# DESIGN CONSIDERATIONS FOR OFFSHORE SHALLOW FOUNDATIONS

susan gourvenec 2004

# >> 1 OFFSHORE FOUNDATION DESIGN



## >> MOTIVATION FOR STUDY

- offshore foundations are subject to combined VMH loads
- conventional bearing capacity theory predicts conservative ultimate limit states under VMH loading
- industry guidelines are based on conventional theory
- results in over-conservative and inefficient foundation designs for offshore structures
- offshore foundations are VERY expensive therefore the financial consequences of the conservatism is significant

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# >> 1 OFFSHORE FOUNDATION DESIGN



## >> ENVIRONMENTAL LOADING

- offshore structures are subject to considerable lateral and overturning loads from the wind, waves and currents

Frigg Platform, North Sea

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# >> 1 OFFSHORE FOUNDATION DESIGN



## >> FOUNDATION LOADS

- offshore foundations are therefore required to carry general combined vertical, moment and horizontal loads (VMH)

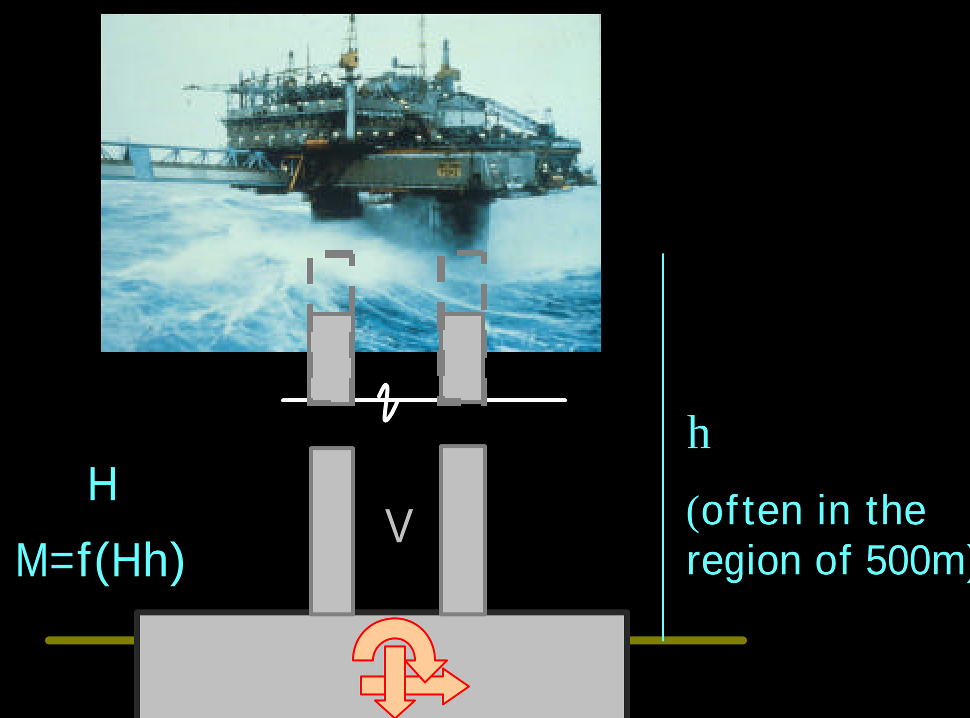
Self-weight of superstructure and foundation system (V)

+

Wind & wave & current forces acting on legs (H, M)

=

VMH foundation loads



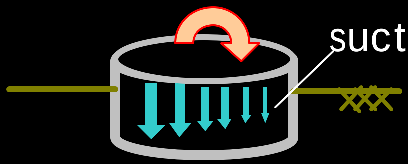
# >> 1 OFFSHORE FOUNDATION DESIGN



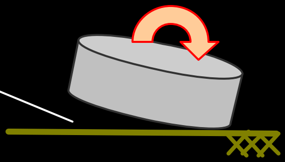
## >> SKIRTED FOOTINGS

- shallow footings with a circumferential skirt penetrating the seabed (sometimes called 'bucket foundations')

- during undrained moment loading suctions are developed within the skirt providing an uplift capacity, allowing moment loads to be withstood at low vertical loads




## >> CONVENTIONAL SURFACE FOOTING



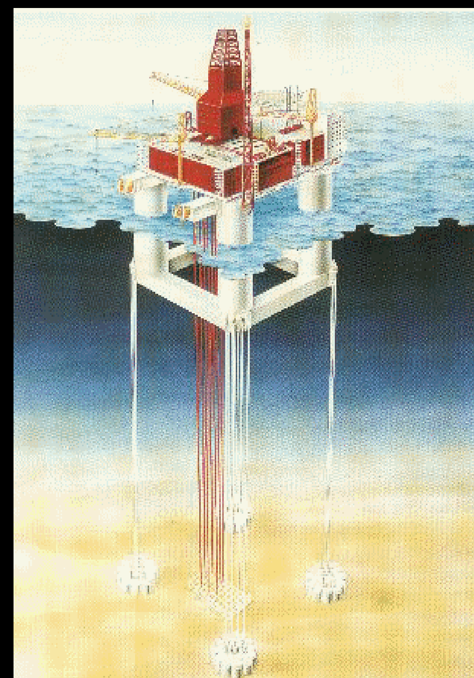
# >> 1 OFFSHORE FOUNDATION DESIGN



## >> APPLICATIONS

TrollA

gravity based structure
(up to 500m)



SnorreB

vertically tethered tension leg platform
(up to 1500m)

TrollOlje

anchored semi-submersible
(> 1500m)

