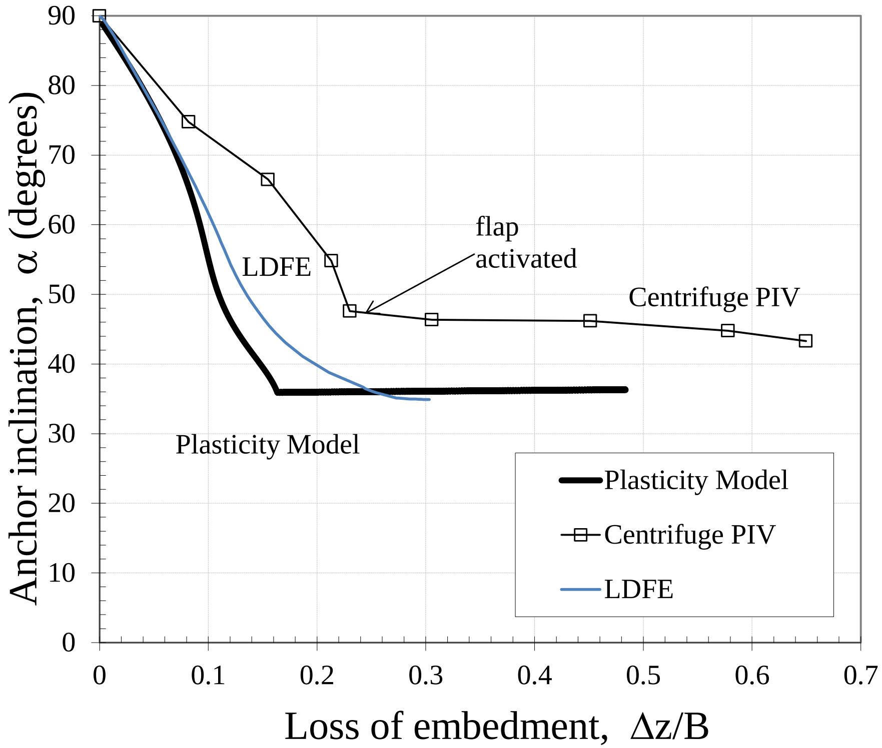
- For offshore conditions, loss of embedment between 0.5B and 0.9B
- Allow period of re-consolidation before keying, as reduces embedment loss
- Used to redesign anchor: keying flap orientation, increase padeye eccentricity

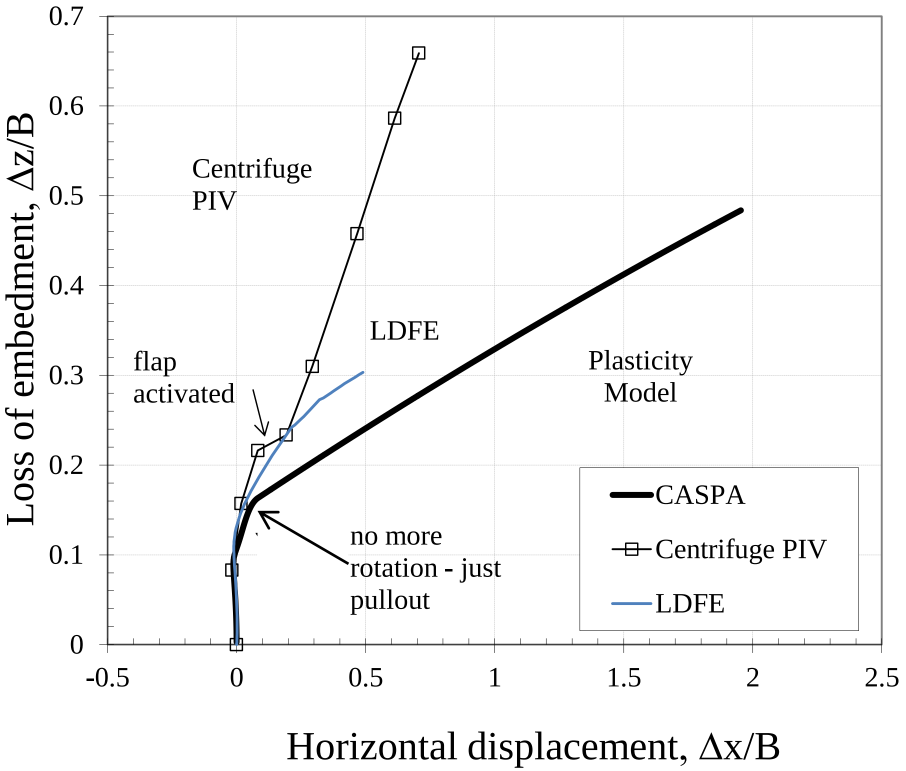
SELPA Keying Example





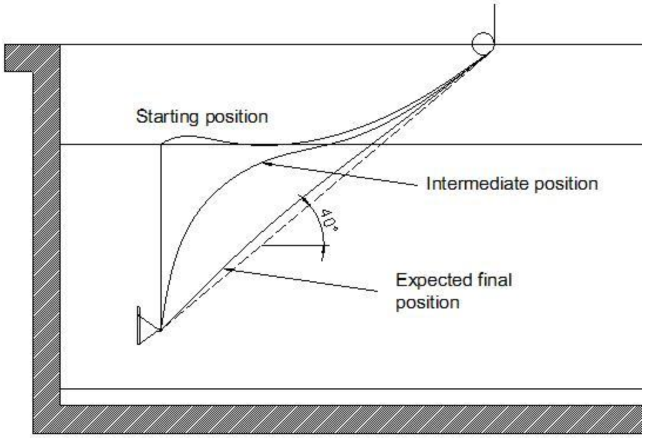
Verification of the Model

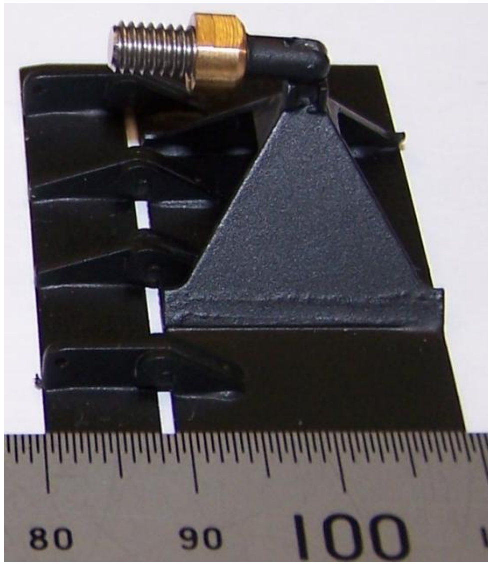




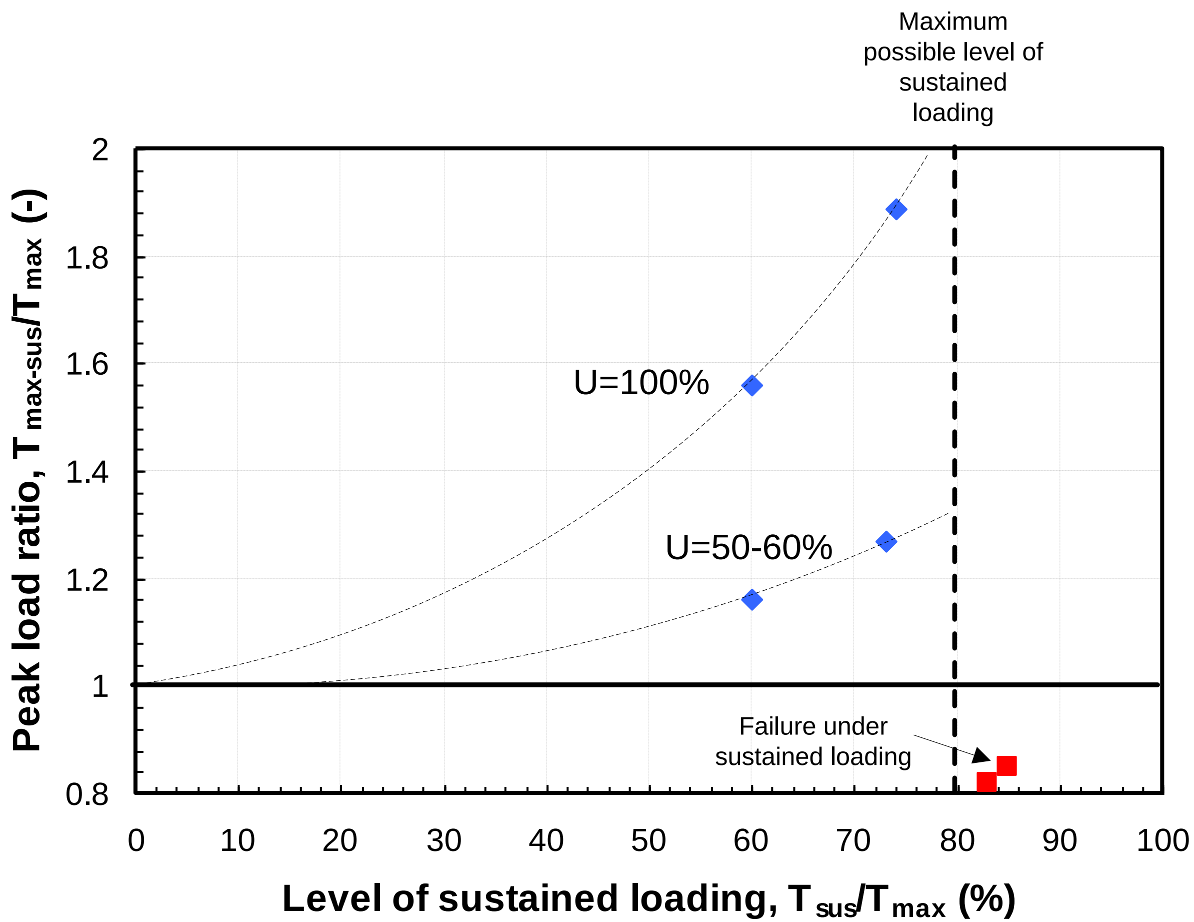
SEPLA Centrifuge Model 离心机模拟

- 1/150 model
- West Africa soil used for centrifuge experiments
- Anchor keying followed by sustained loading / cyclic loading and pull-out to failure



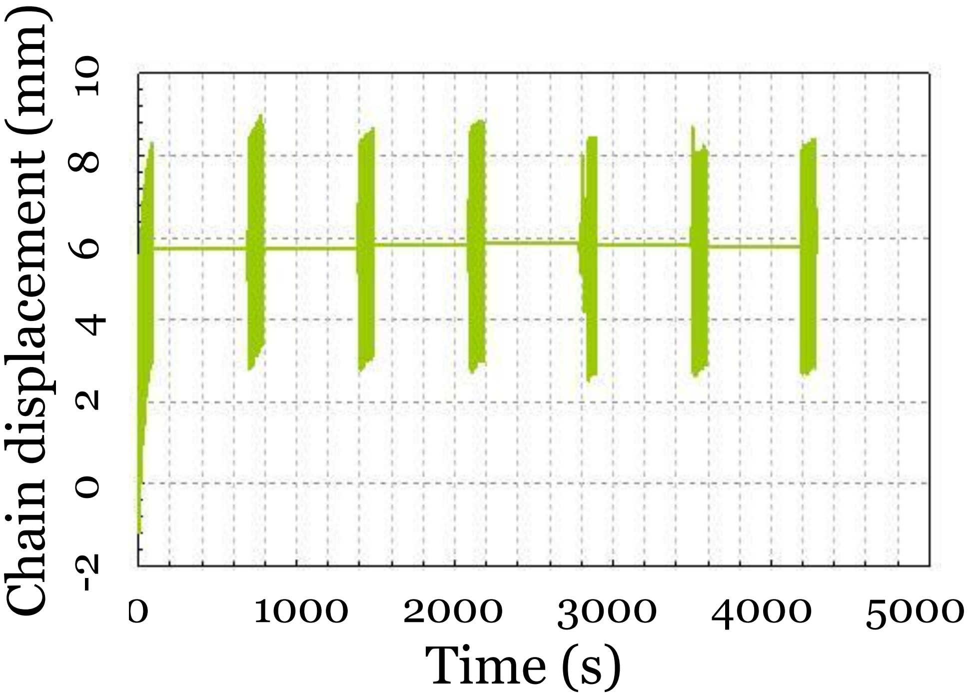


Sustained loading on SEPLA anchors
持续荷载作用下的板锚

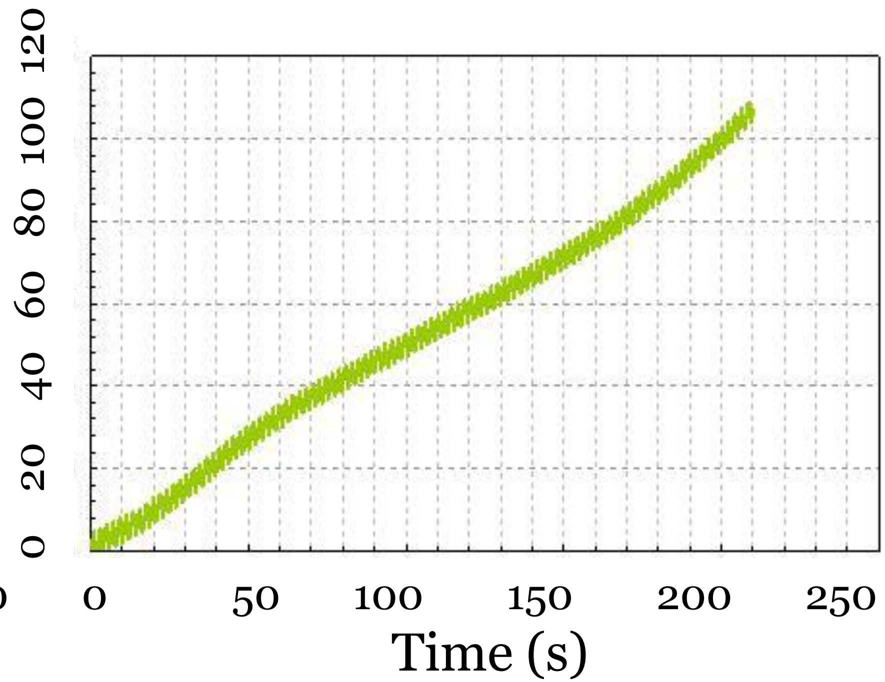


- Failure determined by balance between (i) increased capacity from consolidation, and (ii) reduced capacity due to low strain
- Threshold at 85%

Cyclic loading on SEPLA anchors
往复荷载作用下的板锚



Cycles < 0.75 Max monotonic

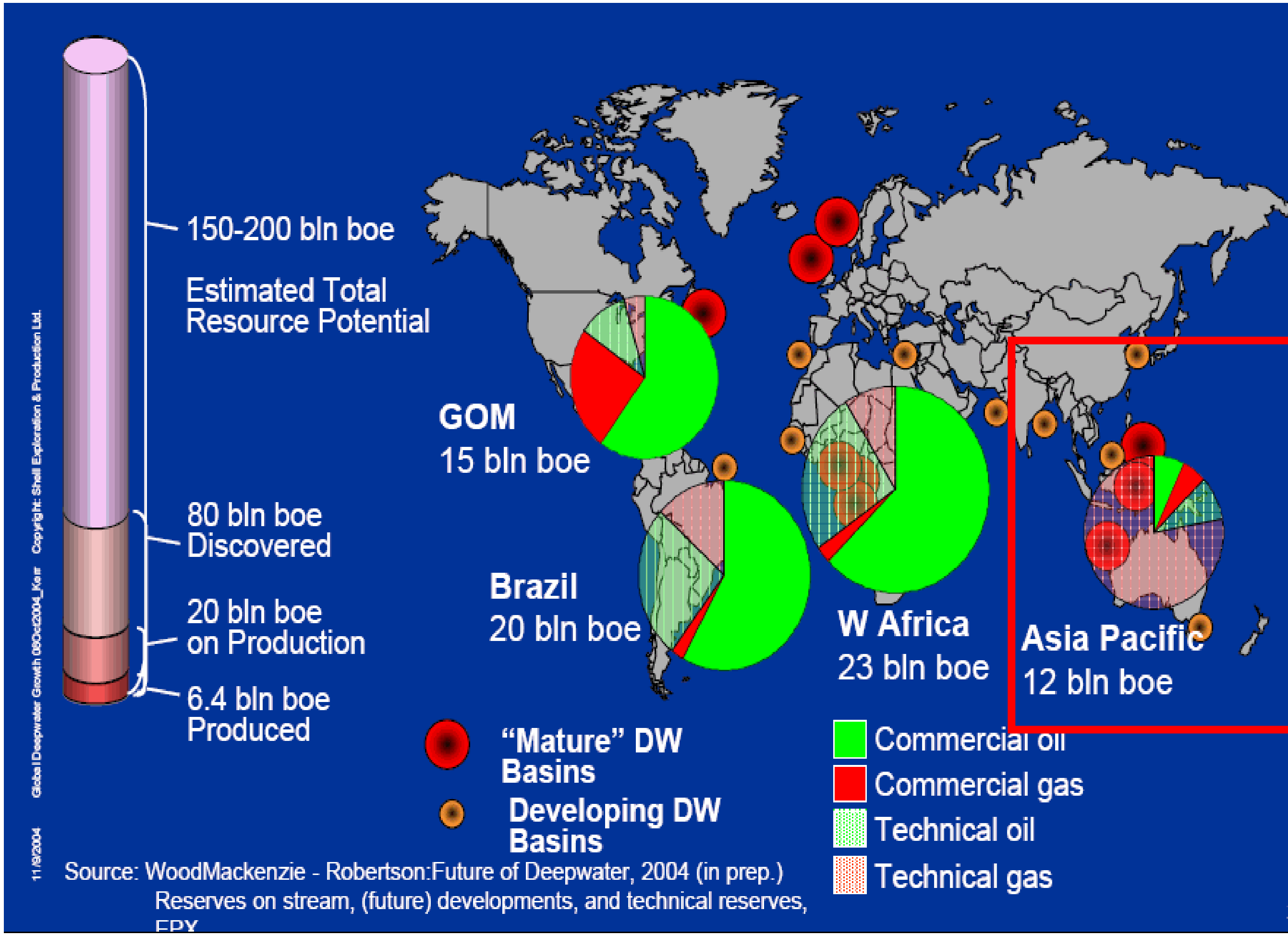


Cycles > 0.75 Max monotonic

Same processes, but
- Further reduced capacity due cycling
- Threshold at 75%

Content 内容

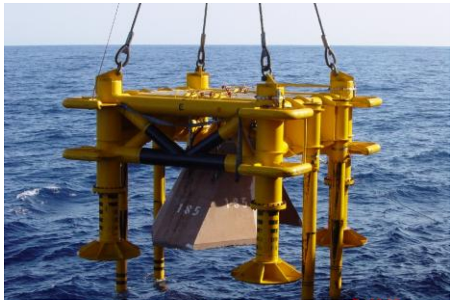
New regions 新水域

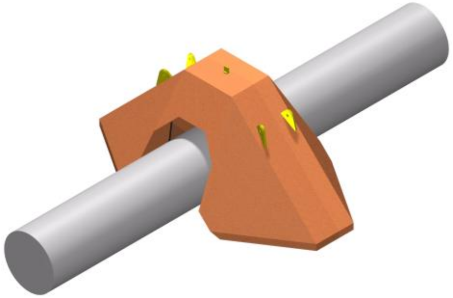


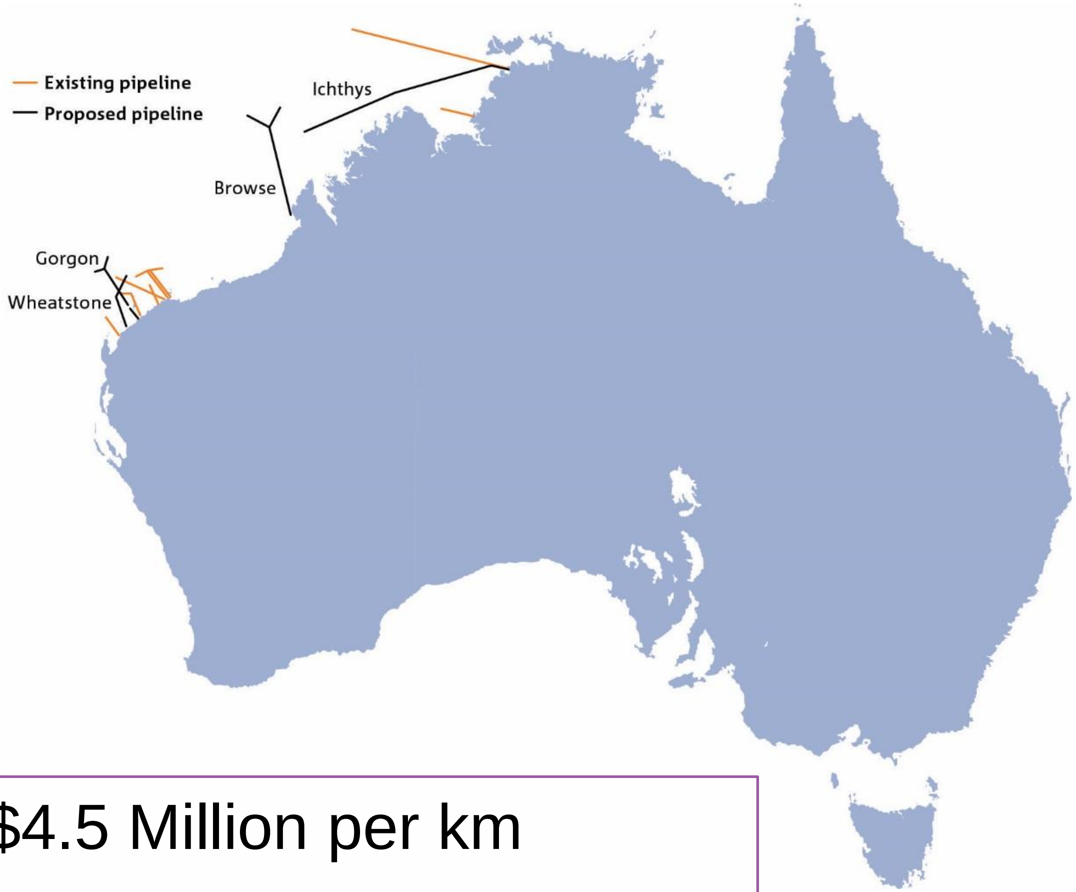
New Regions have great potential to unlock

Shaded regions represent oil and gas reserves requiring technical step change to economically recover

Recent Flurry of Construction
最近的开发热点





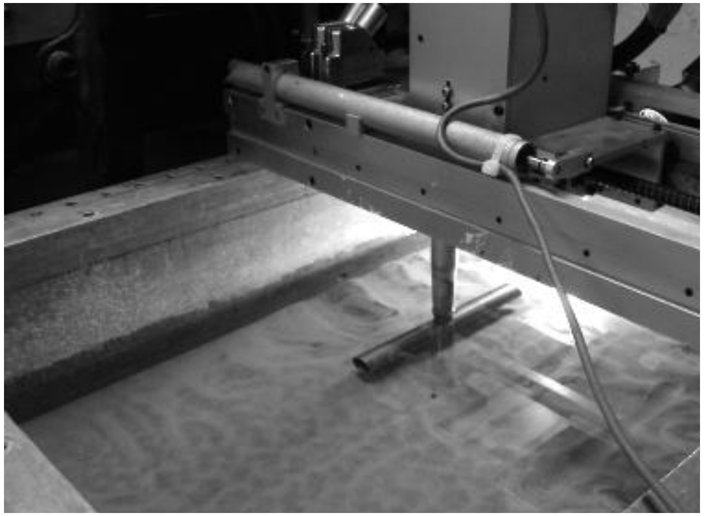


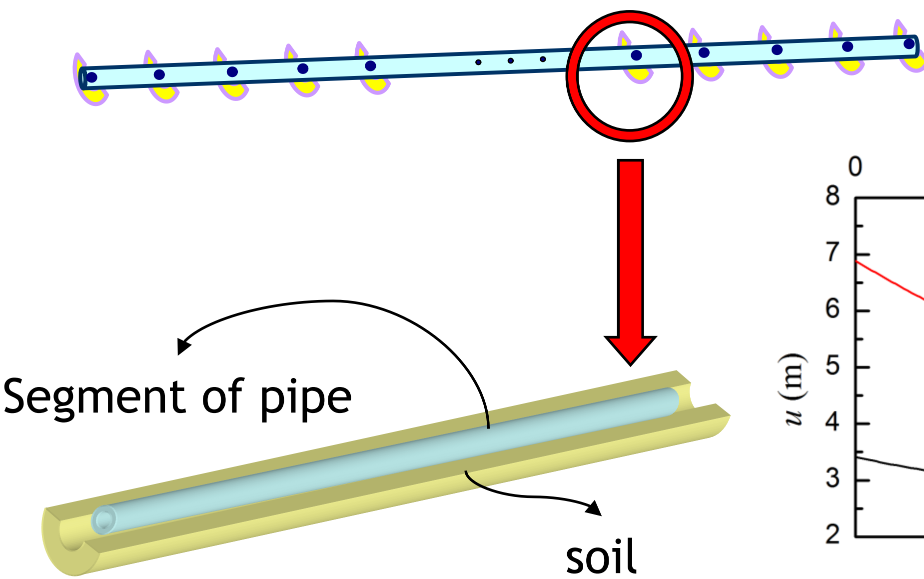
Recently > 2000 km @ ~$4.5 Million per km

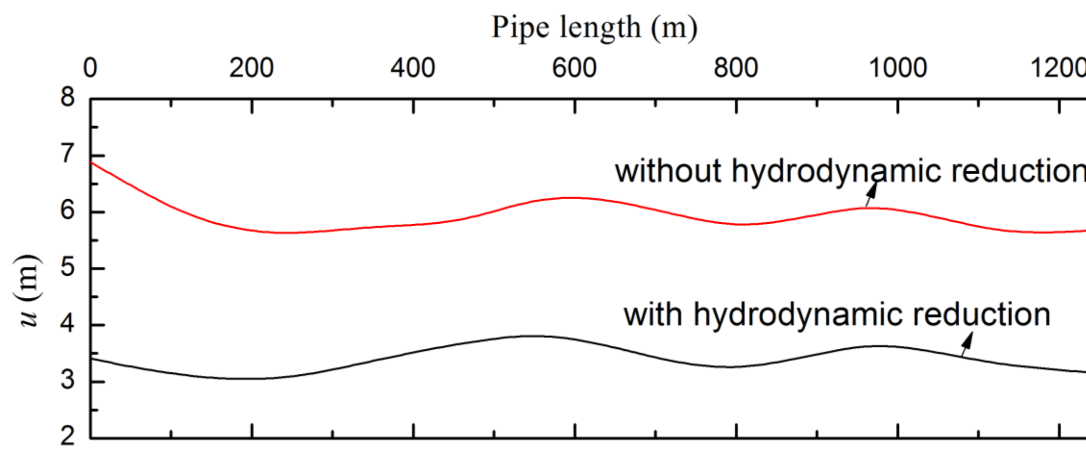
Secondary stabilisation can cost ~ 30% of total

Driven new analysis techniques predicting stability of unburied pipes under storm loading

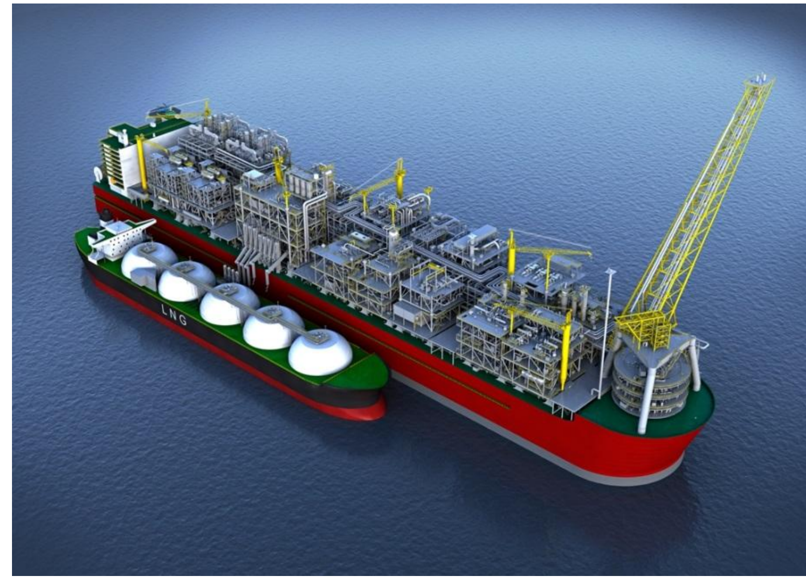
Recent Flurry of Construction
最近的开发热点







Australian Floating LNG
澳大利亚浮动式LNG项目



Liquefy and ship gas offshore

Length: 488 m Width: 74 m

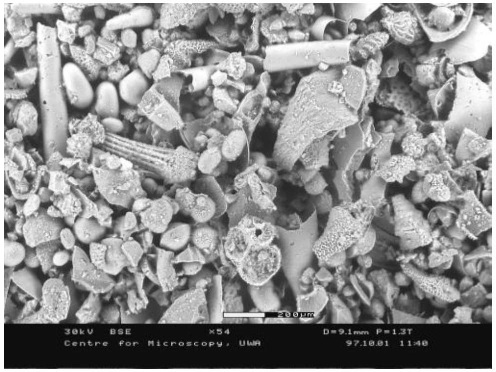
Weighs: 600,000 tonnes

Moored for 25 years

Closest Port: 475 km (Broome)

Geotechnical Challenges: New Regions
岩土工程挑战：新水域

- **Characteristic environment**
  - Australasia: often highly stratified seabeds, carbonates and sensitive silts
- **Example geotechnical challenges**
  - Less offshore experience
  - Can be very remote with long distance
    - E.g. > 500 km pipelines in Australia
  - Prediction of drainage conditions and rate effects
  - High compressibility and occasional cementation
  - Large changes in strength with cycles
  - Installations in layered conditions or into uneven seabeds



Geotechnical Challenges: New Regions

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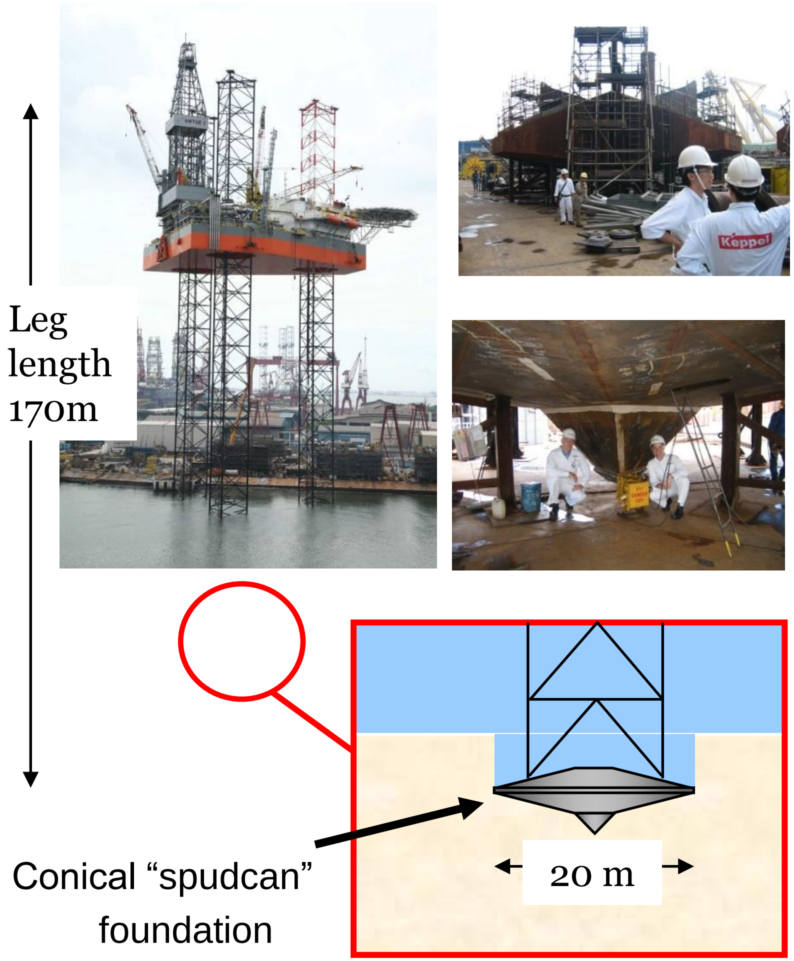
- **Some example solutions**
  - Improved numerical methods that account for rate effects, soil softening through shearing, high sensitivity and strength gain through consolidation
  - Improved pipeline stability models: significant $$ savings
  - Increased emphasis on direct prediction methods from CPTs
  - **Punch-through models that account for soil dilatancy**

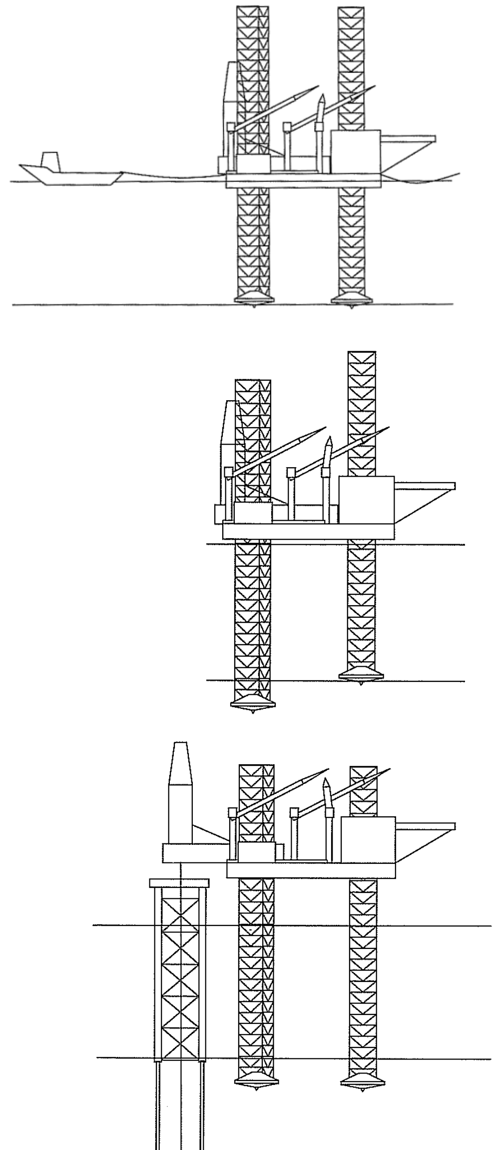
    考虑土体剪胀性的刺穿模型

Discussing today

Mobile "jack-up" rigs 自升式钻井平台



Photos Courtesy of Keppel Offshore and Marine



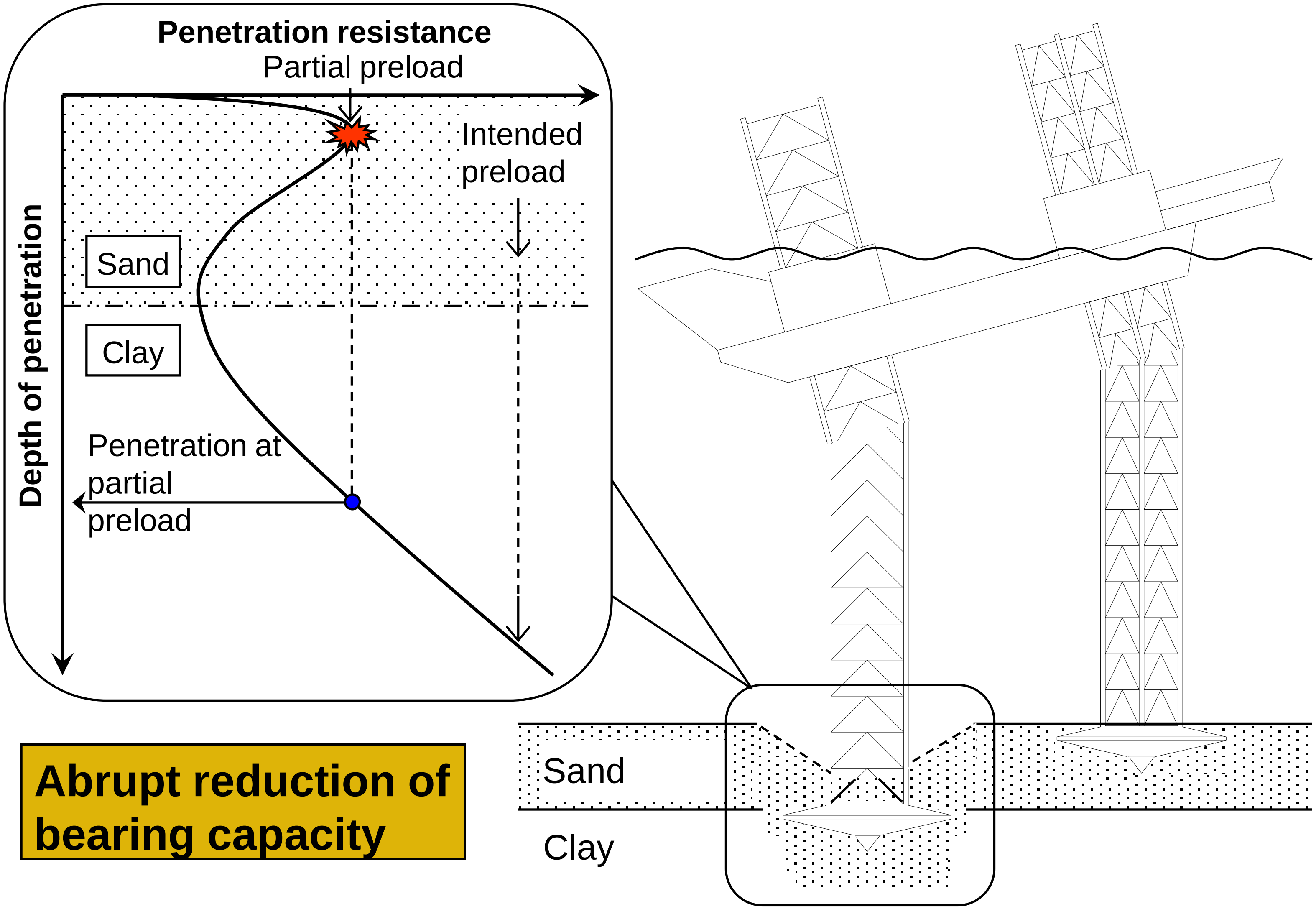
soft pinning

installation

operations

Figure after Dean (2010): Offshore Geotech. Eng.