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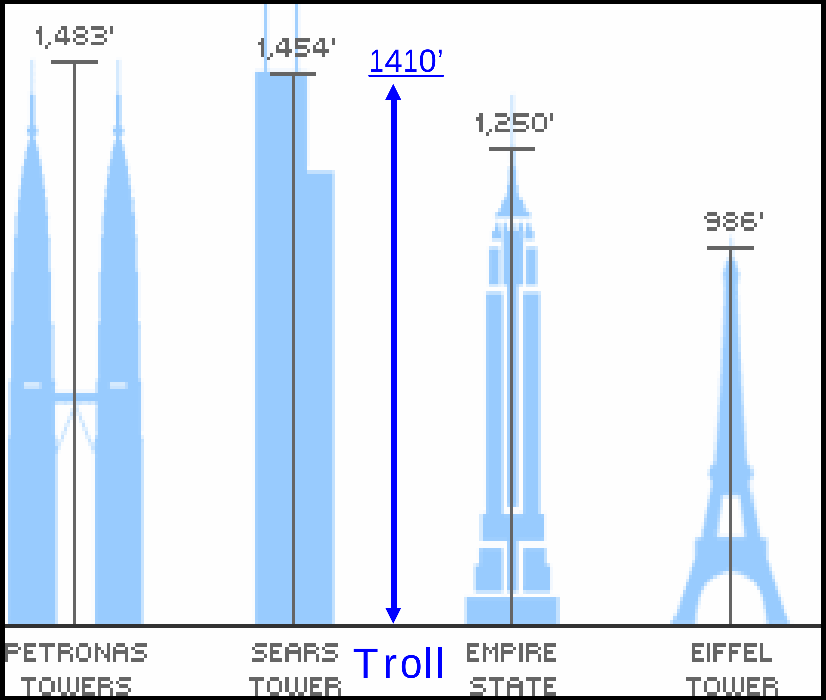
# >> 1 OFFSHORE FOUNDATION DESIGN



## >> COMPARISON WITH ONSHORE

- TrollA Platform: 470 m (1410 feet) tall

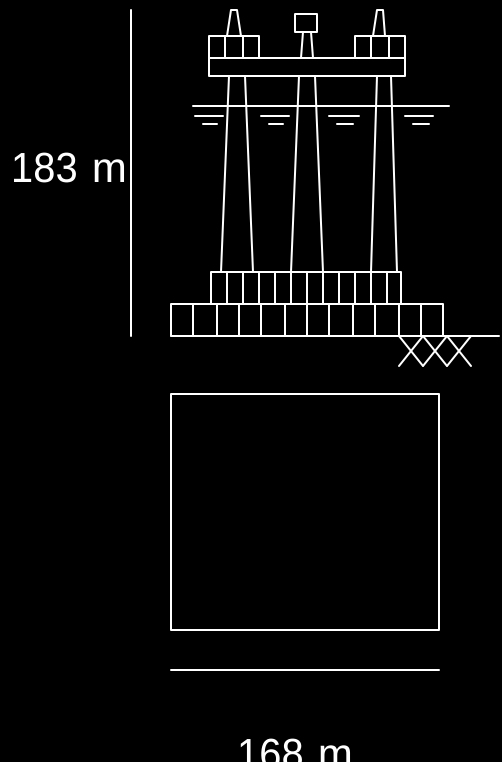
Troll A



# >> 1 OFFSHORE FOUNDATION DESIGN



## >> COMPARISON WITH ONSHORE




Taywood Seltrust

<u>maximum storm loads</u>

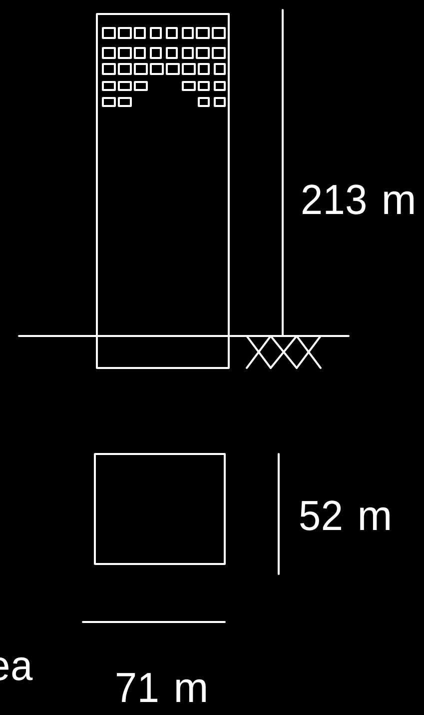
| | | |
|---|---|---|
| 2006 MN | V | 1500 MN |
| 495 MN | H | 29 MN |
| 18850 MNm | M | 3255 MNm |

35% extra V
1600% extra H
500% extra M

<u>foundation plan</u>

| | | |
|---|---|---|
| 9173 $m^2$ | A | 3692 $m^2$ |

150% bigger foundation area




One Shell Plaza
Houston

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# >> 1 OFFSHORE FOUNDATION DESIGN



## >> THE PROBLEM

- offshore design guidance is based on experience and empiricism from onshore, despite the considerable differences in the conditions
- reflected in poor predictions of ultimate limit states for load conditions relevant to offshore foundation designs

## >> AREAS FOR STUDY

- failure of shallow foundations for conditions typically encountered offshore to quantify the degree of conservatism introduced by conventional theory (as proposed in design guidelines) and to try and identify possible practical alternative approaches

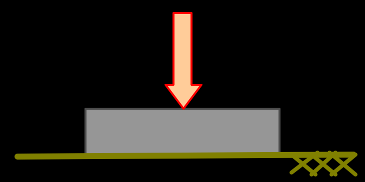
# >> 2 CONVENTIONAL BEARING CAPACITY THEORY



## >> BASIC EQUATION

- ultimate uniaxial vertical load of a strip footing resting on the surface of a homogeneous material

$$V_{ult}=ASuNc$$



'infinitely long' footing

Terzaghi (1943)

| | |
|---|---|
| $V_{ult}$ | unit vertical bearing capacity |
| A | area of the foundation |
| Su | undrained shear strength (uniform with depth) |
| Nc | vertical bearing capacity factor of a strip footing |
| | = 5.14 (Prandtl, 1921) |

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# >> 2 CONVENTIONAL BEARING CAPACITY THEORY