Punch-through failures 刺穿破坏



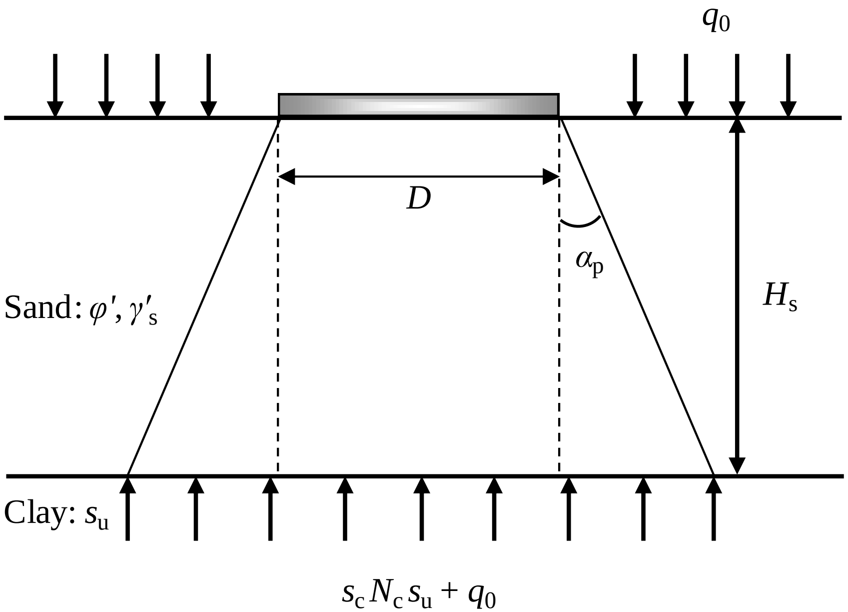
Abrupt reduction of bearing capacity

Punch-through failures 刺穿破坏

Punch-through off Qatar, 8 May 2009

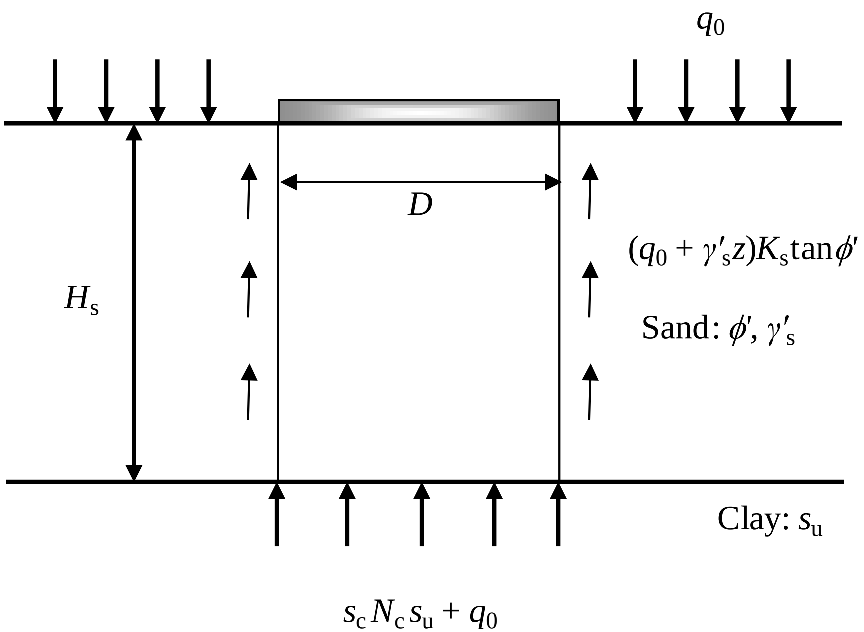
q_{peak}: Methods in ISO 19905-1

Load spread method



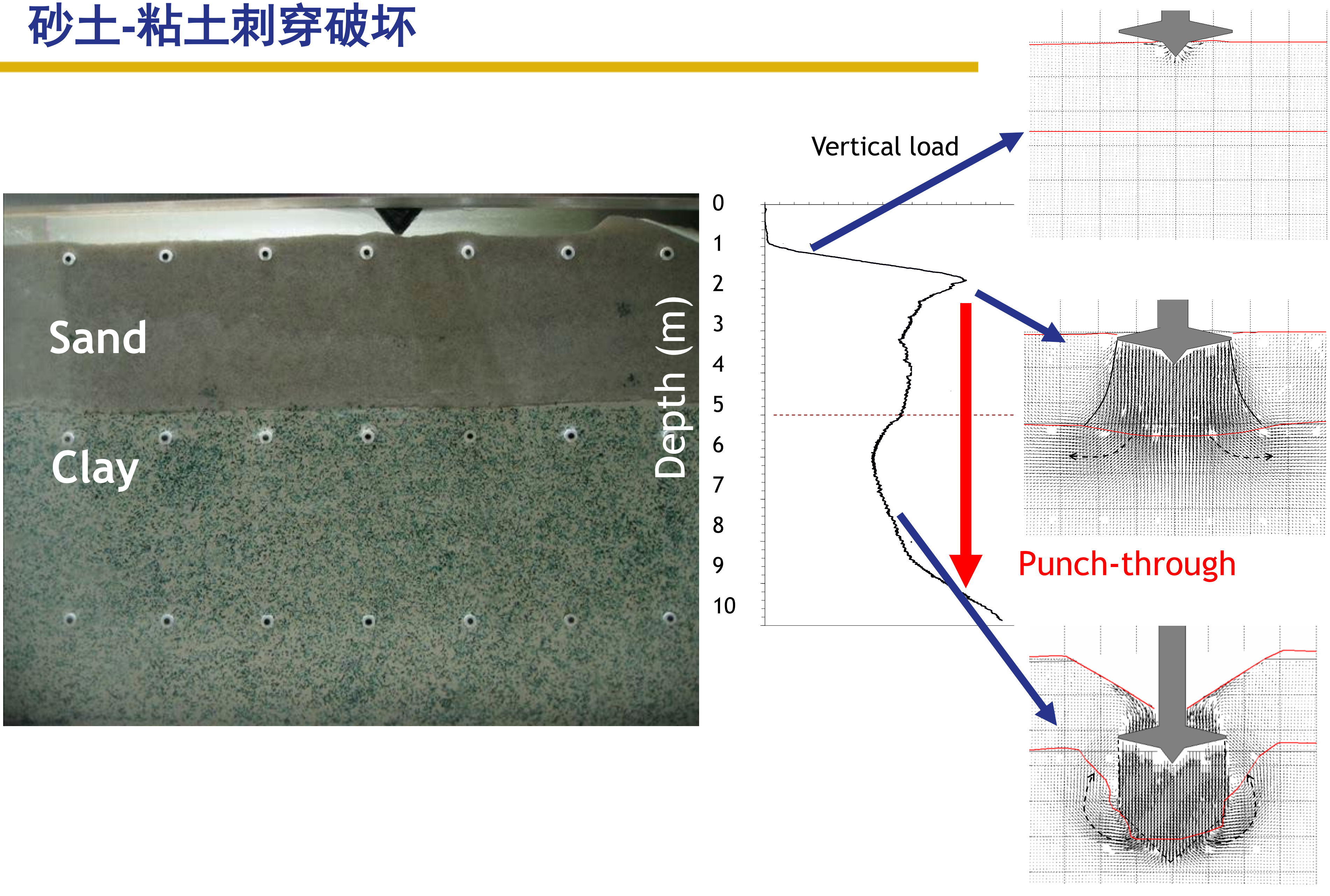
$$\alpha = \tan^{-1}\frac{1}{5} \quad (\text{or} \quad \tan^{-1}\frac{1}{3})$$

Punching shear method



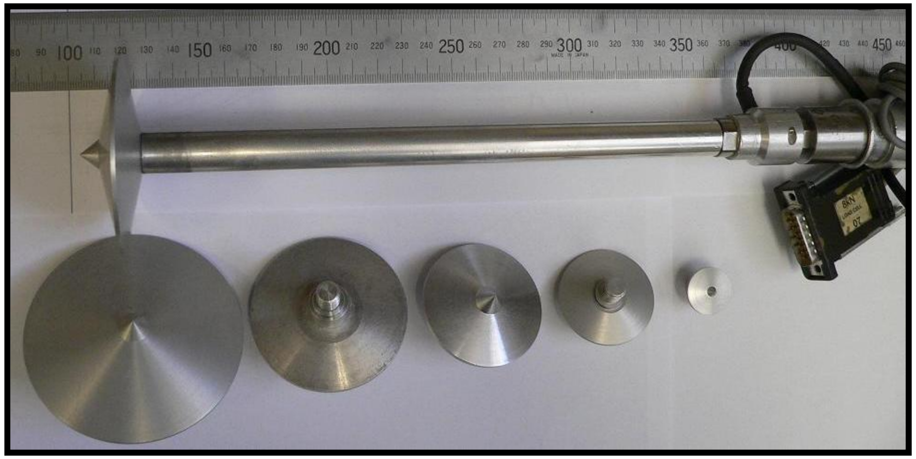
$$K_s \tan\phi' = 3\frac{s_u}{\gamma'_s D}$$

Punch-through in sand-over-clay
砂土-粘土刺穿破坏



Centrifuge testing 离心机模拟

UWA drum centrifuge



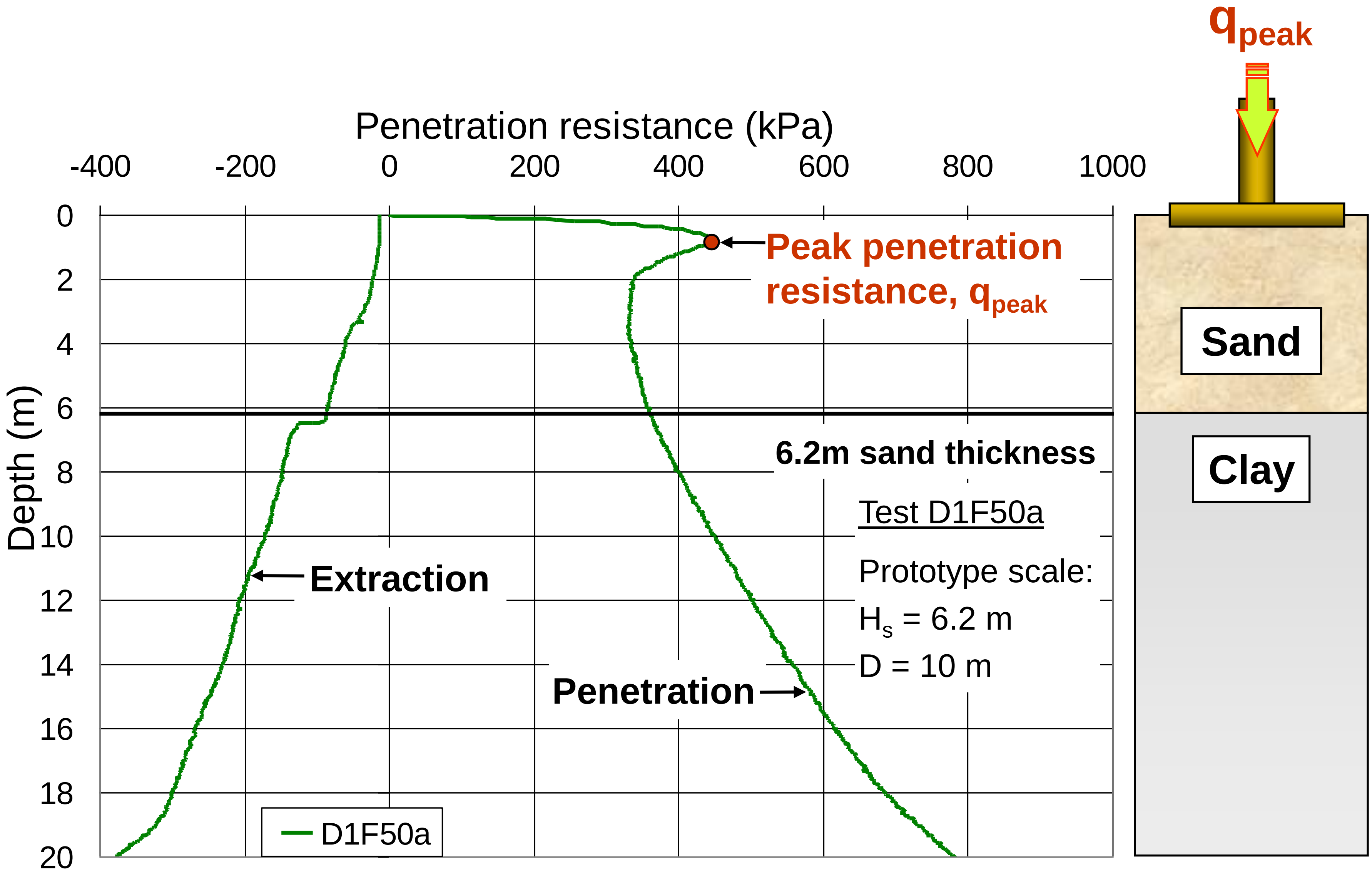
Series of model spudcan foundations

Total tests performed : 70

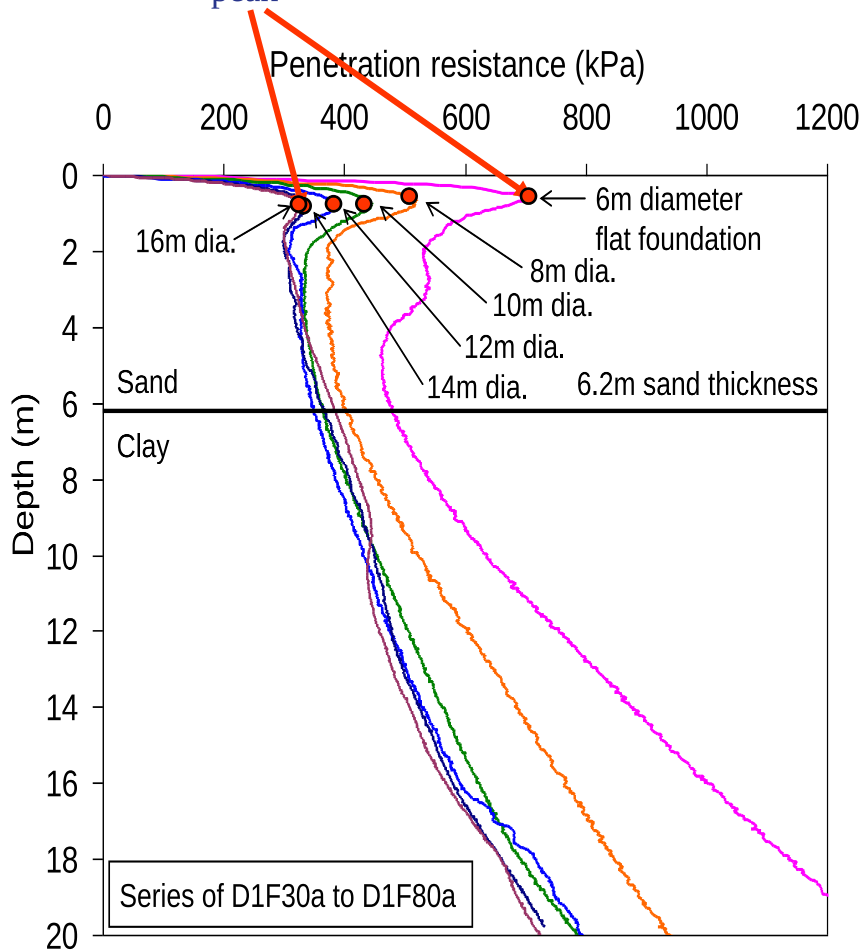
Range of tests	
Sand thickness, H_s	3.05 m – 7.25 m
Foundation diameter, D	6 m – 20 m
H_s/D ratio	0.16 – 1.12
Spud. shape	angle 0°, 7°-21°
I_D	0.43, 0.74, 0.95

After testing

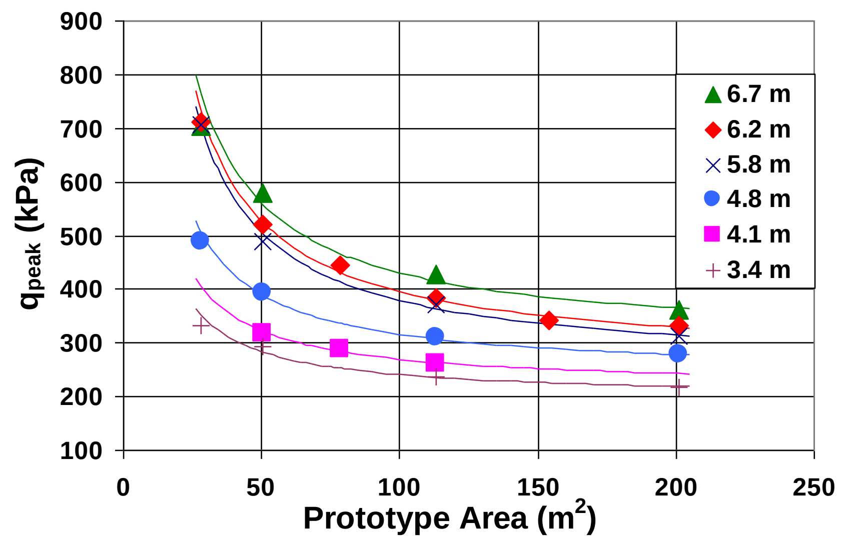
Centrifuge testing 离心机模拟



Peak penetration resistance, q_{peak}



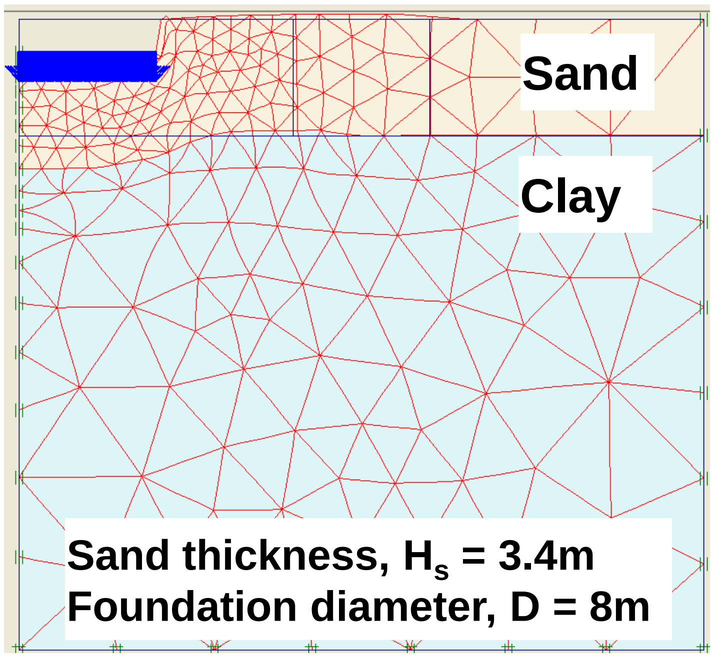
Plot together

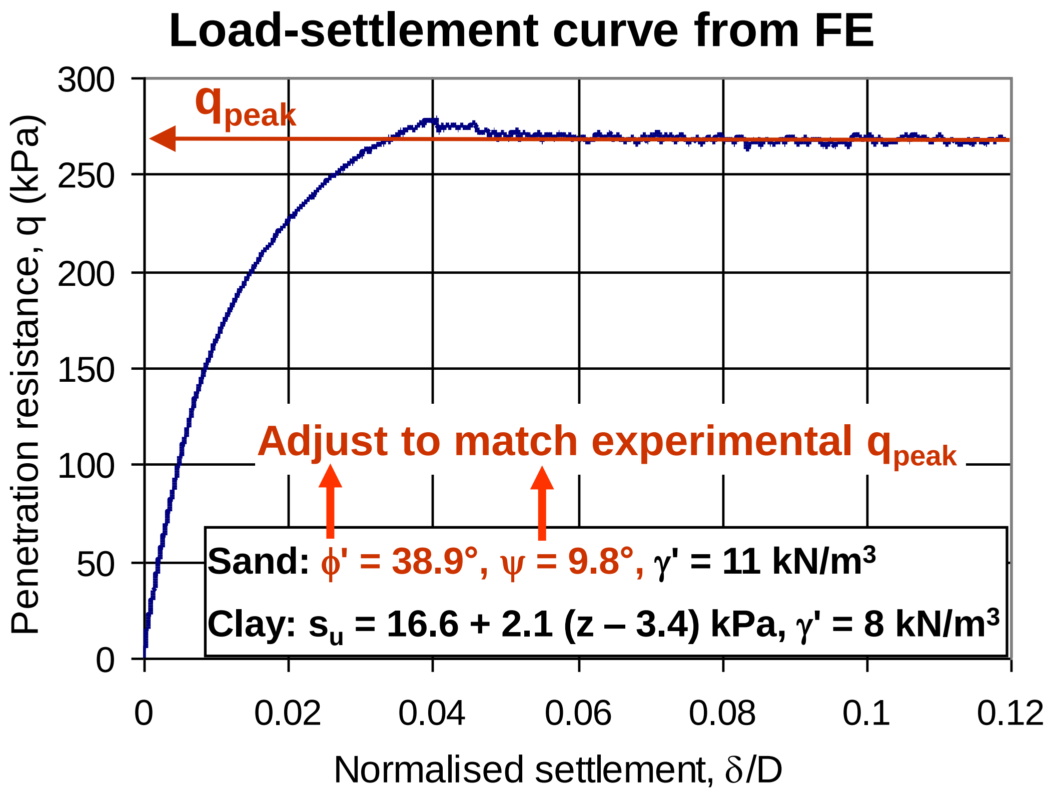


For this case, Sand Layer = 6.2 m

Diameter = 6, 8, 10, 12, 14 and 16 m

Supporting finite element analysis
有限元分析

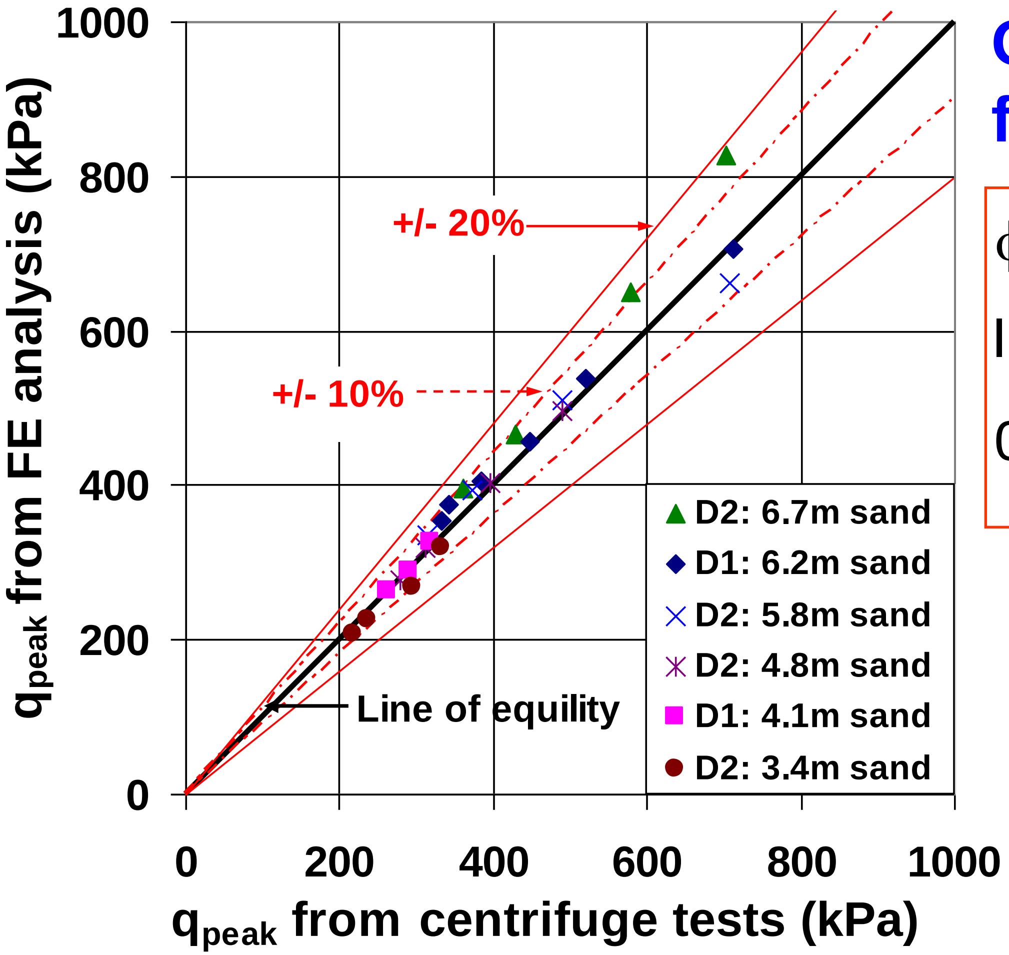




Aim: Incorporate stress level and dilatant response of sand

Method: Back-calculate operative ϕ' and ψ

Relationship between q_{peak} and operative ϕ' and ψ
q_{peak}和等效ϕ'、ψ 的关系



Obtain relationships for ϕ' and ψ :

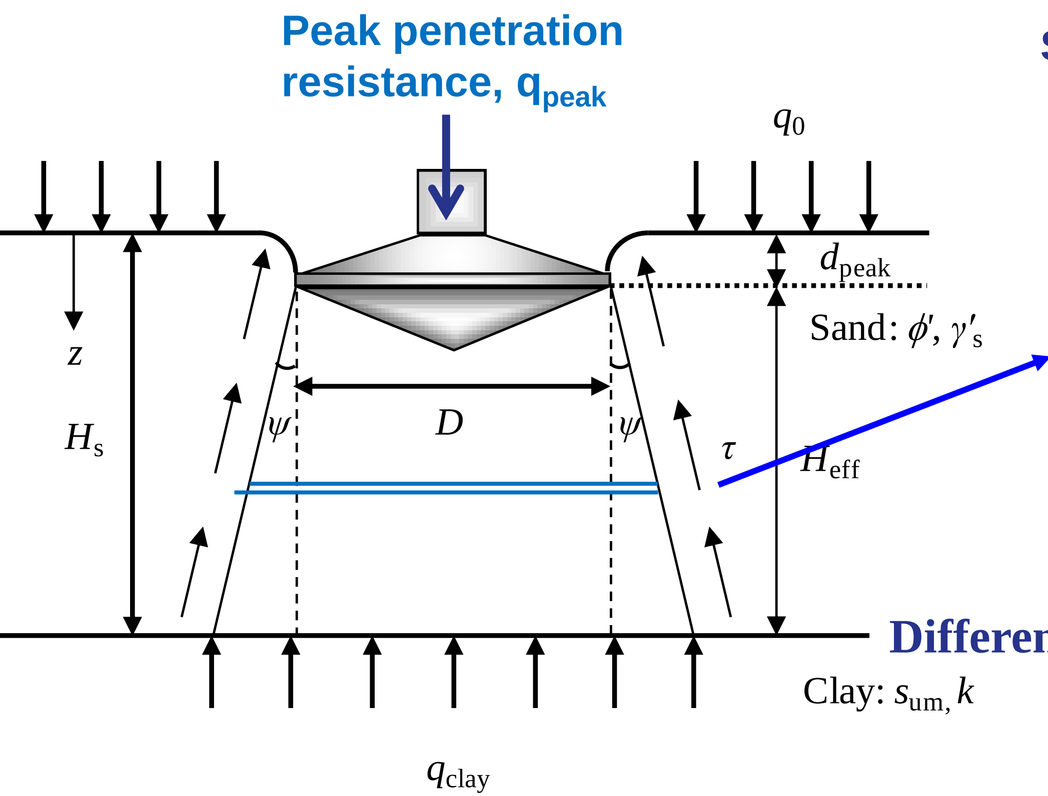
$$\phi' - \phi_{cv} = 2.65 I_R$$

$$I_R = I_D\left(10 - \ln q_{peak}\right) - 1, \quad 0 < I_R < 4$$

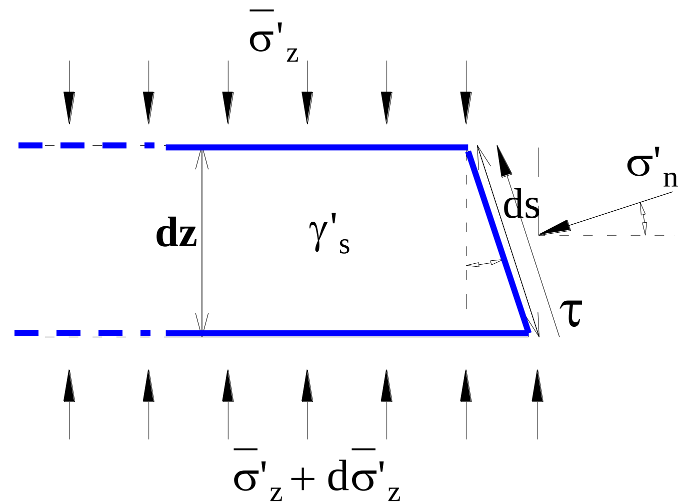
$$0.8\,\psi = \phi' - \phi_{cv}, \quad \psi \geq 0$$

Modified form of Bolton (Geotechnique, 1986)

Analytical derivation 解析方法



Stresses on a thin horizontal disc:



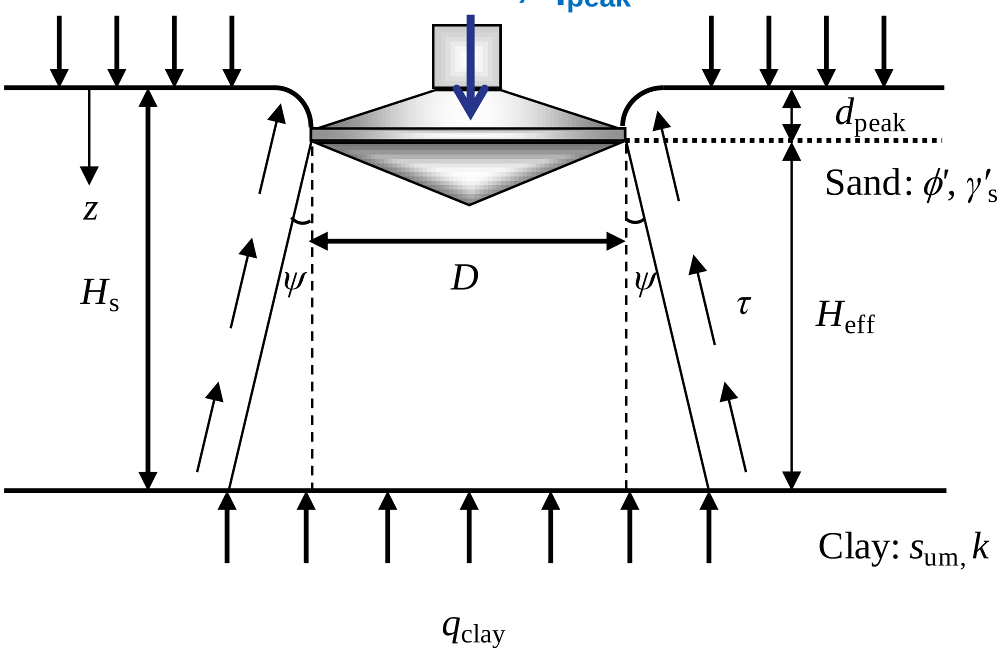
Differential equation of vertical force equilibrium

$$\frac{d\bar{\sigma}'_z}{dz} + \frac{E \tan\psi}{(D/2 + z\tan\psi)}\bar{\sigma}'_z - \gamma'_s = 0$$

where $$E = 2\left[1 + D_F\left(\frac{\tan\phi^*}{\tan\psi} - 1\right)\right]$$

(see Lee, Randolph, Cassidy, *Géotechnique*, 63(15), 2013 & Hu, Wang, Stanier, Cassidy, *Géotechnique*, 65(11) 2015)

Analytical model (Hu et al.) 解析模型



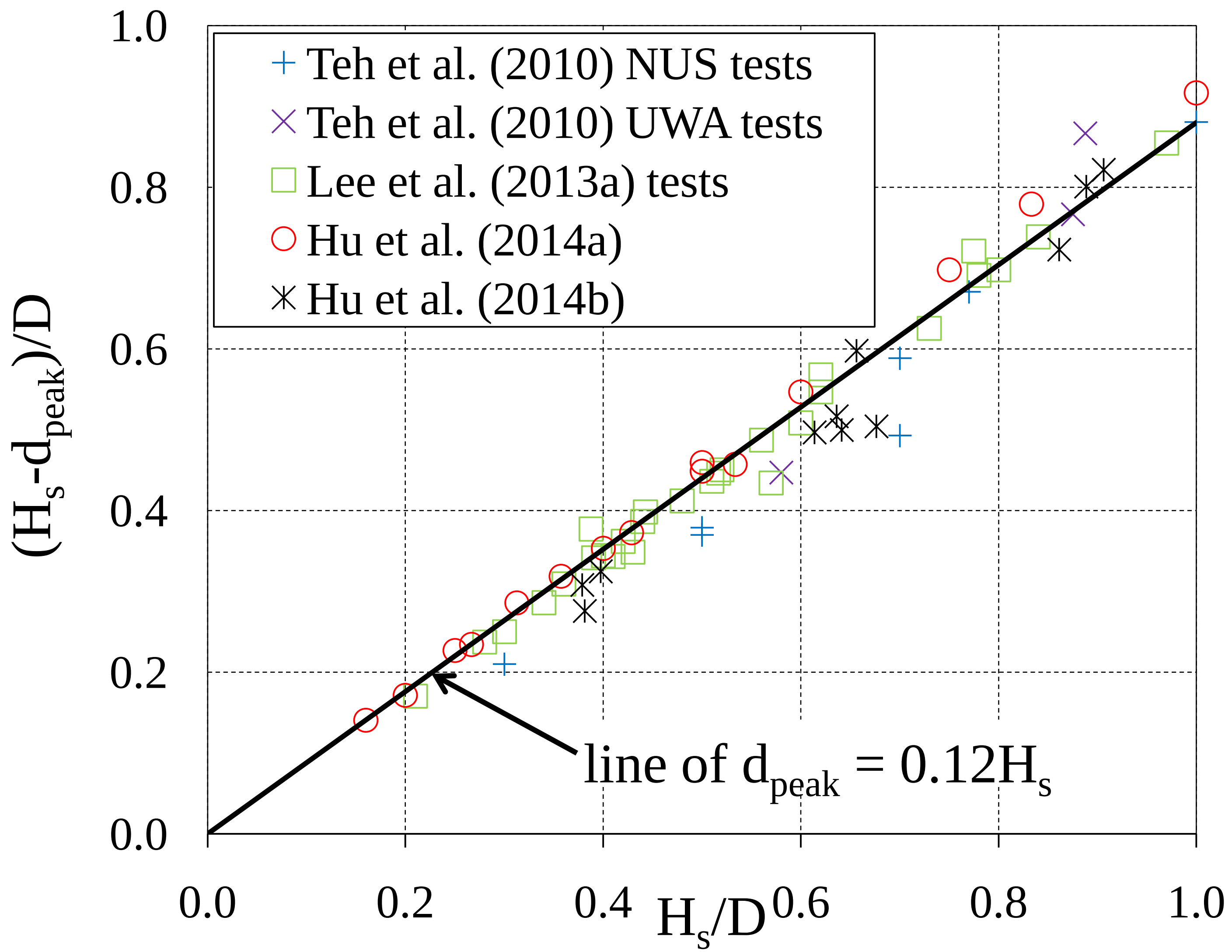
Geom	D	Diameter
	H_s	Sand thickness
Sand	I_D	Relative density
	γ'_s	Effective unit weight of sand
	ϕ_{cv}	Critical state friction angle
	Q	Bolton's (1986) equation
Clay	s_{um}	Undrained shear strength at sand-clay interface
	K	Gradient of increasing shear strength

$$q_{peak} = \left(N_{c0}s_{um} + q_0 + 0.12\gamma'_s H_s\right)\left(1+\frac{1.76H_s}{D}\tan\psi\right)^E + \frac{\gamma'_s D}{2\tan\psi(E+1)}\left[1-\left(1-\frac{1.76H_s}{D}E\tan\psi\right)\left(1+\frac{1.76H_s}{D}\tan\psi\right)^E\right] \le q_{sand}$$

where $E = 2\left[1+D_F\left(\frac{\tan\phi^*}{\tan\psi}-1\right)\right]$; $q_{sand} = s_\gamma N_\gamma \frac{\gamma'_s D}{2} + s_q N_q q_0$

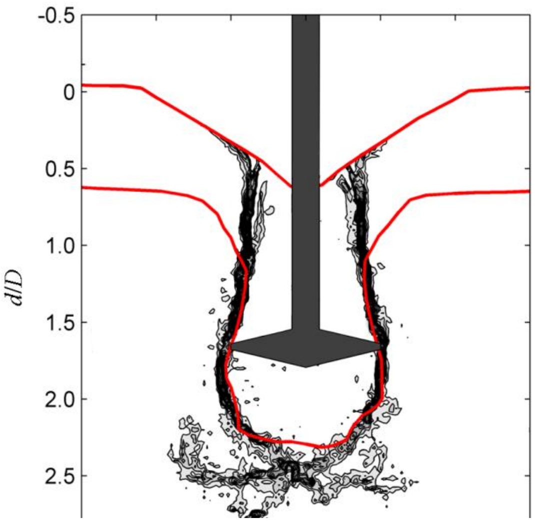
(see Lee, Randolph, Cassidy, *Géotechnique*, 63(15), 2013 & Hu, Wang, Stanier, Cassidy, *Géotechnique*, 65(11) 2015)

Depth of punch-through (d_{peak})
刺穿深度d_{peak}

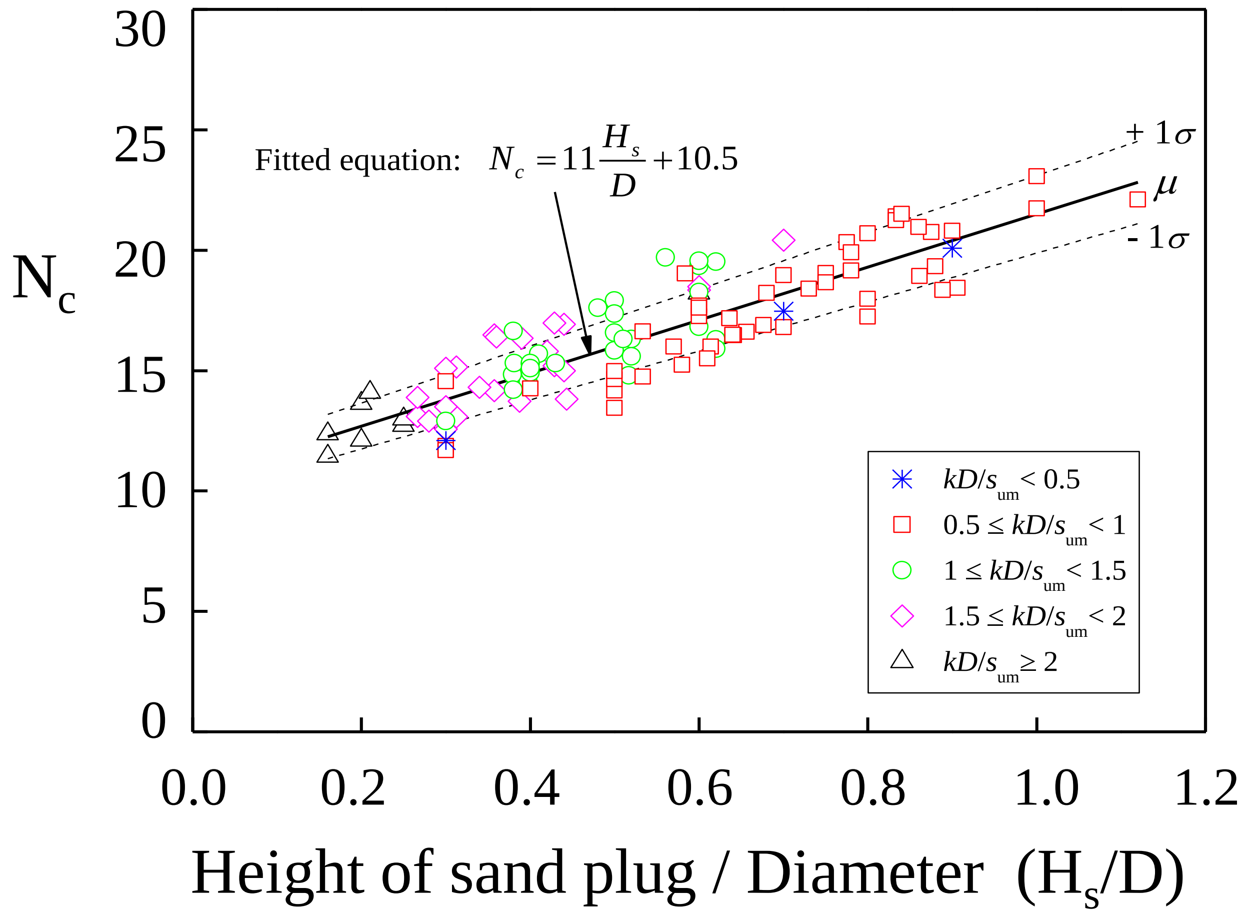


Bearing capacity N_c in underlying clay
下层粘土的承载力系数

$$q_{clay} = N_c s_{um} + h_{plug}\gamma'_c \qquad N_c = 11\frac{H_s}{D} + 10.5$$