## >> CORRECTION FACTOR

- non-verticality of load i.e. inclination or eccentricity
- finite foundation length

$$V_{ult} = ASuNc\mathbf{Kc}$$

correction factor

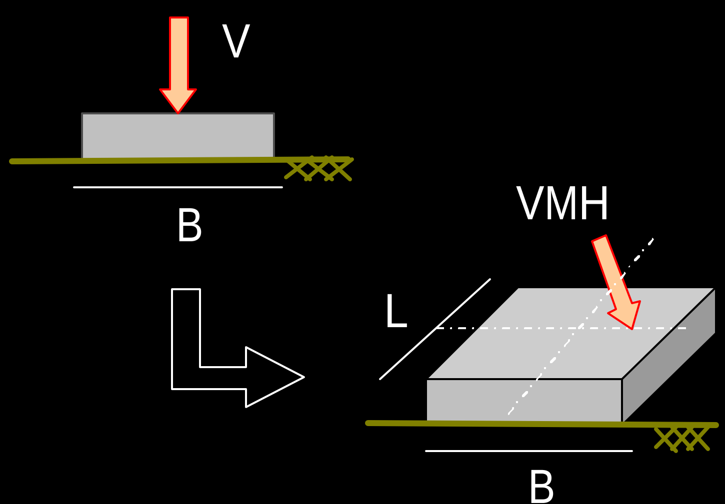
$$Kc = 1 - i_c + s_c$$

load orientation factor

$$i_c = 0.5 - 0.5\sqrt{(1 - H/A'Su)}$$

foundation shape factor

$$s_c = s_{cv}(1 - 2i_c)B'/L$$




Source: **ISO 1990 (2002)**

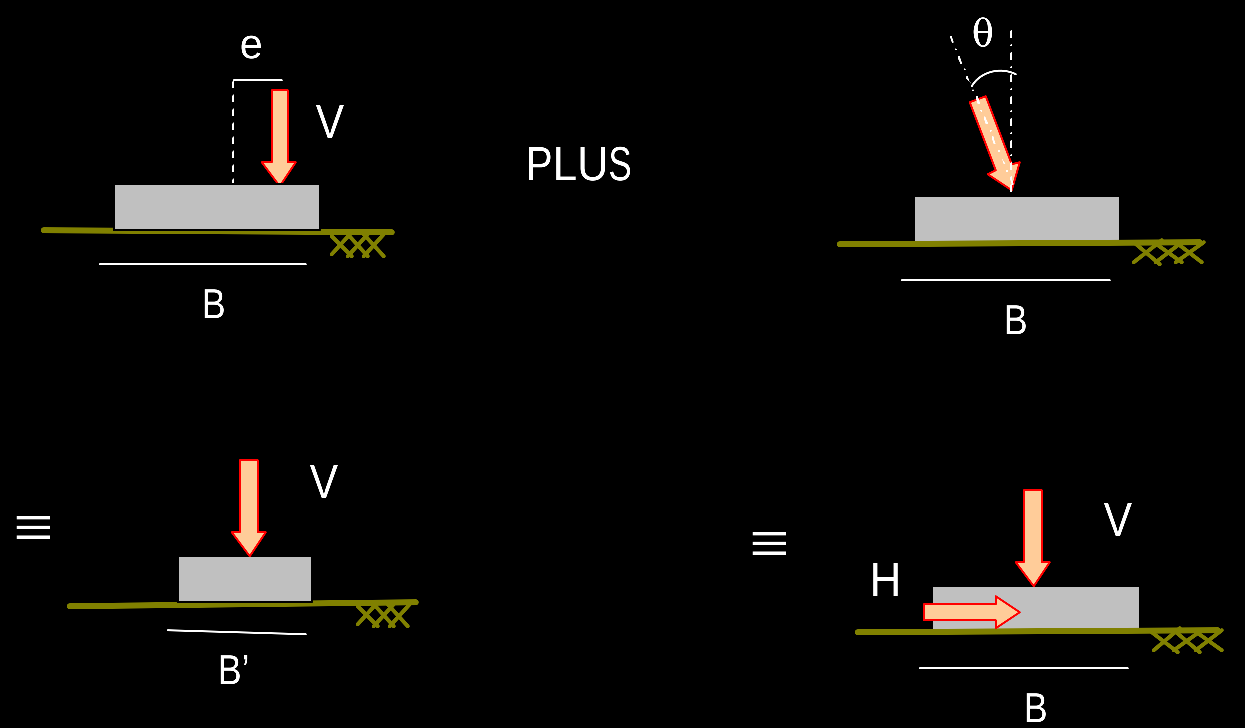
Petroleum and natural gas industries - Offshore structures Part 4 >>

# >> 2 CONVENTIONAL BEARING CAPACITY THEORY



## >> LOAD ORIENTATION CORRECTION

- based on solutions for load eccentricity and load inclination




effective width B’ = B-2e

effective area A’ = B’ L

Meyerhof (1953)

$V_{ult}/As_u = 0.5+0.5\sqrt{(1-H/ASu)}$

Green (1954)

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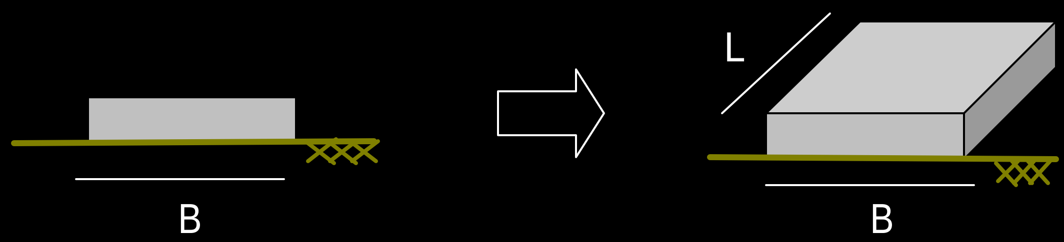
# >> 2 CONVENTIONAL BEARING CAPACITY THEORY