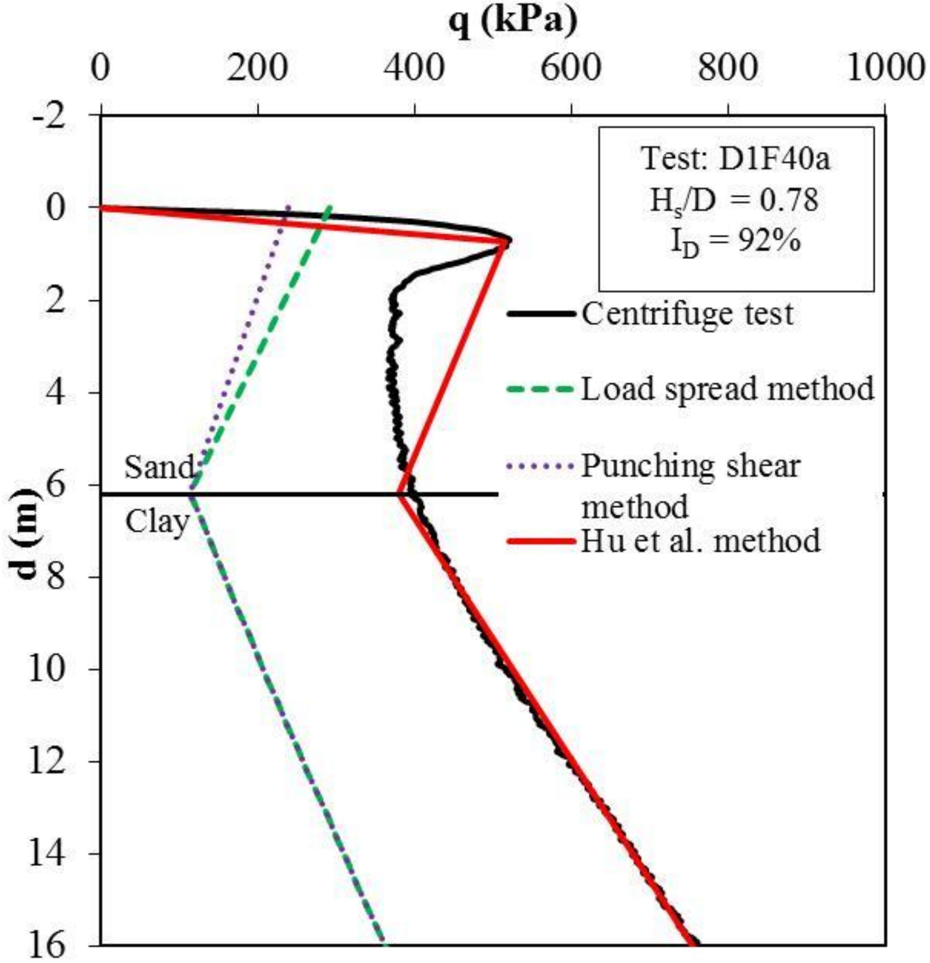
From Centrifuge PIV:
at 1D below sand



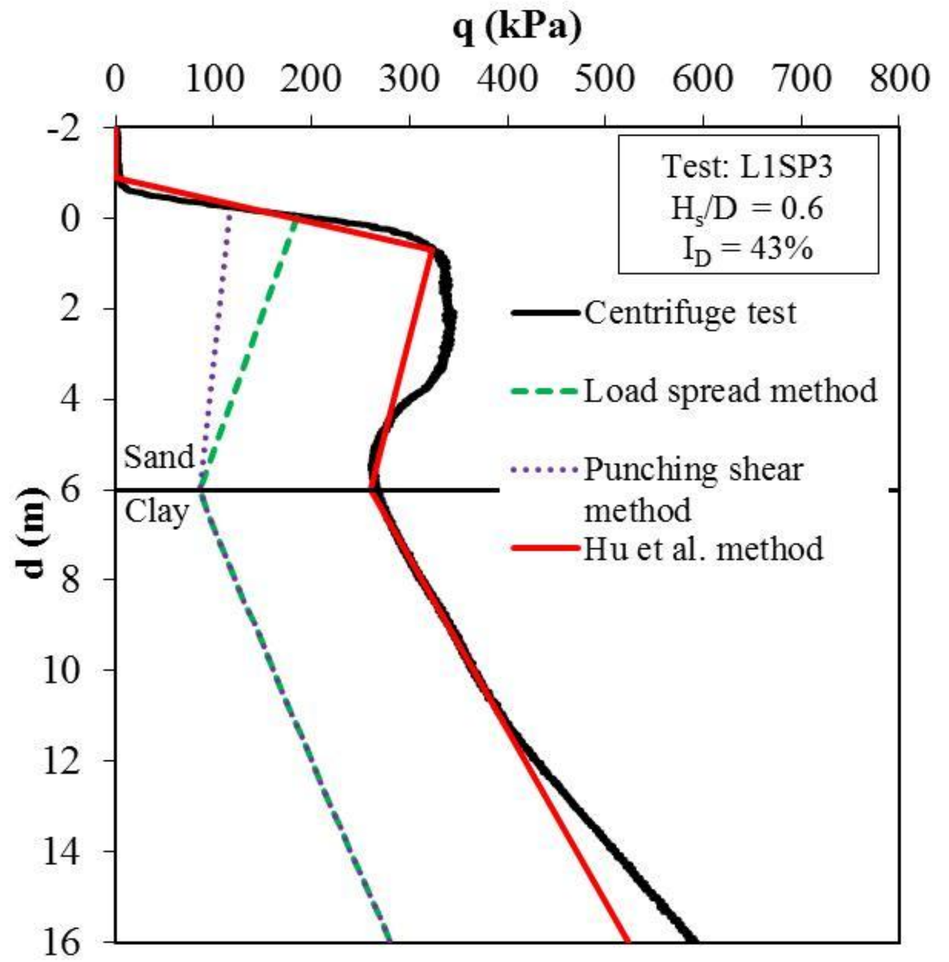
Performance against database
和数据库对比

UWA Drum Centrifuge tests:

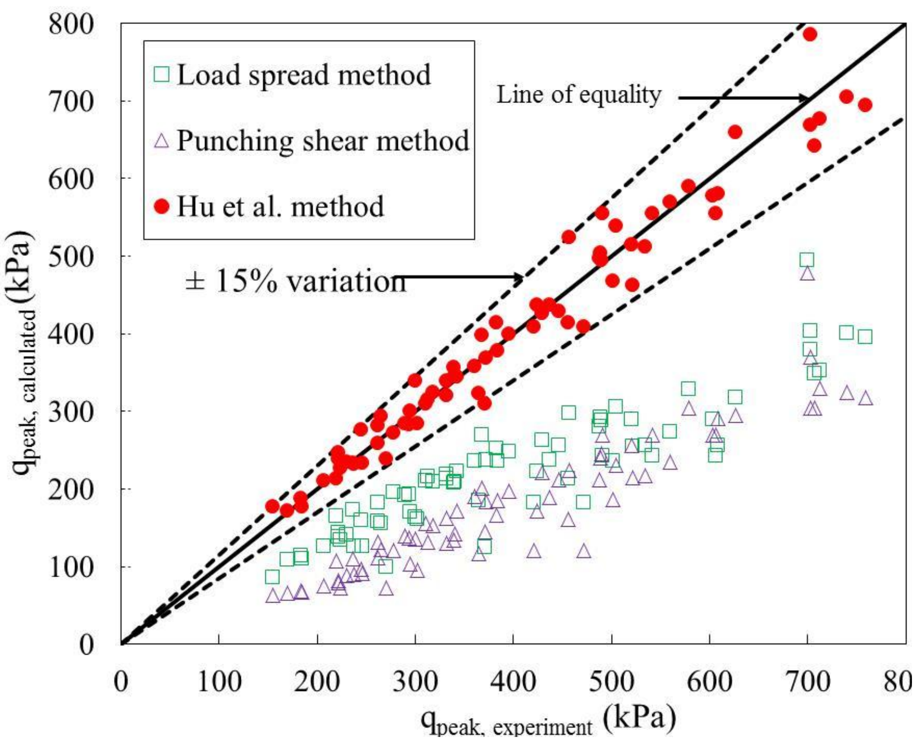
D1F40a (I_D=0.92, Hs= 6.2 m, D = 8m)

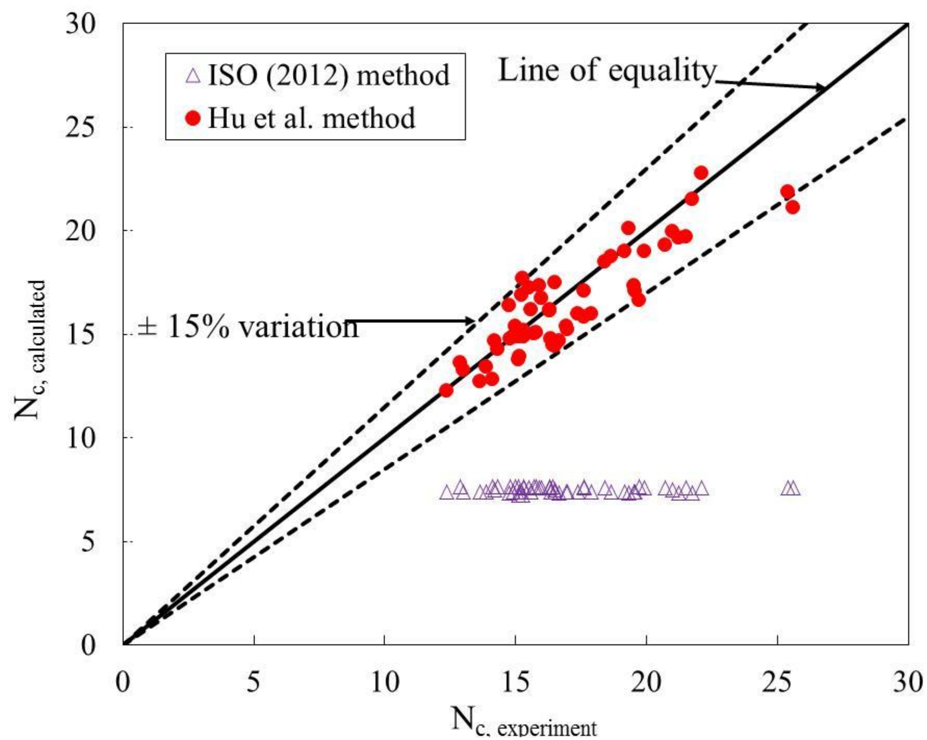


L1SP3a (I_D=0.43, Hs= 6.0 m, D = 10m)



Performance against database
和数据库对比





		ISO 19905-1		Hu et al. method
		Load spread	Punch. shear	
$q_{peak, calculated}$ / $q_{peak, measured}$	Mean	0.58	0.44	1.01
	σ	0.09	0.07	0.08
	CoV	15.8%	14.1%	8.2%

		ISO 19905-1		Hu et al. method
		Load spread	Punch. shear	
$N_{c, calculated}$ / $N_{c, measured}$	Mean	0.45		0.97
	σ	0.07		0.07
	CoV	15.7%		7.7%

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   - Use of probabilistic methods 非确定性分析方法
3. Renewable Energy Infrastructure 可再生能源工程
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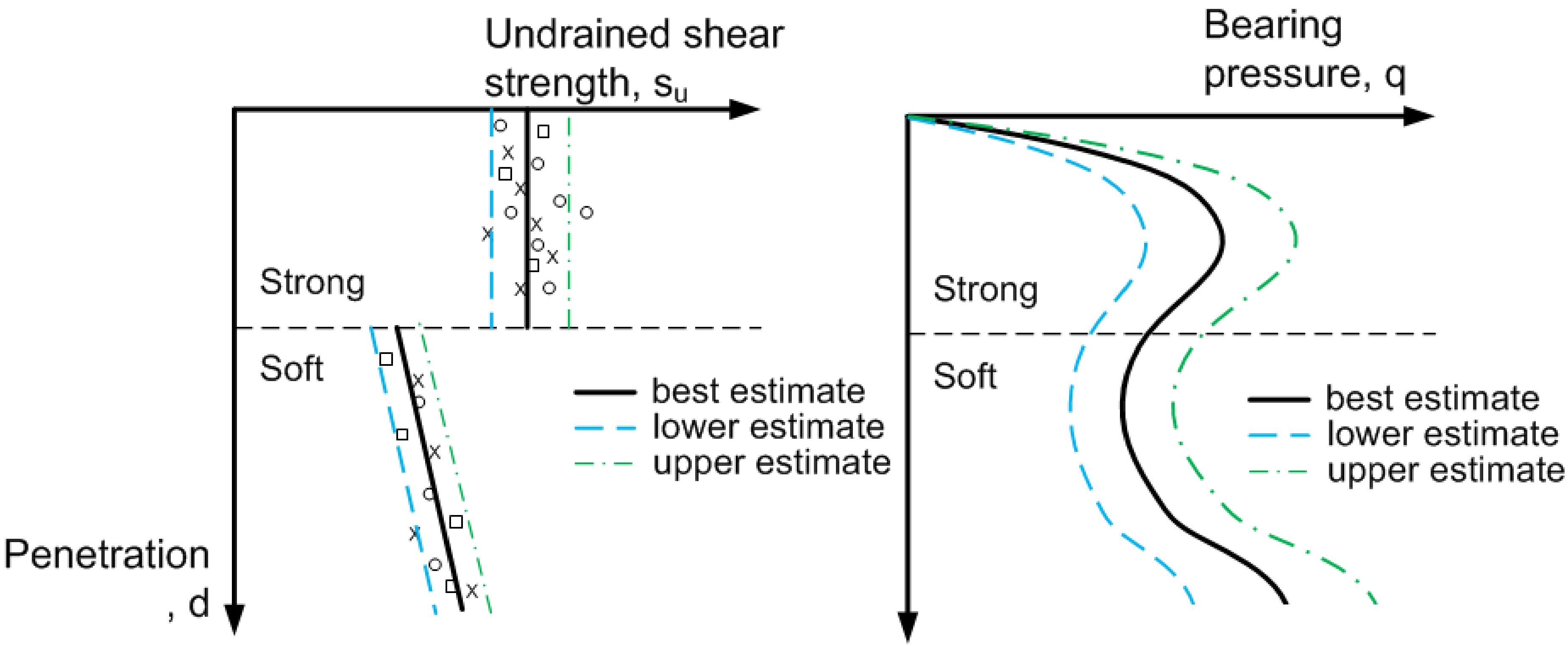
4. Conclusions 结论

Introduction to probabilistic methods
非确定性方法介绍

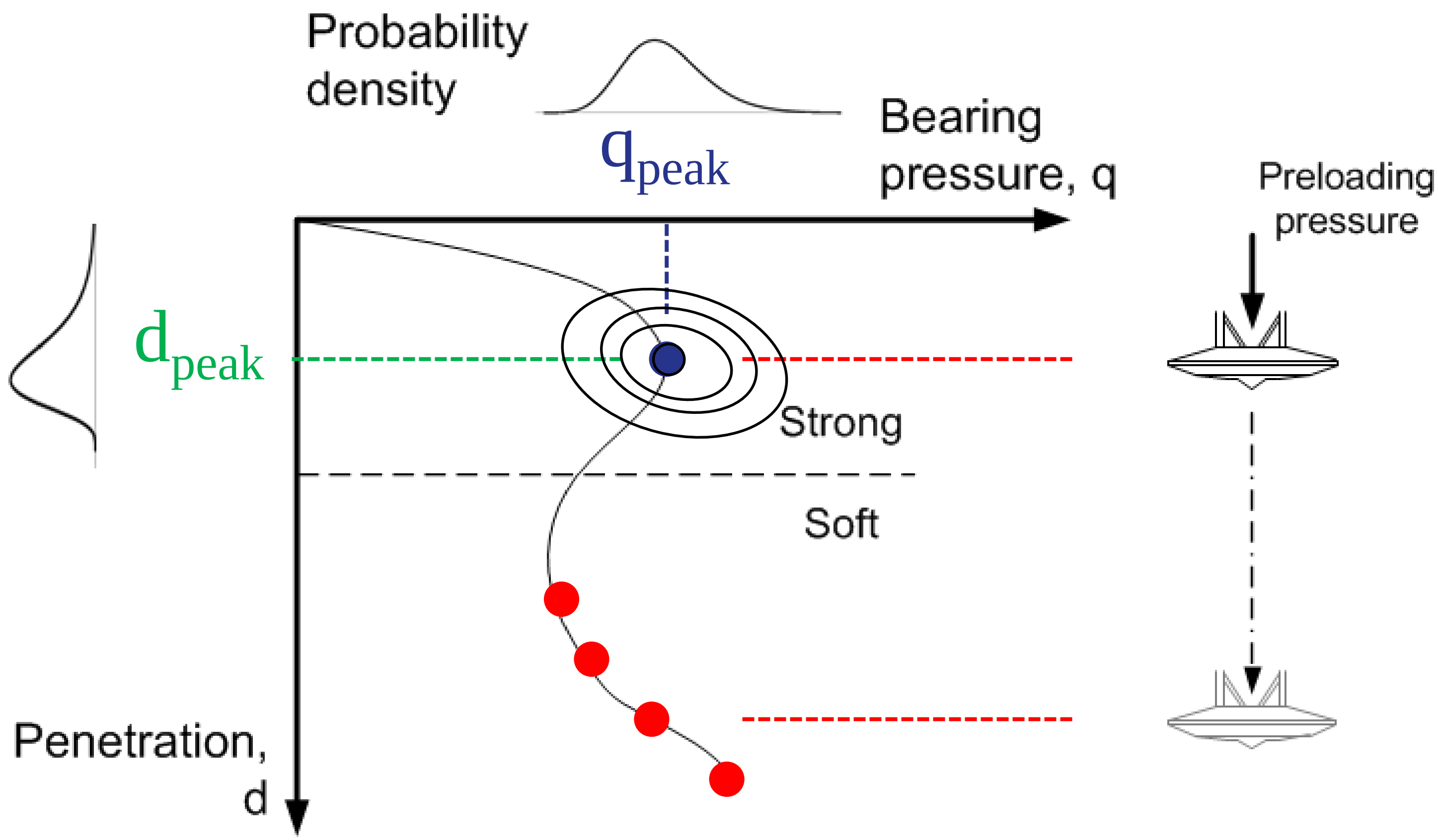
In preparing a load-penetration curve, there are uncertainties in 荷载-位移曲线的不确定性

- measuring and deriving the properties of the soils (predominantly, but not limited to, strength);
- locations of layer boundaries;
- variation in properties across the site; and
- the application of the predictive model.

Experience from InSafe JIP
InSafe联合项目的经验

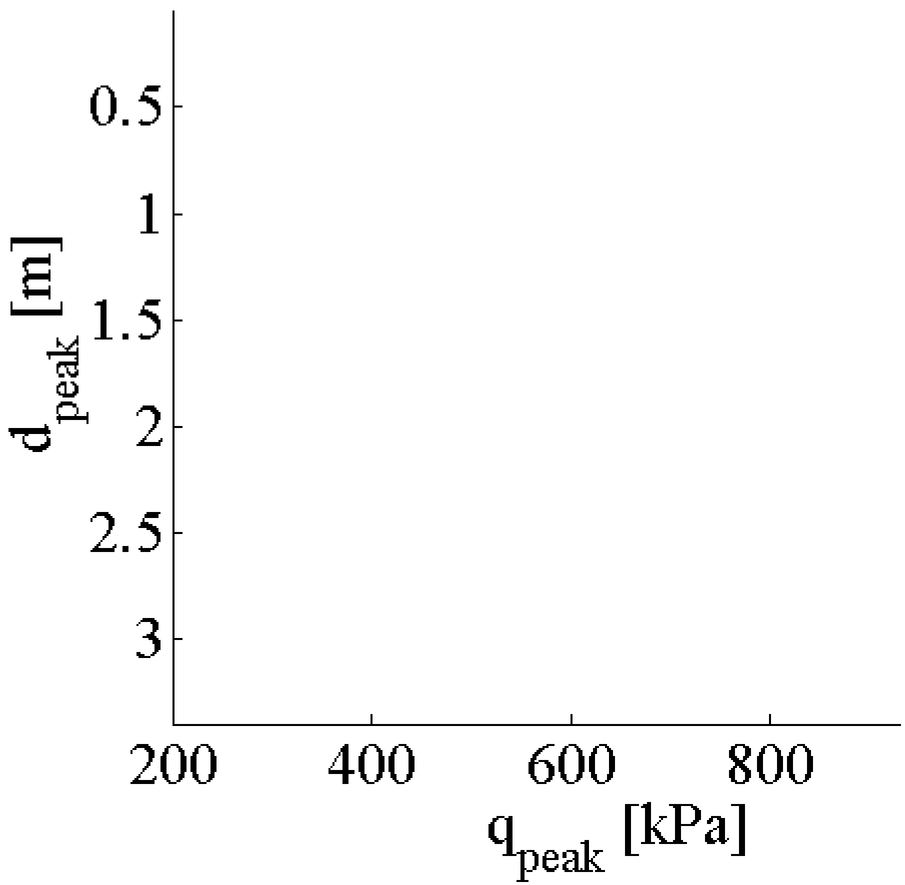


Challenges during installation
安装过程中的挑战



Simple probabilistic method
简单的非确定性分析方法

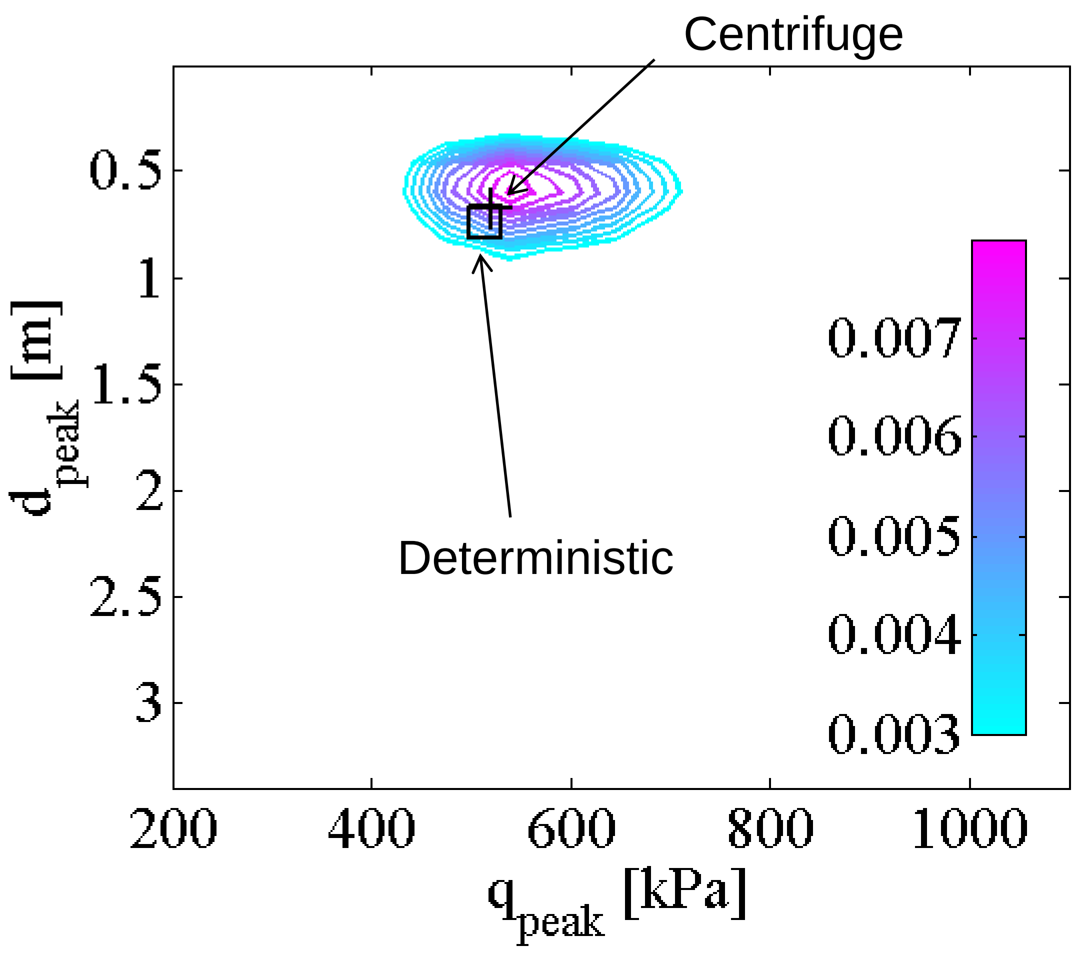
UWA Drum Centrifuge test D1F40a (I_D=0.92, Hs= 6.2 m, D = 8m)

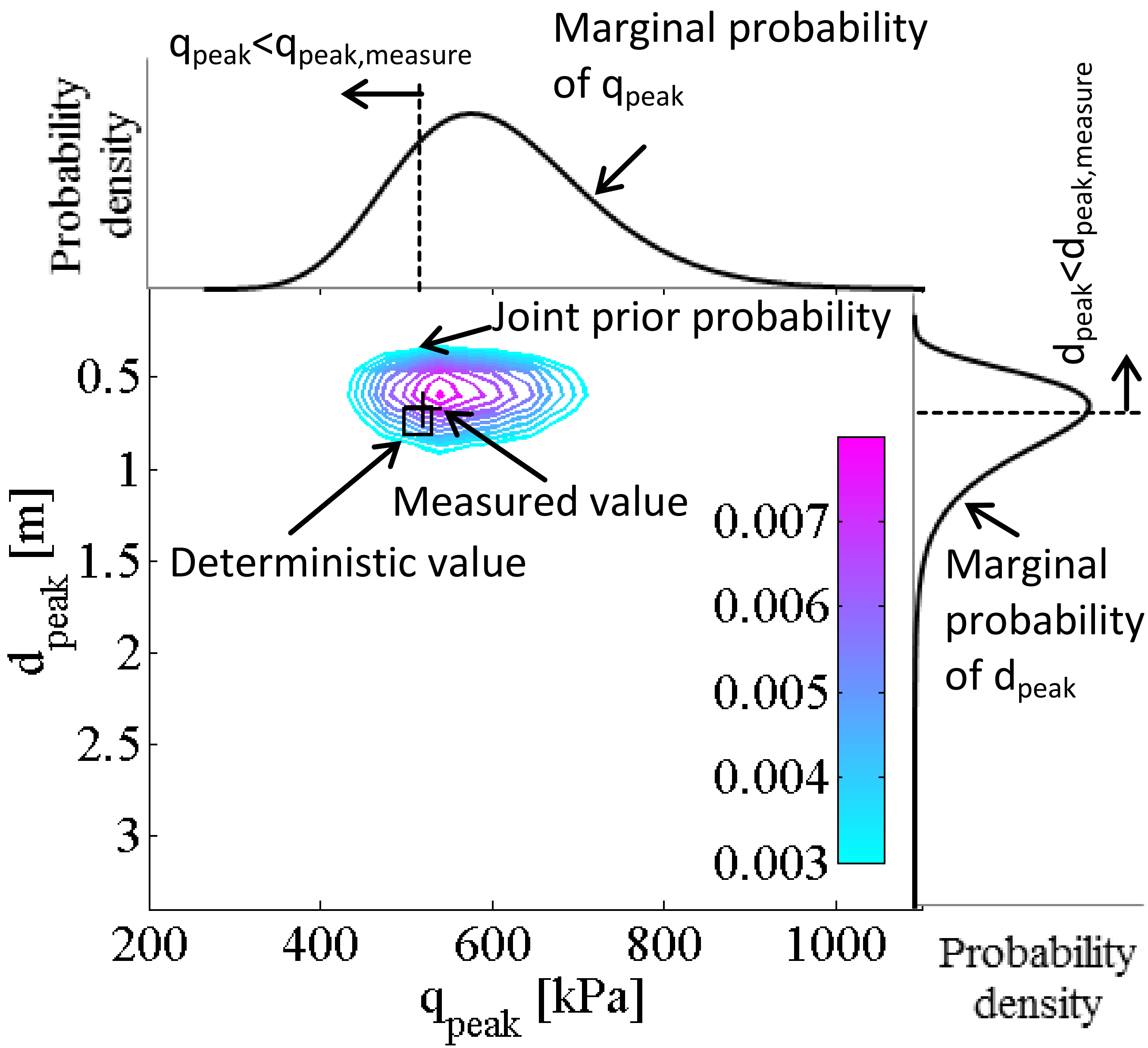


0.5
1
1.5
2
2.5
3
200
400
600
800
d_{peak} [m]
q_{peak} [kPa]

Simple probabilistic method
简单的非确定性分析方法

UWA Drum Centrifuge test D1F40a (I_D=0.92, Hs= 6.2 m, D = 8m)

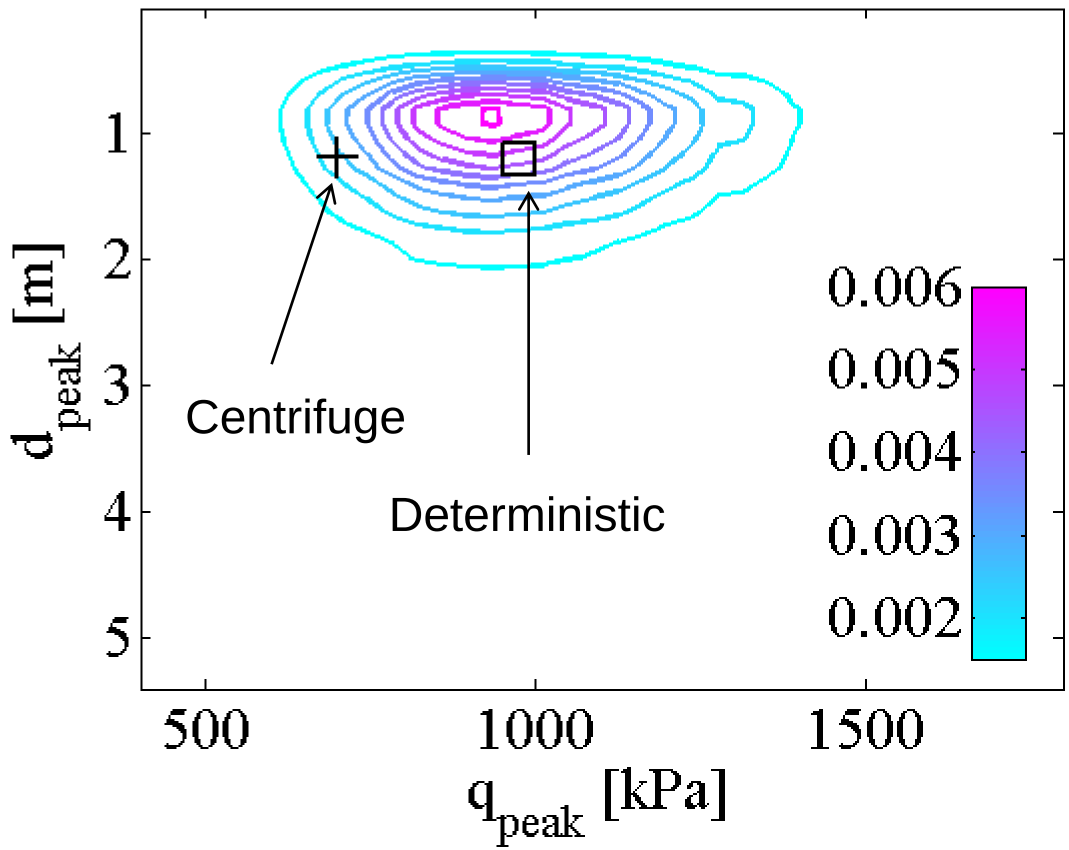




q_{peak}<$q_{peak,measure}$
Marginal probability of q_{peak}
Probability density
d_{peak}<$d_{peak,measure}$
Joint prior probability
0.5
1
1.5
2
2.5
3
d_{peak} [m]
Measured value
Deterministic value
0.007
0.006
0.005
0.004
0.003
Marginal probability of d_{peak}
200
400
600
800
1000
q_{peak} [kPa]
Probability density

Simple probabilistic method
简单的非确定性分析方法

NUS Beam Centrifuge test NUS-F5 (I_D=0.95, Hs= 10 m, D = 10 m)



Bayes' theorem 贝叶斯理论

Bayes' theorem:

Used to provide a theoretical framework to allow updating of load-penetration with monitored data …

$$P(A \mid B) = \frac{P(B \mid A) P(A)}{P(B)}$$

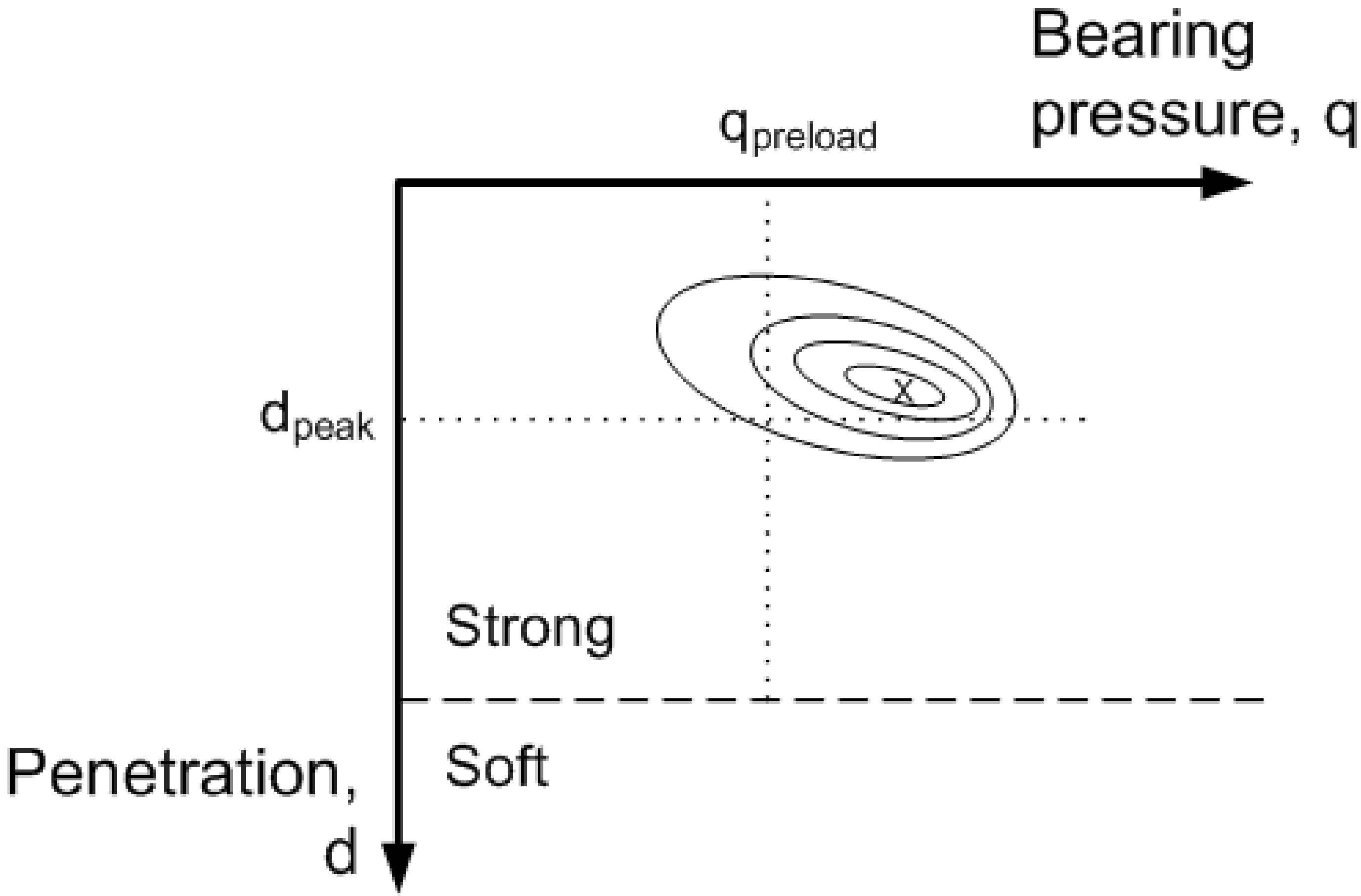
A = Prior

B = Observation … monitored data

P(A|B) = Probability of A given B to be true

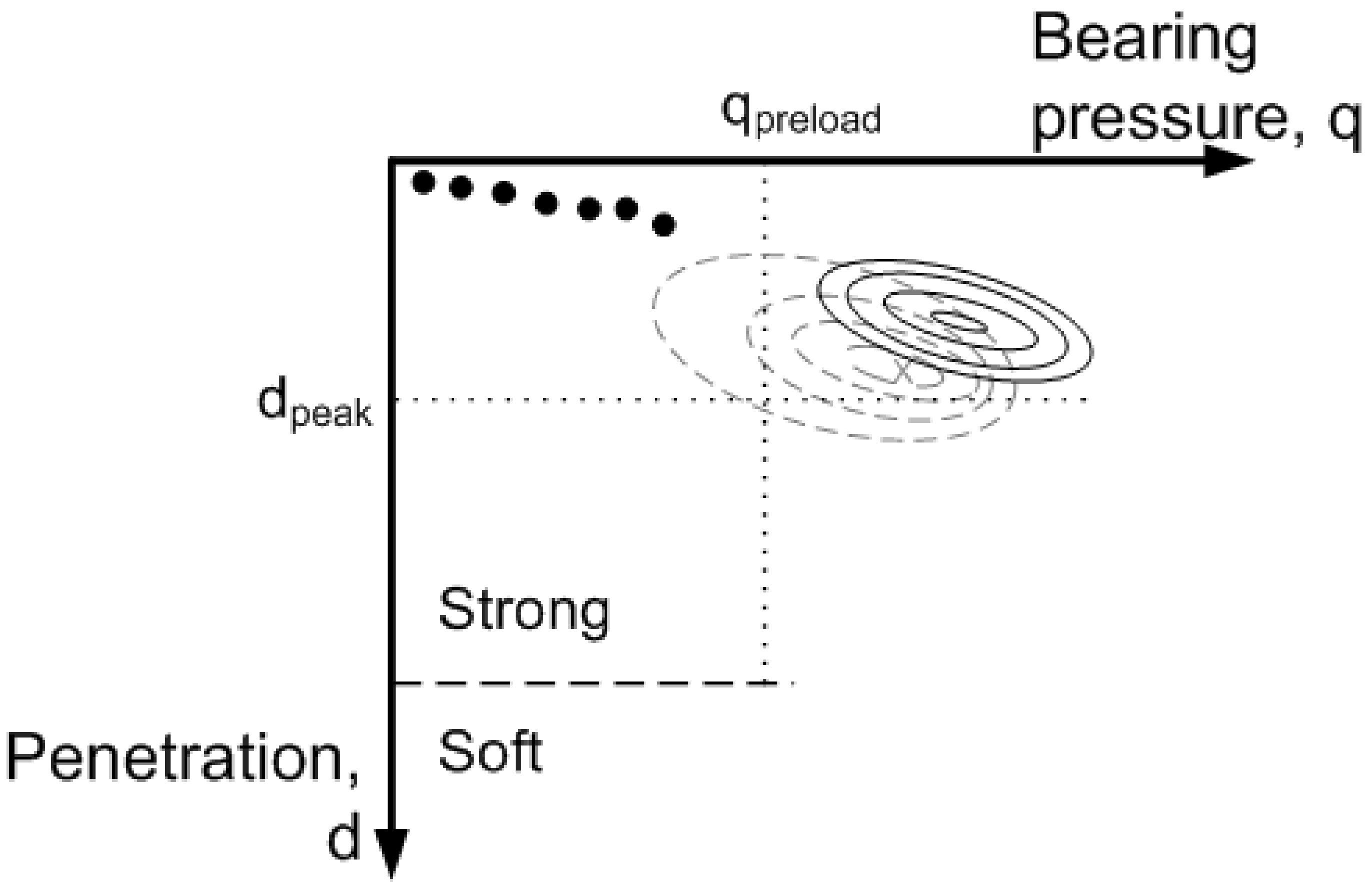
Use of monitored data 观测数据的应用

Prior Assessment:



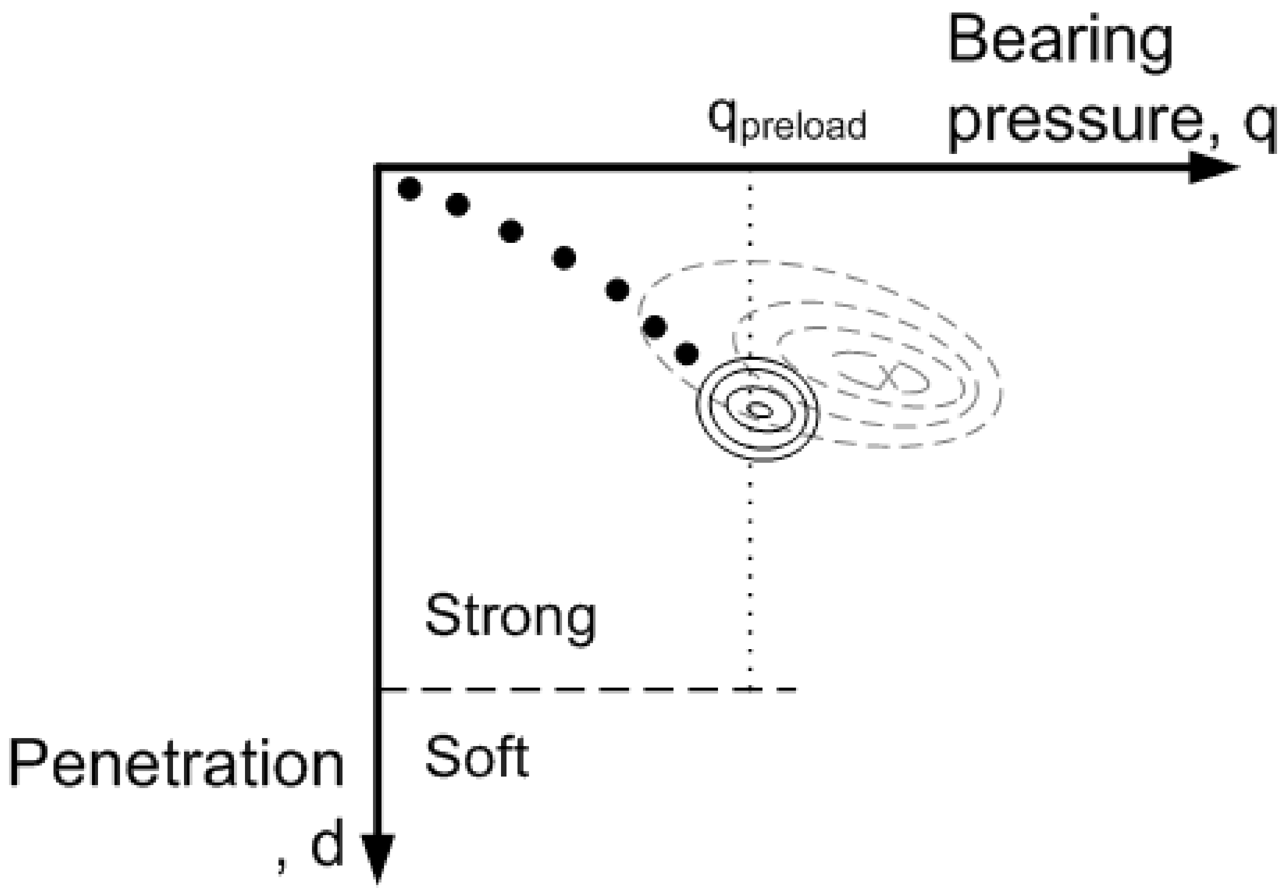
Use of monitored data 观测数据的应用

Posterior Assessment:

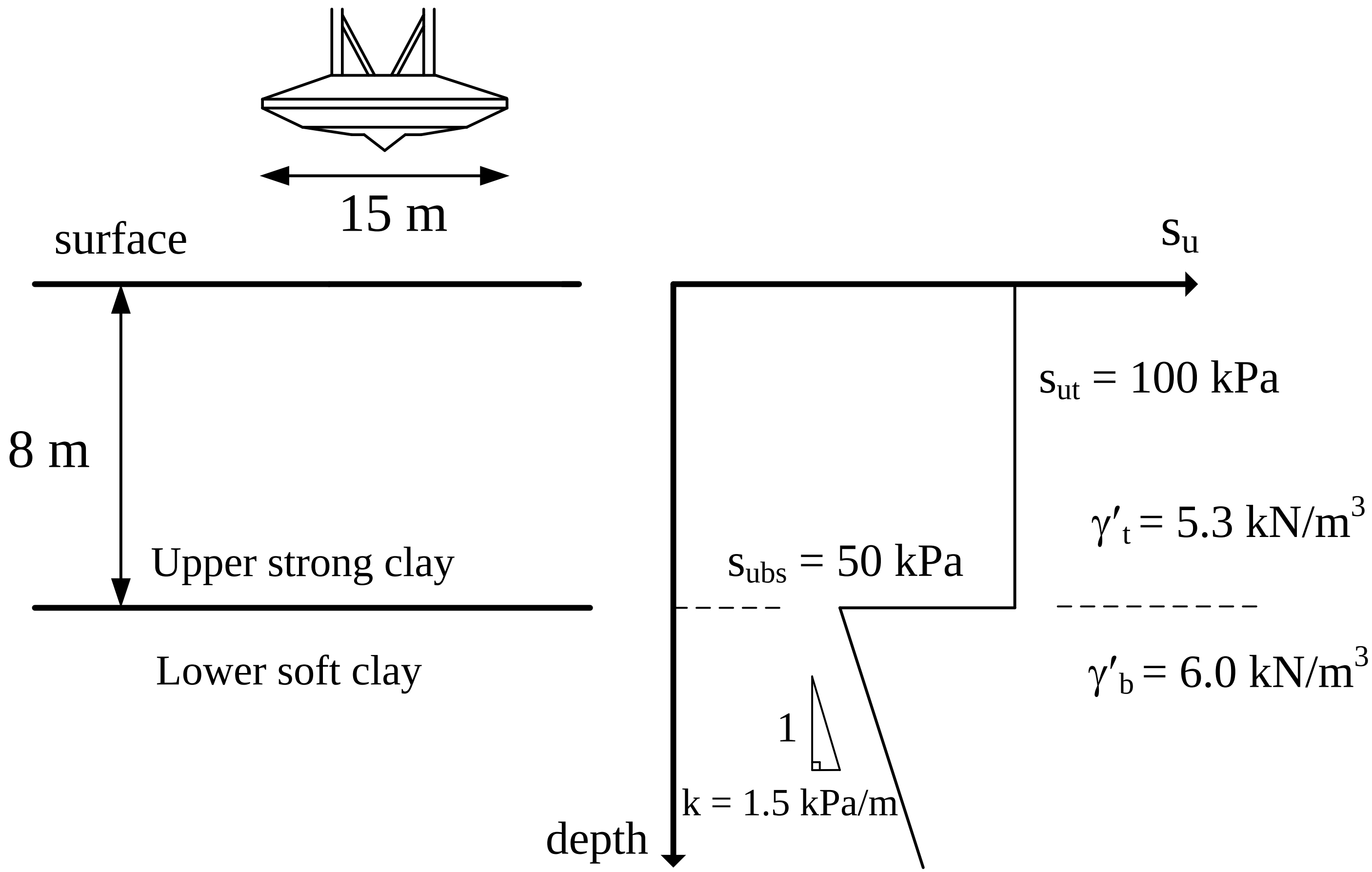


Use of monitored data 观测数据的应用

Posterior Assessment:



Use of monitored data? 观测数据的应用？

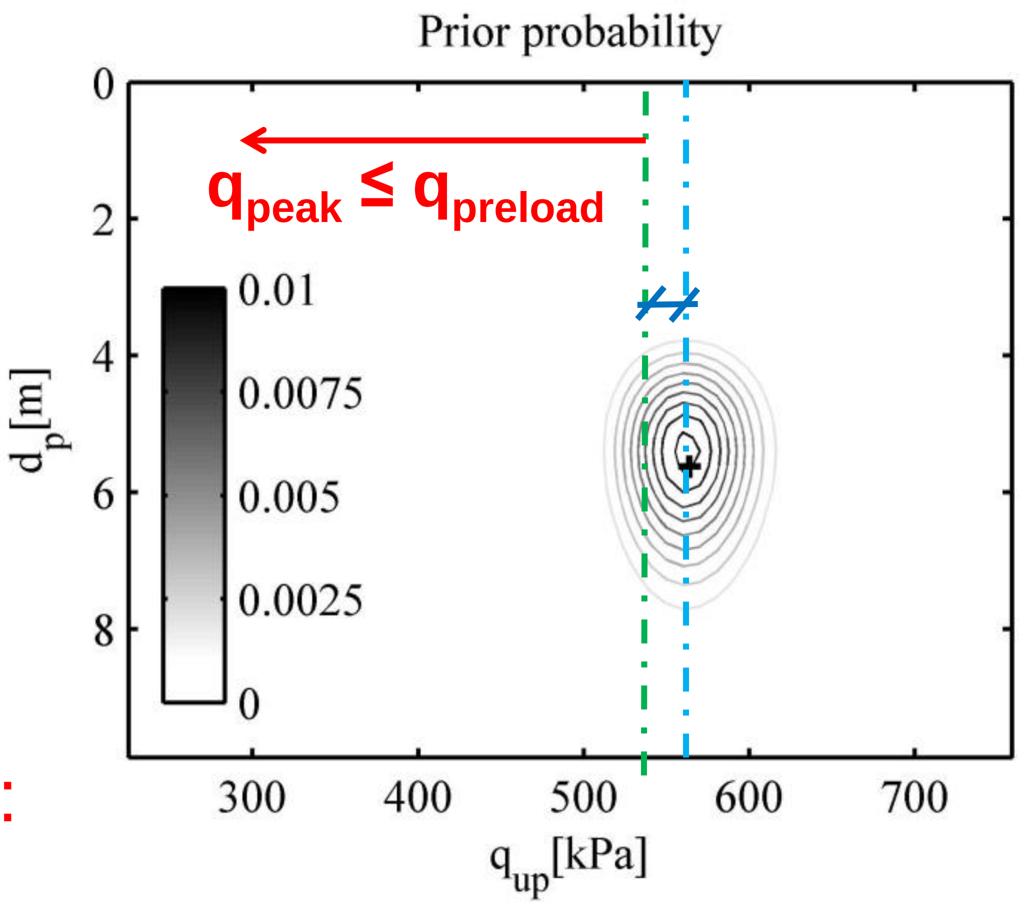


(use probabilistic development of method of Hossain and Randolph, OTC 2009)

Probability of failure: prior
失效概率：前验

$q_{preload}$ =530 kPa

q_{peak} =565 kPa



Factor of Safety:

$$FS = \frac{q_{peak}}{q_{preload}}$$

$$FS = \frac{565kPa}{530kPa} = 1.07$$

Probability of failure:

$$P_f = 0.08$$

Updating with monitored data
应用观测数据进行修正

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Prior probability

Likelihood

$$P\left(q_p, d_{pj} \mid q_{mon}, d_{mon}\right) = \frac{P\left(q_{pi}, d_{pj}\right) \cdot P\left(q_{mon}, d_{mon} \mid q_{pi}, d_{pj}\right)}{\sum_{i,j} P\left(q_{pi}, d_{pj}\right) \cdot P\left(q_{mon}, d_{mon} \mid q_{pi}, d_{pj}\right)}$$

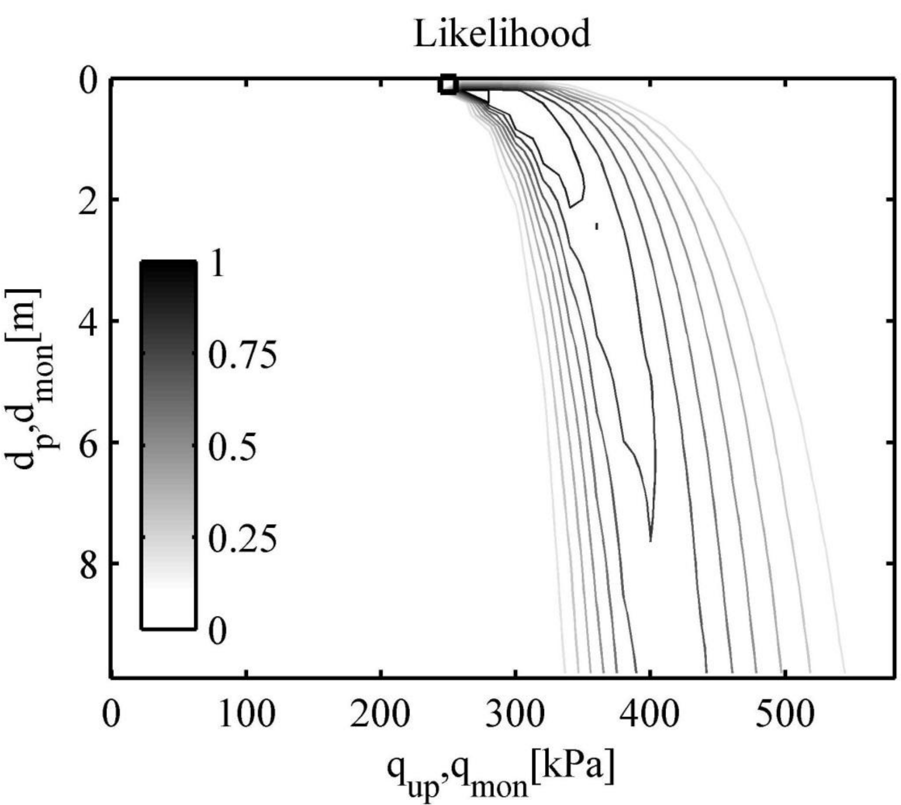
Posterior probability

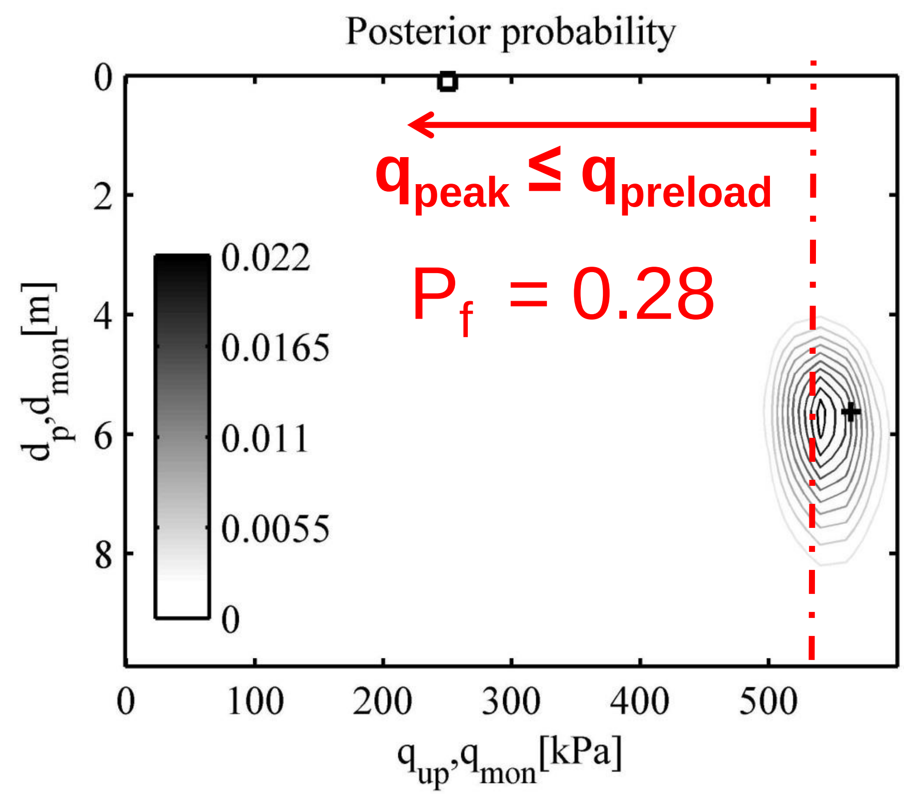
Normalizing constant

q_{mon} =250 kPa

d_{mon} = 0.1 m

$q_{preload}$ =530 kPa

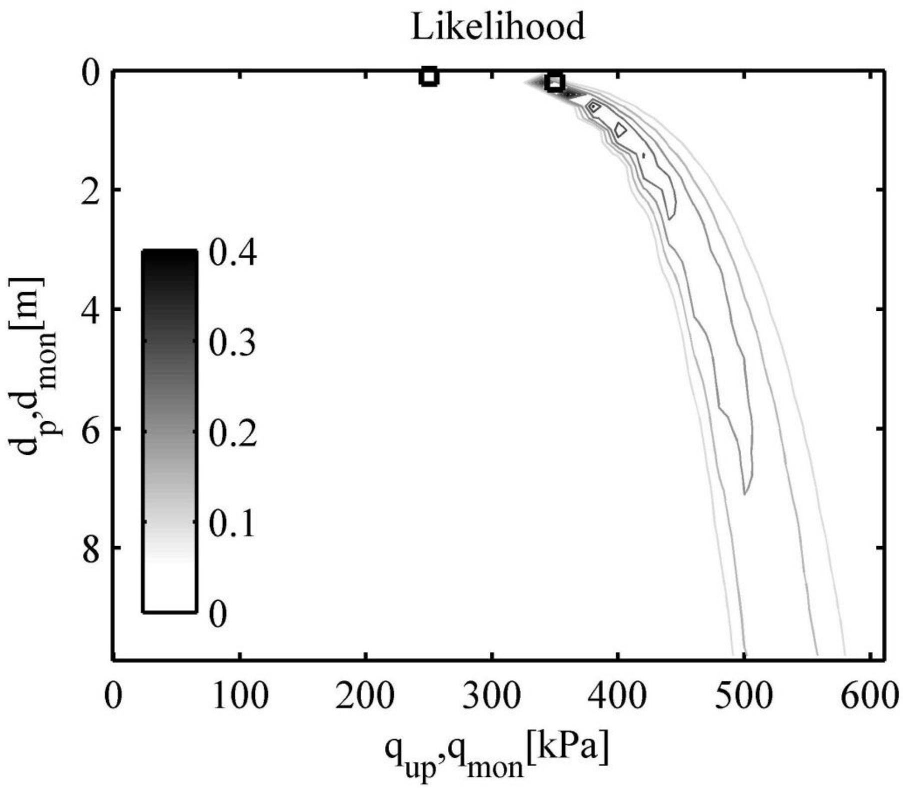


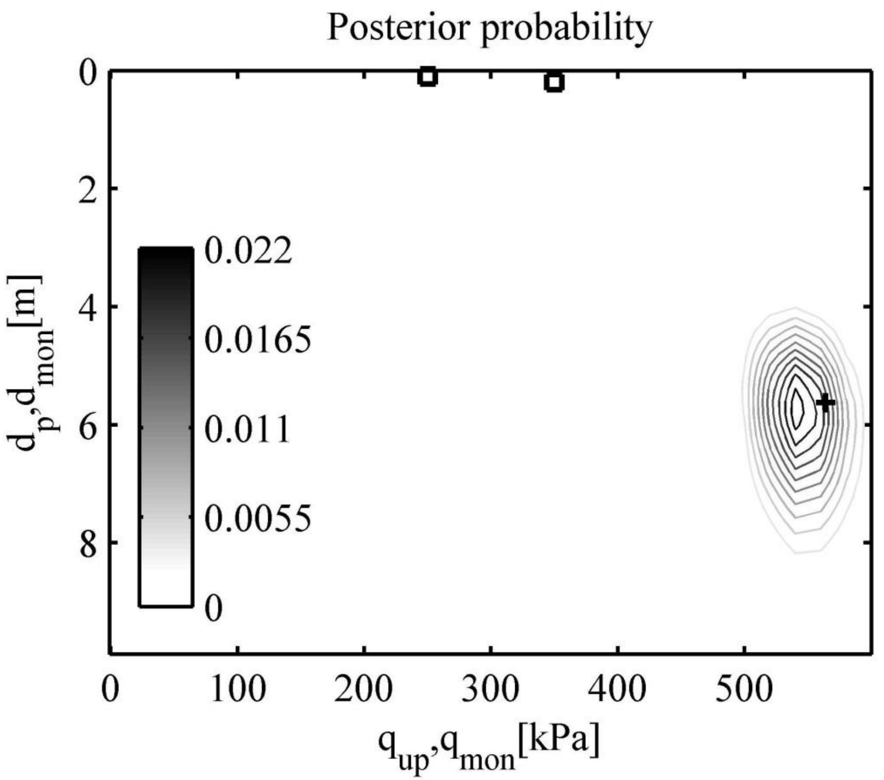


Updating with monitored data
应用观测数据进行修正

After 2 sets of monitored points: $d_{mon1} = 0.1$ m $q_{mon\,1} = 250$ kPa;

$d_{mon2} = 0.2$ m $q_{mon\,2} = 350$ kPa;





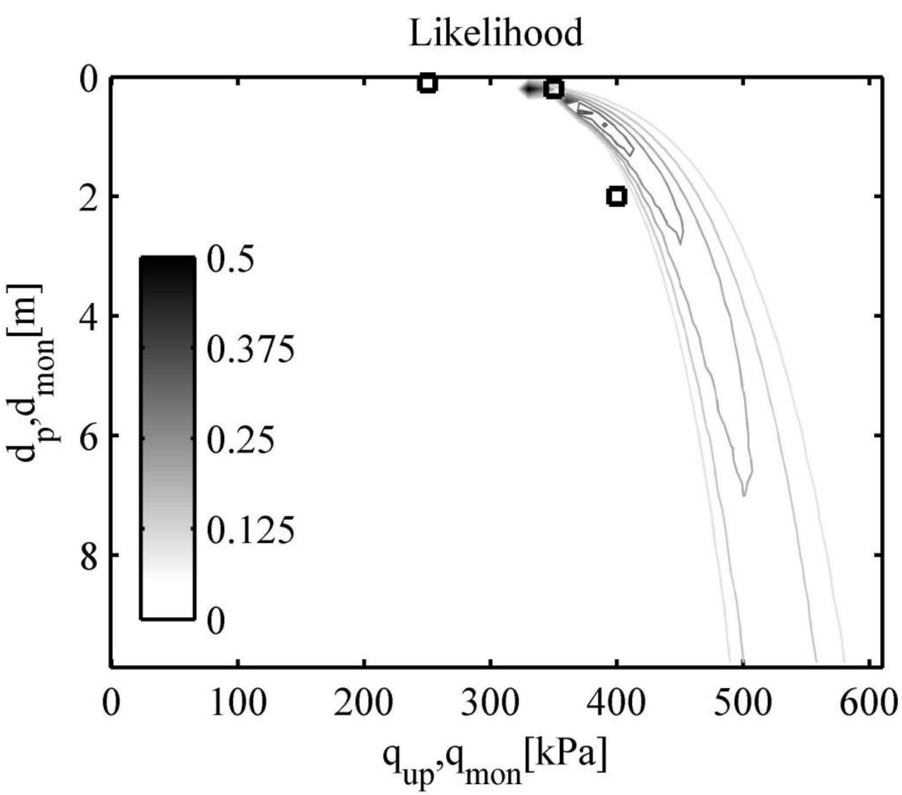
Updating with monitored data
应用观测数据进行修正

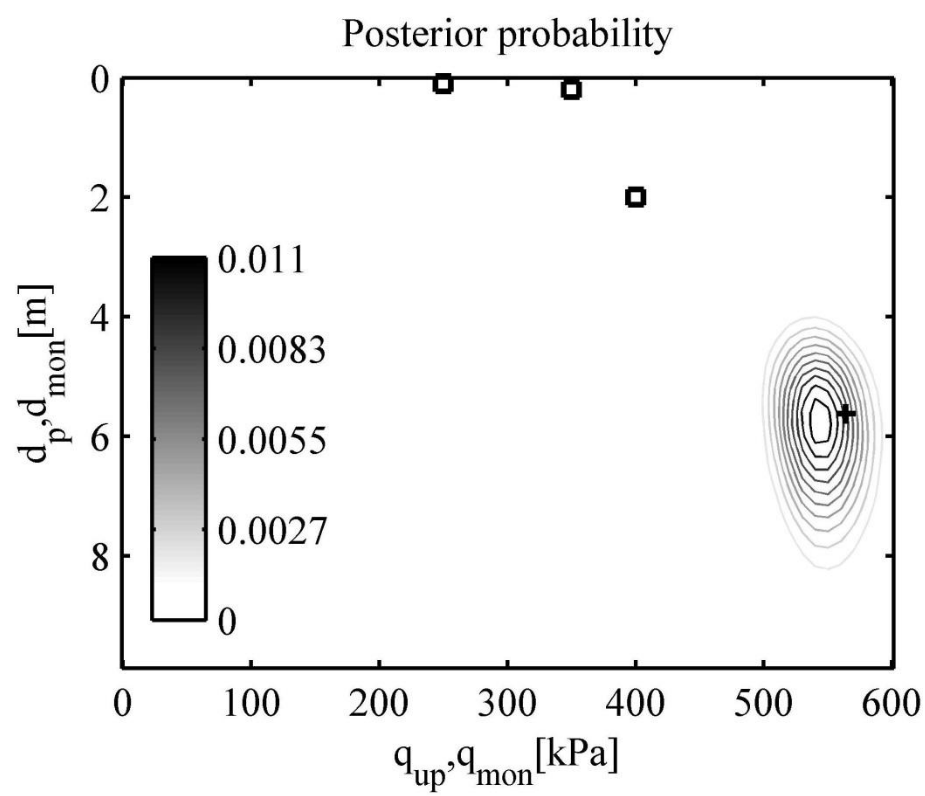
After 3 sets of monitored points:

$d_{mon1} = 0.1$ m $q_{mon\ 1} = 250$ kPa;

$d_{mon2} = 0.2$ m $q_{mon\ 2} = 350$ kPa;

$d_{mon3} = 2.0$ m $q_{mon\ 3} = 400$ kPa;





Updating with monitored data
应用观测数据进行修正

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Case	$q_{preload}$ = 530 kPa	
	FS	P_f
Prior	1.07	0.08
After monitored 1		0.28
After monitored 2		0.26
After monitored 3		0.21

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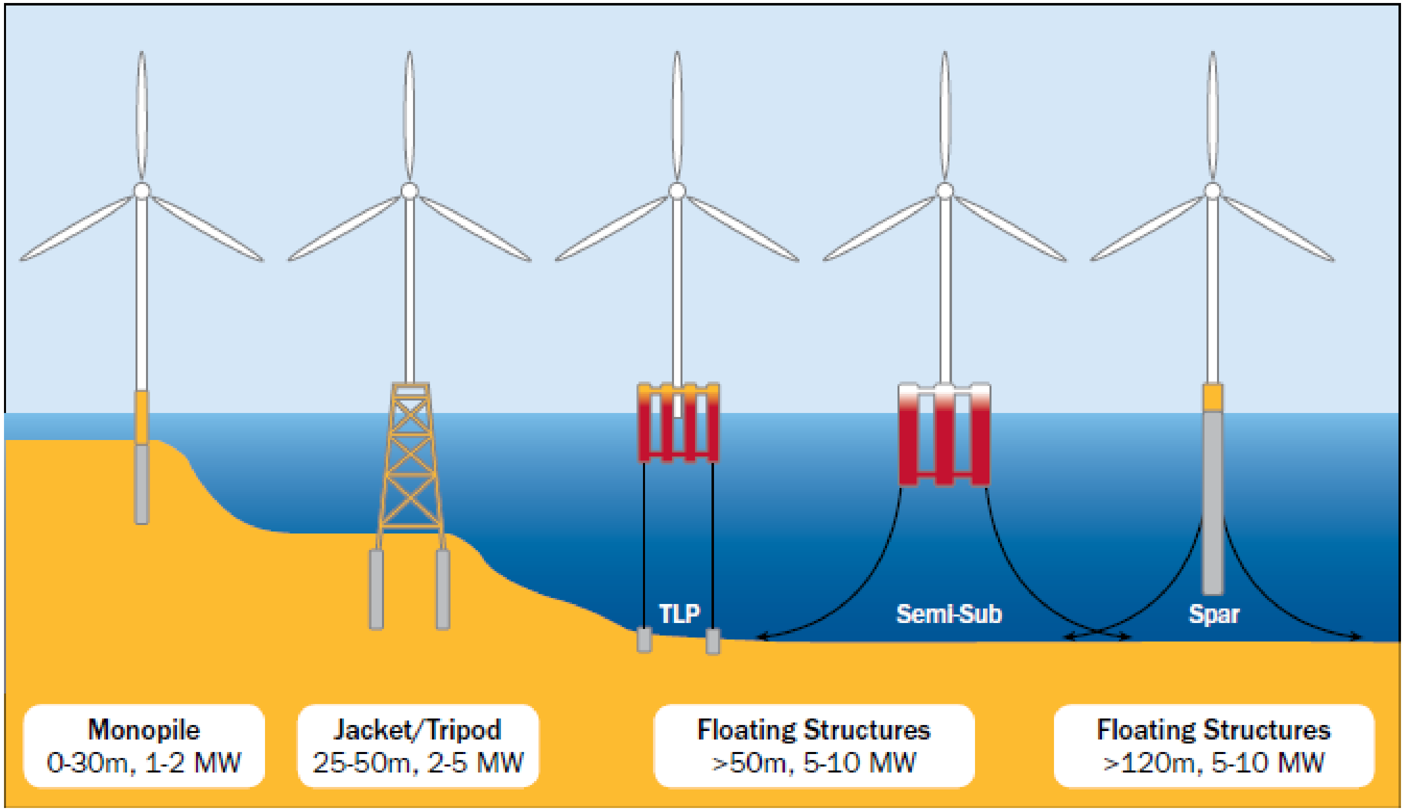
Similar transition to oil / gas
与油气工程相近的趋势



Source: Principle Power

> 50% of offshore wind resources > 100 m

Geotechnical Challenges in Offshore Renewables
海洋可再生能源的岩土力学挑战

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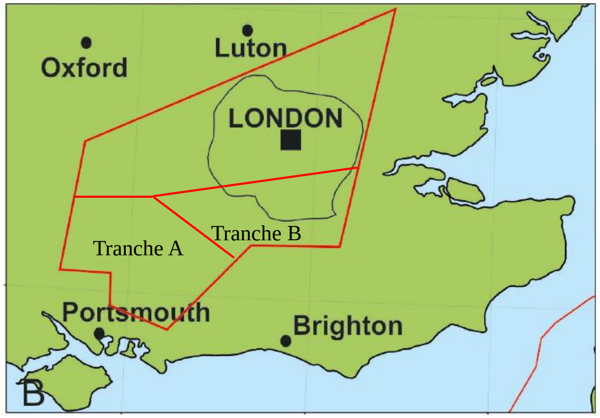
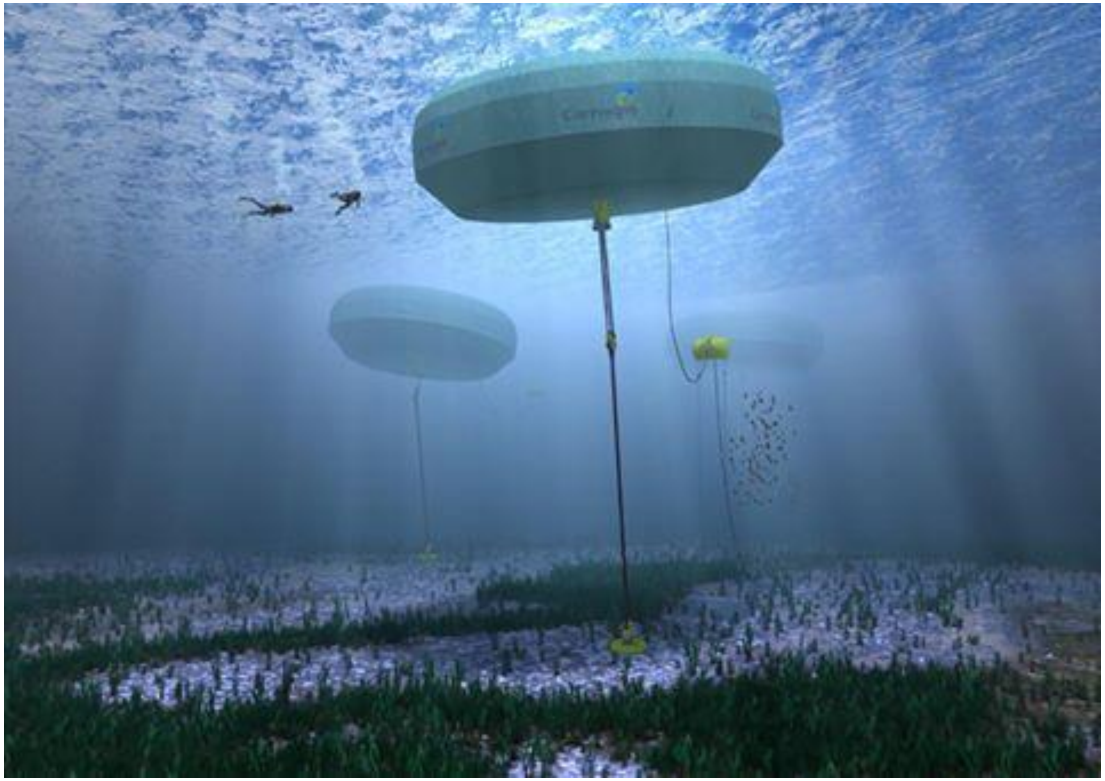
- **Characteristic environment**
  - Close to shore, high energy sites, shallower waters (prevalence of sands / rocks)



- **Example geotechnical challenges**
  - Large site to characterize
    - e.g. Dogger Bank in UK: 8600 km^2
    - Needs cheaper site-investigation
  - Very light vertical loads (with large H and M)
  - Stringent serviceability requirements
    - Accumulation of rotations over many cycles
  - Cost pressures
    - Potential for savings in foundations (~15 – 30% of costs)
  - High monitoring and serviceability costs.

- **Some example solutions**
  - Utilizing previous experience from offshore oil and gas
  - Statistical methods for site characterization with integrated geophysical / geological data
  - Testing under large numbers of cycles and **multidirectional loading (shared anchor points)**
  - Purpose built “jack-up” installation vessels
  - Integrated hydrodynamic and geotechnics
  - Secondary mooring systems

Example Solution: Floating systems
方案举例：浮动系统

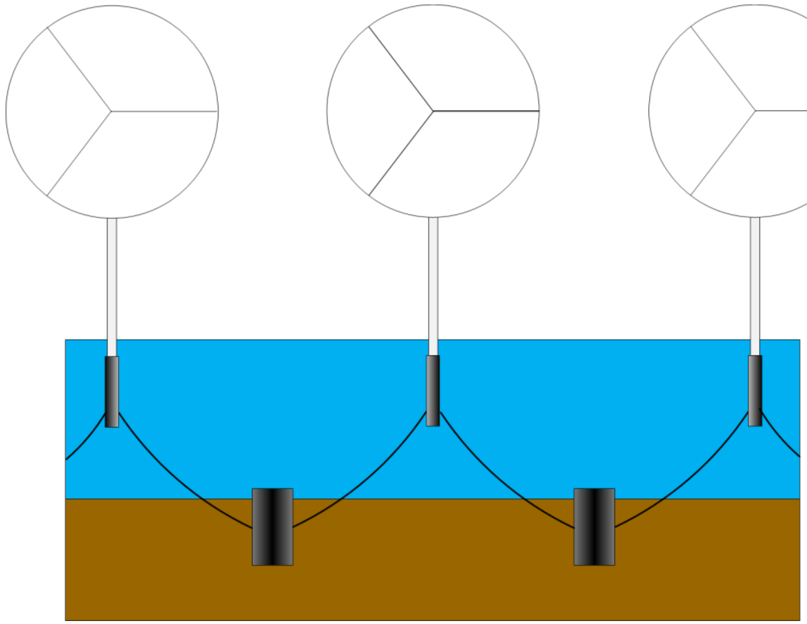


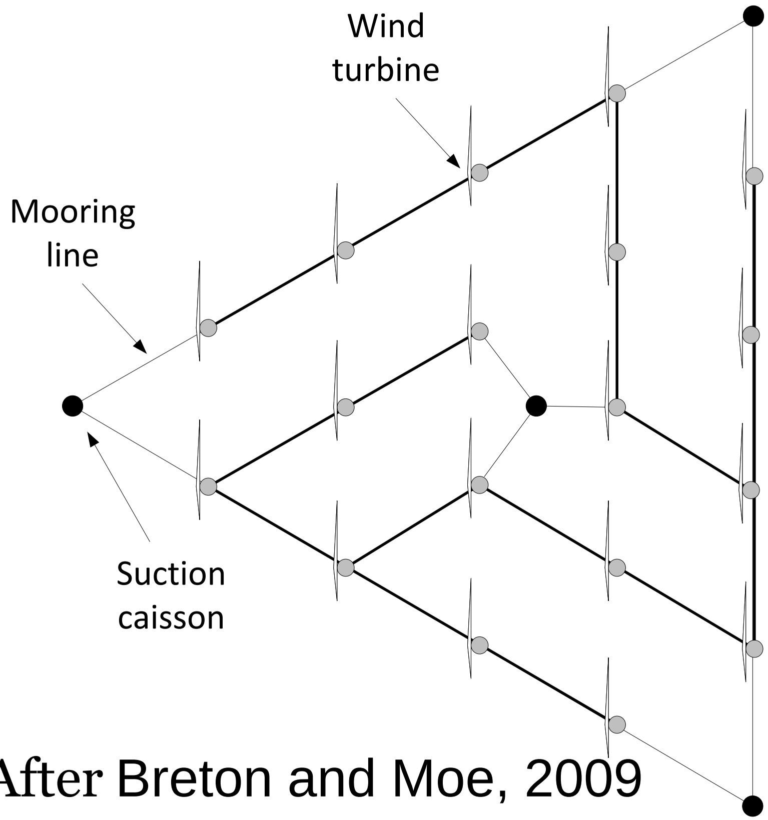
Carnegie Wave Energy (Point absorber)

Power generation:

CETO 5: 240 kW
CETO 6: 1000 kW

Shared Moorings 共享系泊

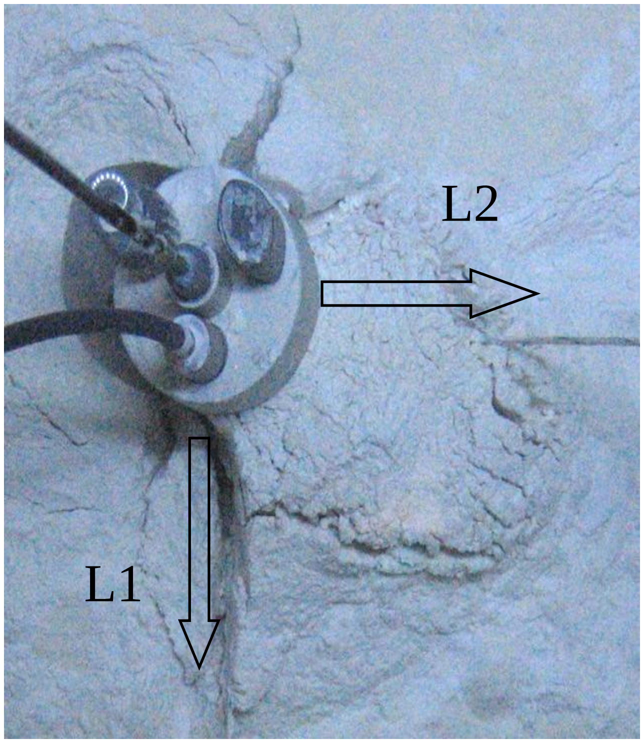


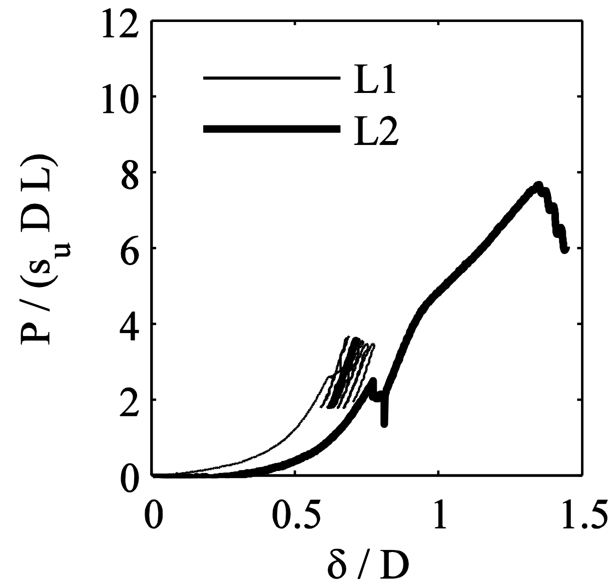


After Breton and Moe, 2009

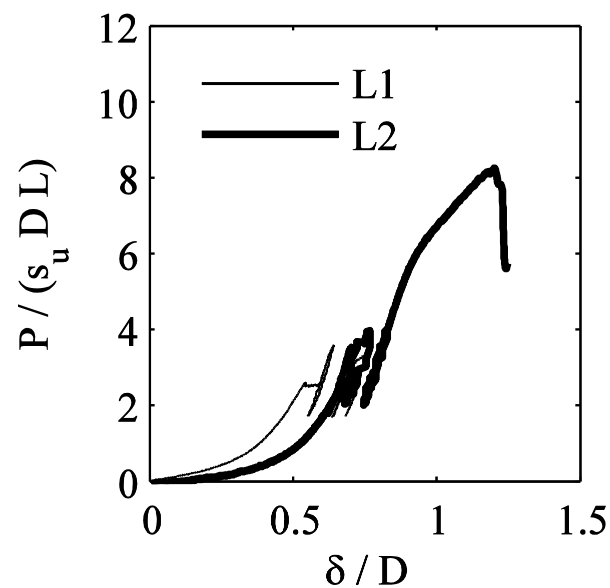
Advantages:
Save on 3- or 4-point mooring on 200 turbines
Reduce footprint
Reduce impact, e.g. on fisheries, marine habitat

Example Solution: Renewable Energy
方案举例：可再生能源





(1) Cyclic L1
(2) Sustained L2



(1) Cyclic L1
(2) Cyclic L2

Testing reported by Burns et al. 2014; ICPMG

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Conclusions　结论

In an era of increasing energy demand, geotechnical engineering is rapidly evolving to meet challenges in

- Deep water
- New development regions
- Offshore renewables

Significant technical challenges still remain in the offhsore environment, including

- Geotechnical transformations
- Cyclic loading
- Integrated wave-structure-soil modelling
- Quantitative system risk assessment

Acknowledgements 致谢

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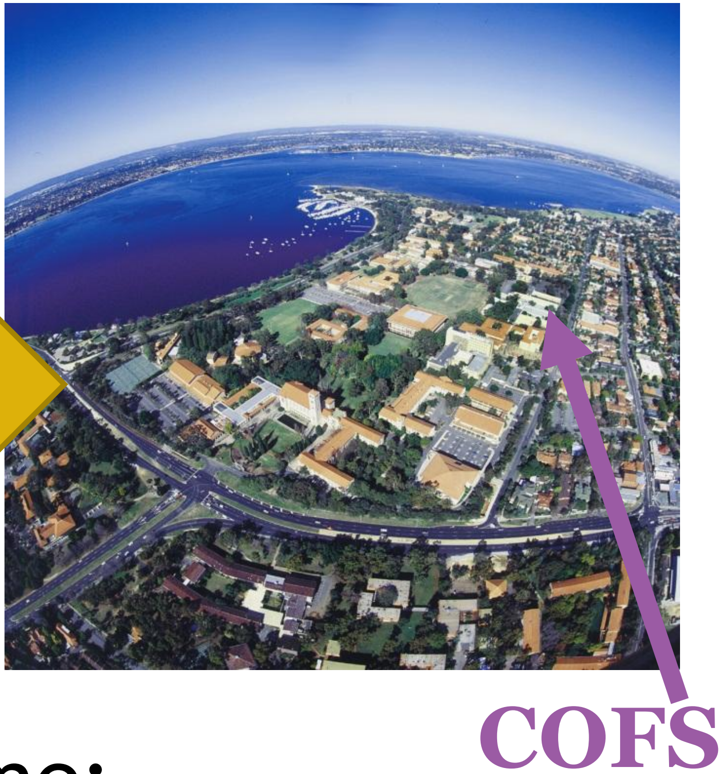

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