## >> 3D FOUNDATION GEOMETRY CORRECTION

- semi-empirical reduction factor to account for end effects



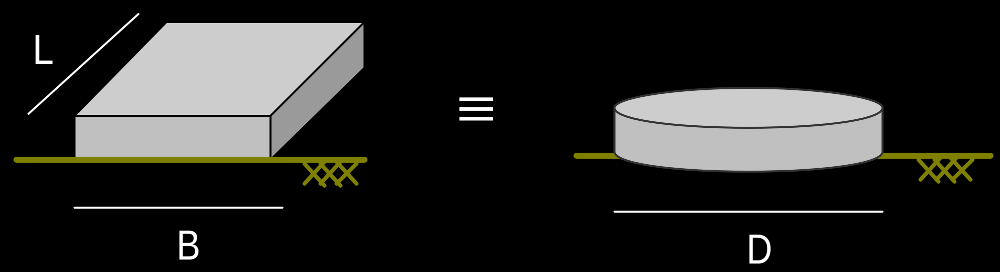

## >> CIRCULAR FOOTINGS

- assume equivalent area and areal moment of inertia

$$BL = A = \frac{\pi D^2}{4}$$

$$\frac{B^3 L}{12} = I_{xx} = \frac{\pi D^4}{64}$$

$$D \equiv 1.128B$$

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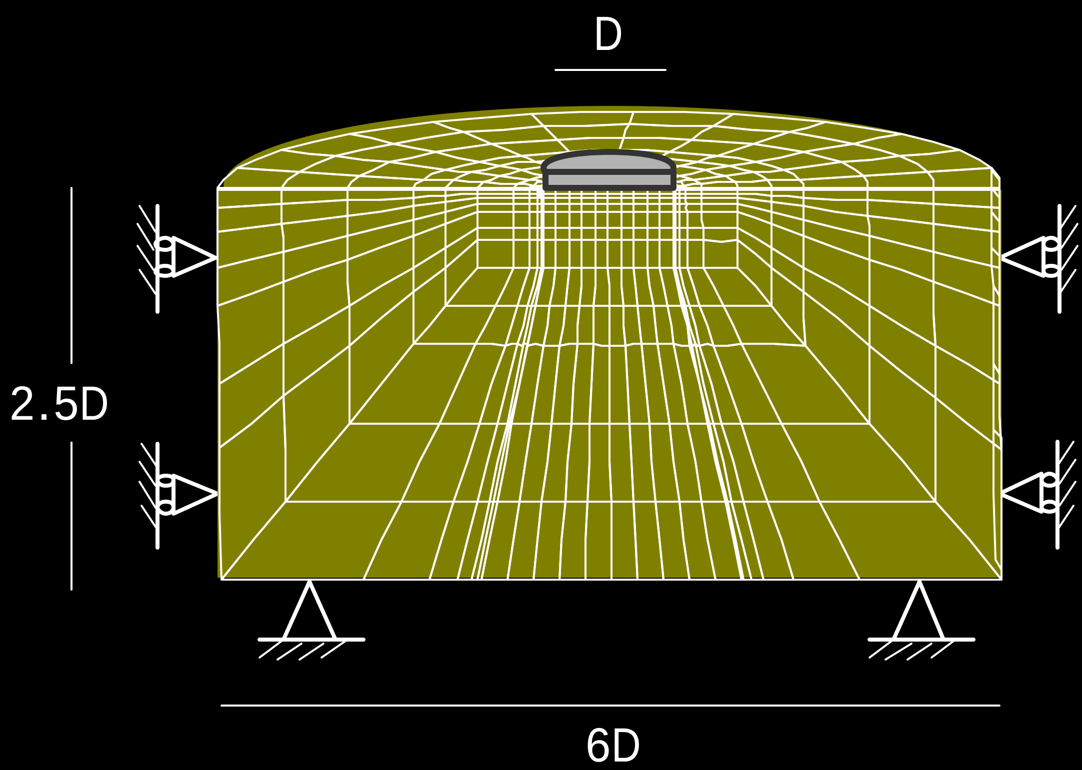
# >> 3 FINITE ELEMENT ANALYSES (FEA)



ABAQUS (HKS 2002)

## >> FINITE ELEMENT MESH




SOIL – *soft clay*
homogeneous
linear elastic
tresca plastic
Eu/Su=500, $\nu$=0.49

FOOTING –*concrete*
linear elastic
E=$10^7$Eu, $\nu$= 0.15

- bonding on footing/seabed interface models uplift capacity

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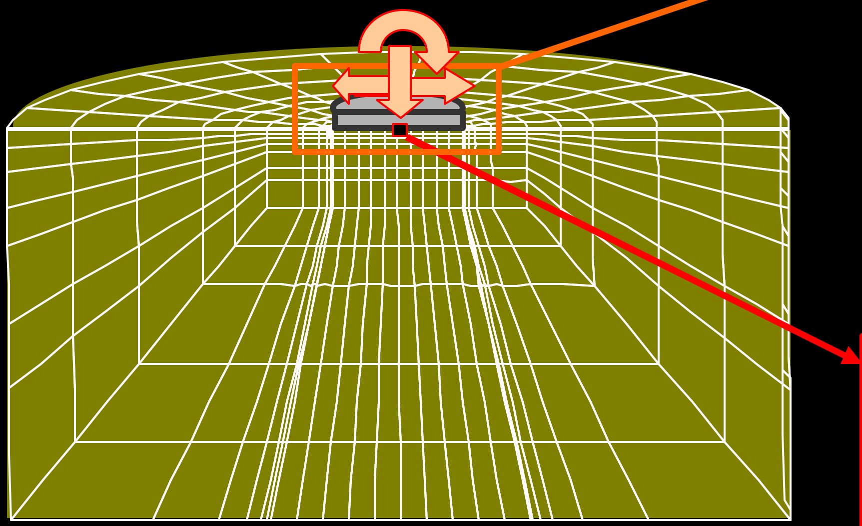
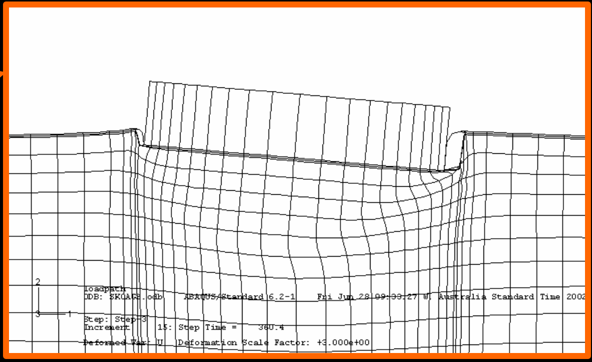
# >> 3 FINITE ELEMENT ANALYSES (FEA)

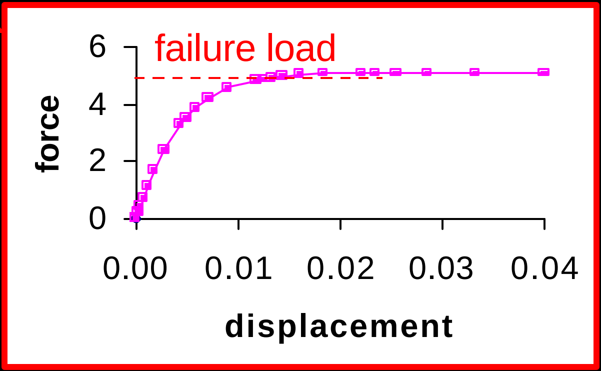


## >> LOAD PATHS

- combined VMH and (VM-H)







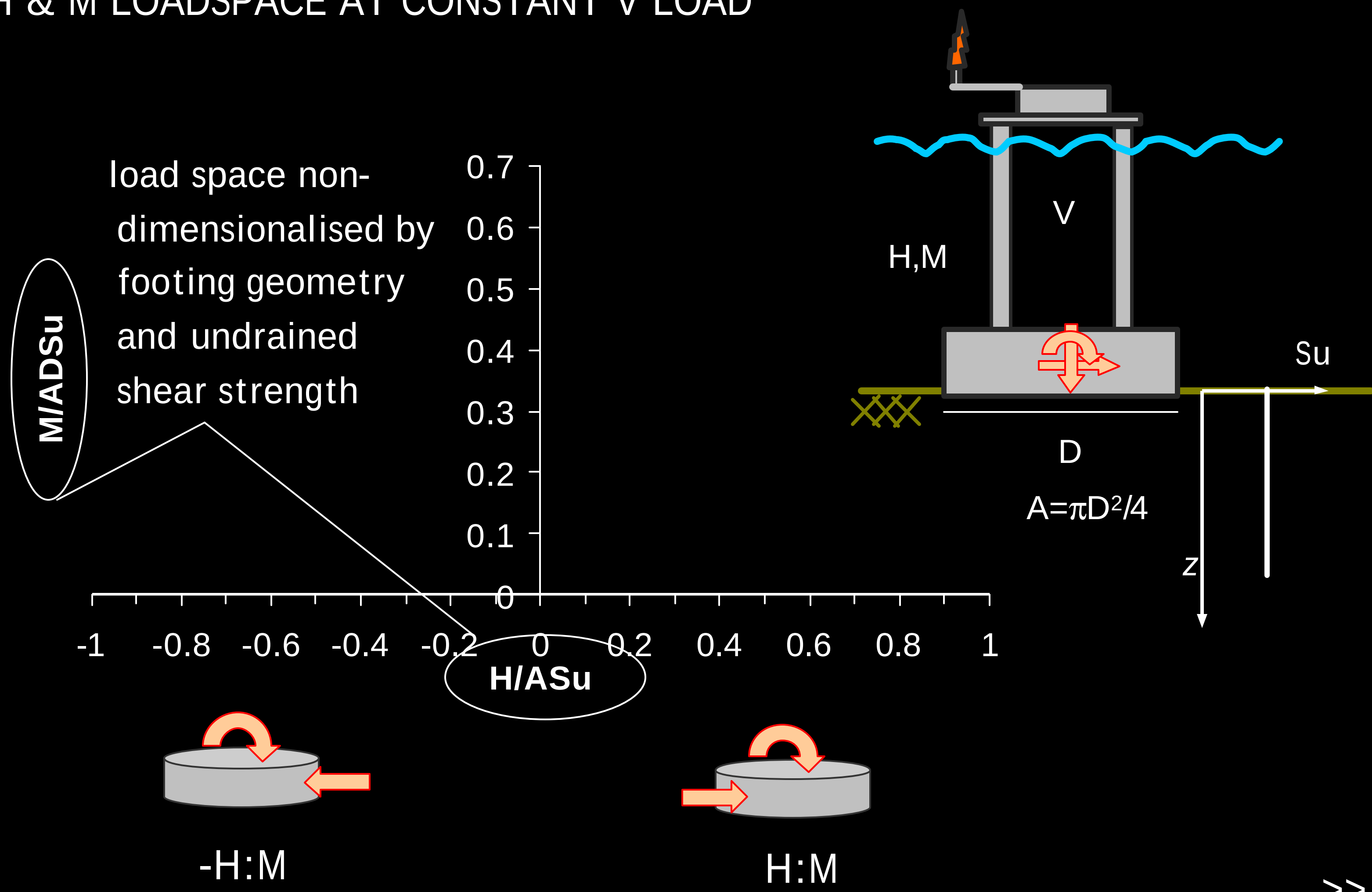

- ultimate limit failure loads from each analysis combines to form a continuous failure locus

# >> 4 FAILURE LOCI



## >> H & M LOADSPACE AT CONSTANT V LOAD

load space non-dimensionalised by footing geometry and undrained shear strength

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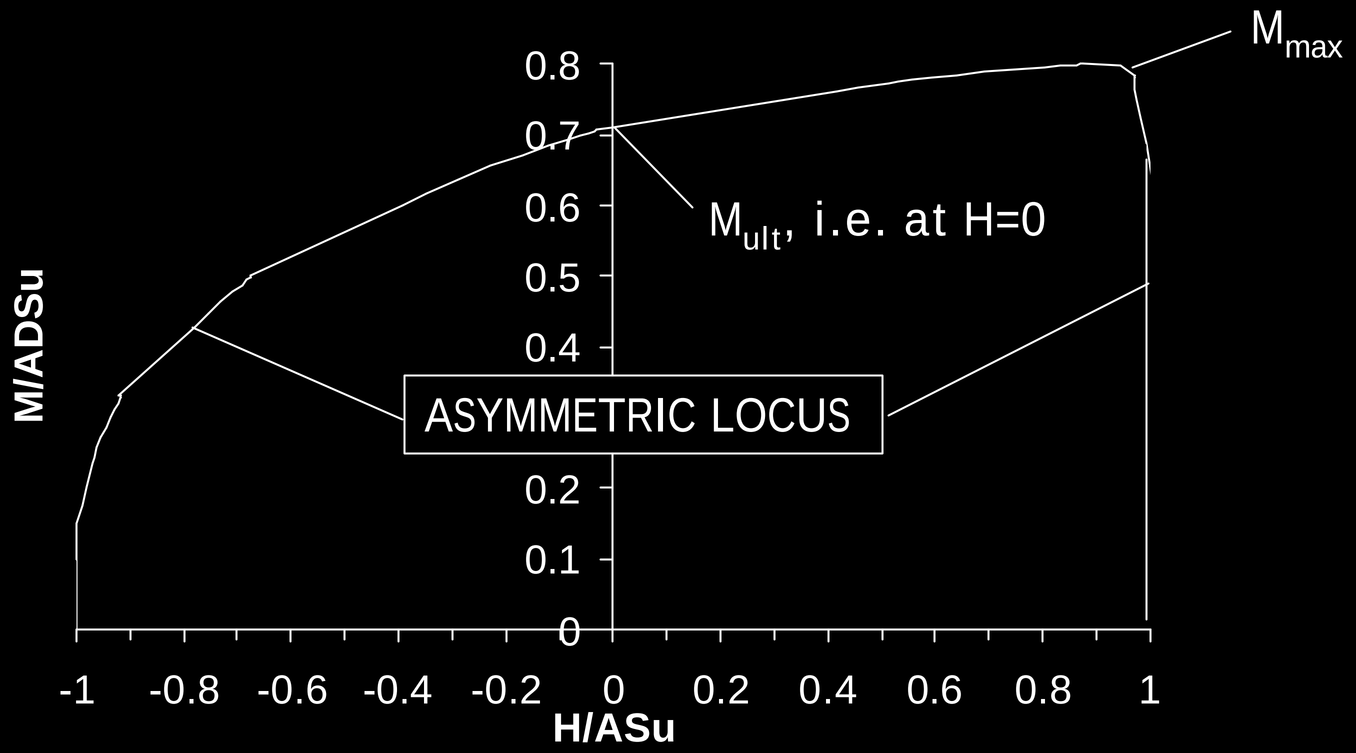
# >> 4 FAILURE LOCI - FINITE ELEMENT ANALYSES (FEA)

>> BASELINE CASE V=0 (idealised situation as implies weightless structure)



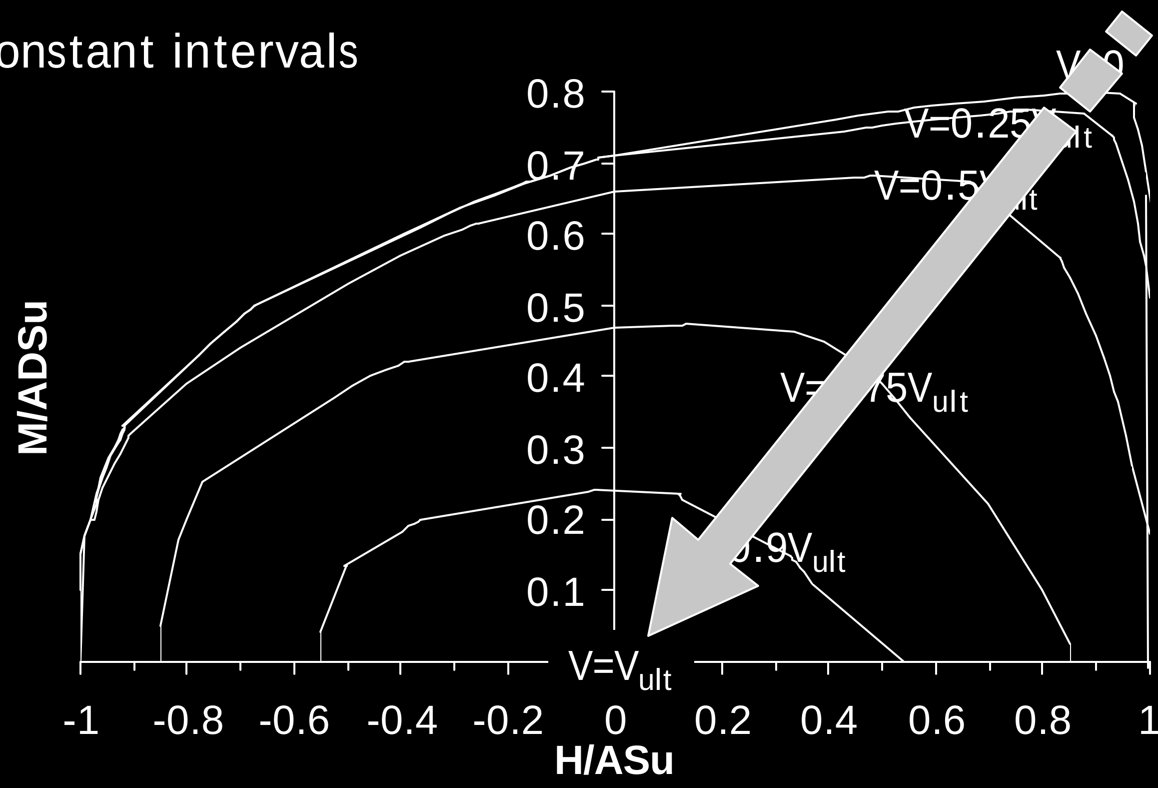

- locus is asymmetric
- **ultimate moment corresponds to zero lateral load**
- maximum moment mobilised in conjunction with lateral load >>

# >> 4 FAILURE LOCI - FINITE ELEMENT ANALYSES (FEA)



>> NON-ZERO VERTICAL LOAD

- constant intervals



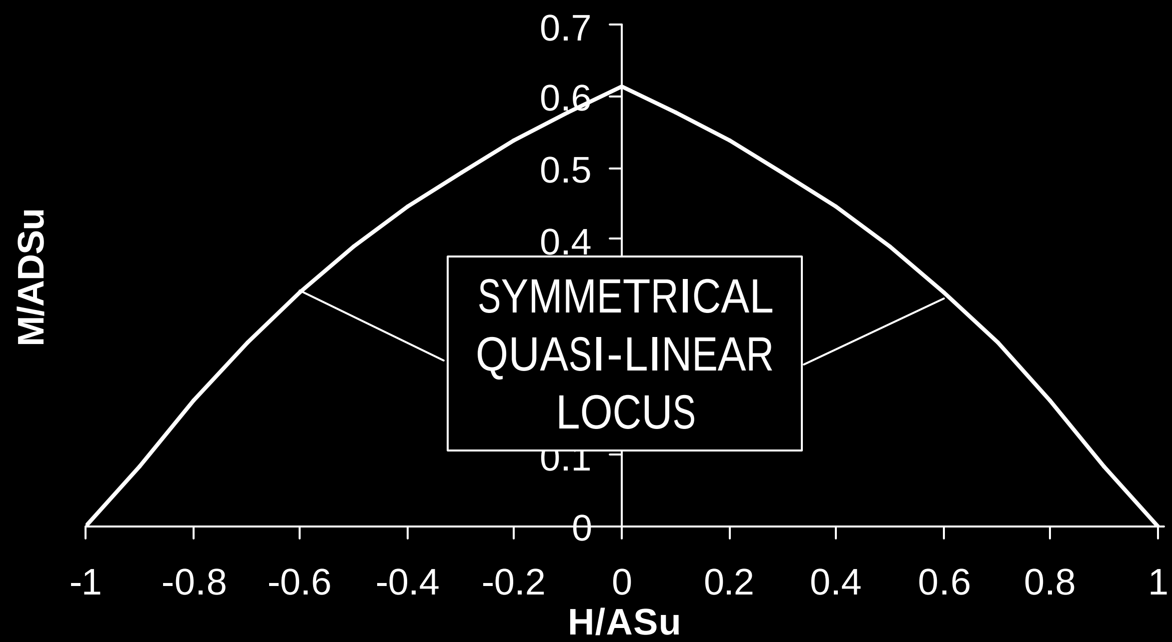

- maximum capacity at V=0
- diminishing load capacity with increasing vertical load
- shape of locus is function of V load

# >> 4 FAILURE LOCI - CONVENTIONAL CALCULATION (ISO)



>> $V=0.5V_{ult}$

- maximum capacity at $V=0.5V_{ult}$ due to 'lift-off' at lower V




- symmetry reflects neglecting the difference in modes of H & M
- quasi-linearity indicates inadequacy of representation of simultaneous load inclination and eccentricity

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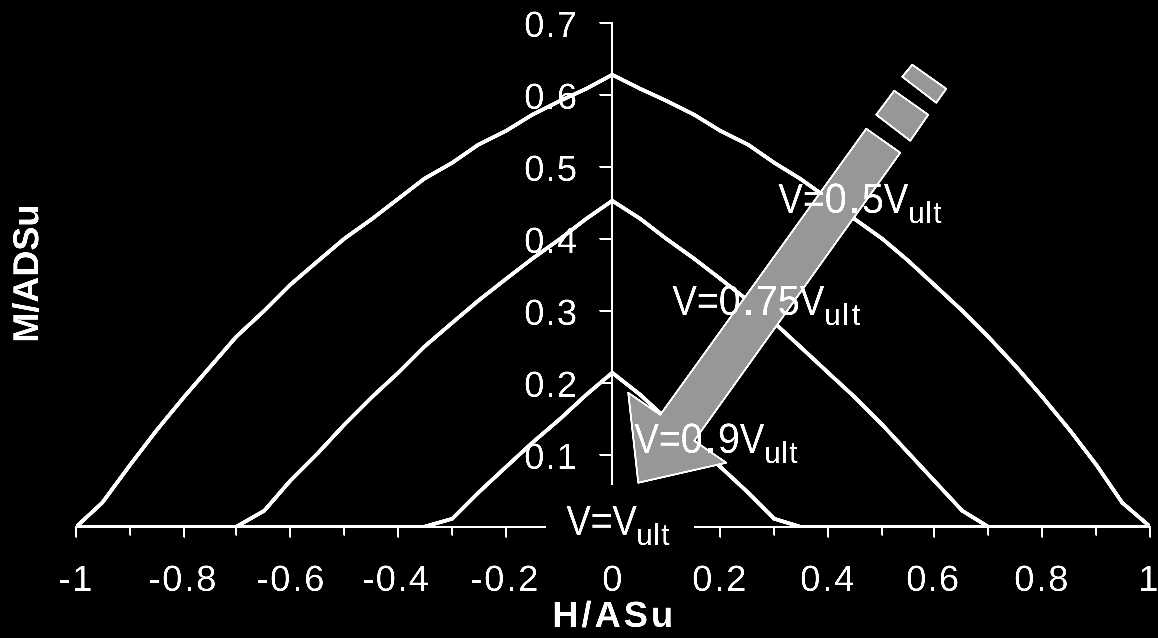
# >> 4 FAILURE LOCI- CONVENTIONAL CALCULATION (ISO)



>> CHANGES IN VERTICAL LOAD

- diminishing load capacity with increasing vertical load



# >> 4 FAILURE LOCI - CONVENTIONAL CALCULATION (ISO)



>> CHANGES IN VERTICAL LOAD

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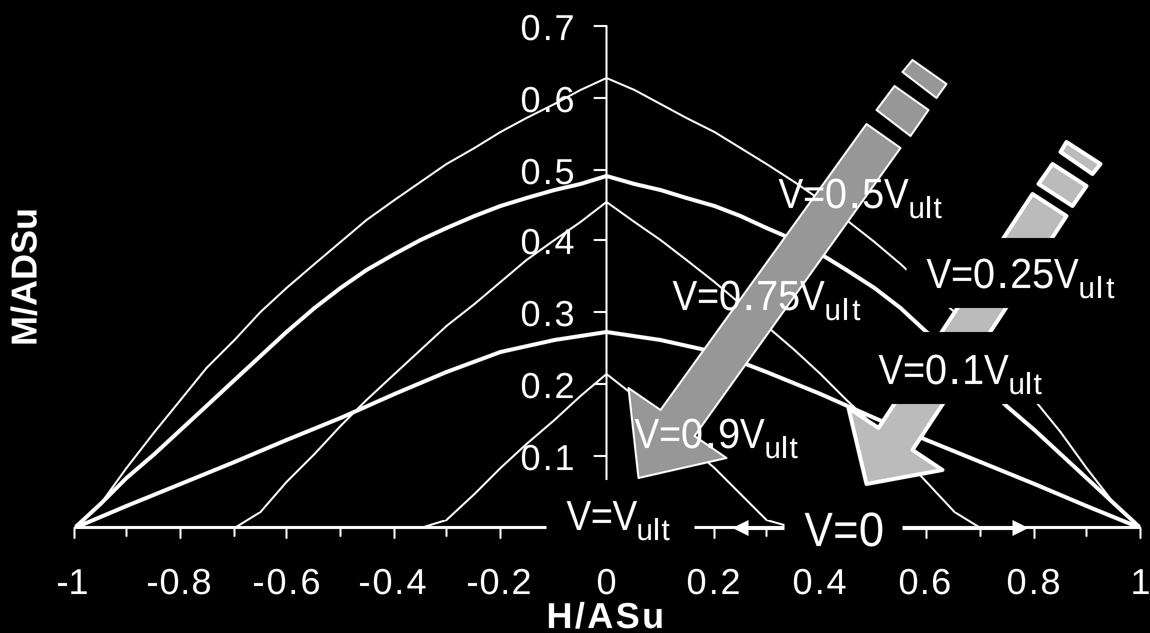


AND with DECREASING vertical load

- zero moment capacity at zero vertical load

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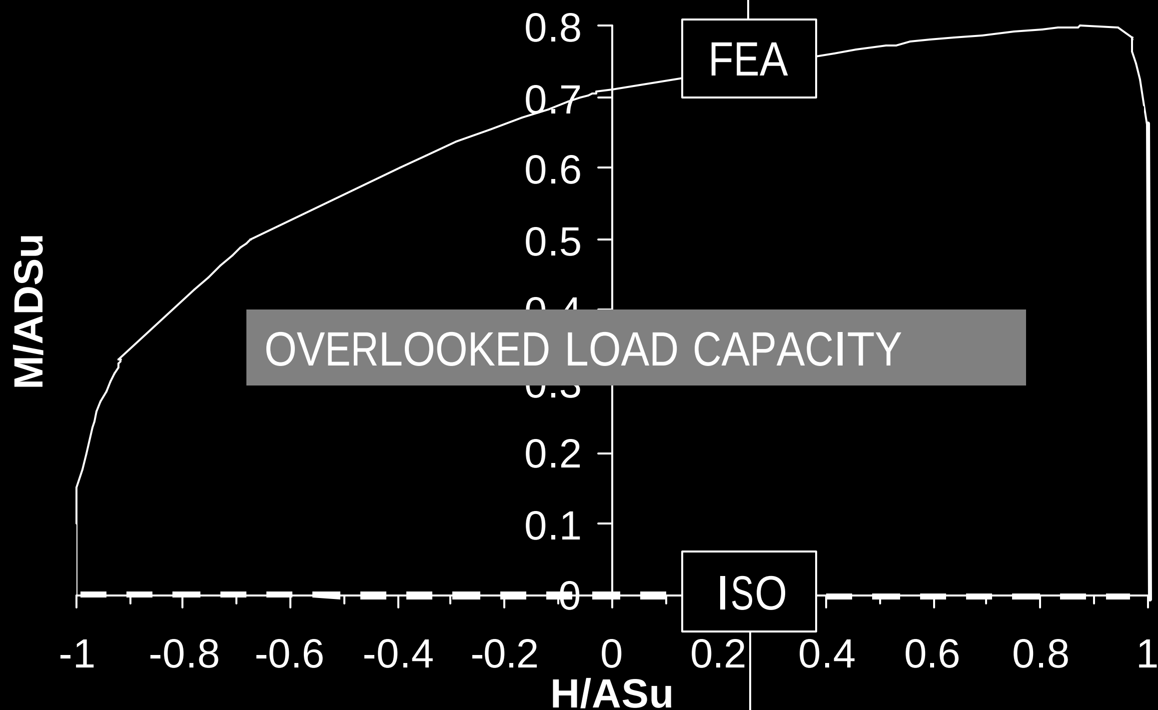
# >> 5 COMPARISON - ISO vs FEA RESULTS



>> V=0

MAXIMUM load capacity
at zero vertical load




ZERO load capacity
at zero vertical load

- oversight of tension capacity at low vertical loads

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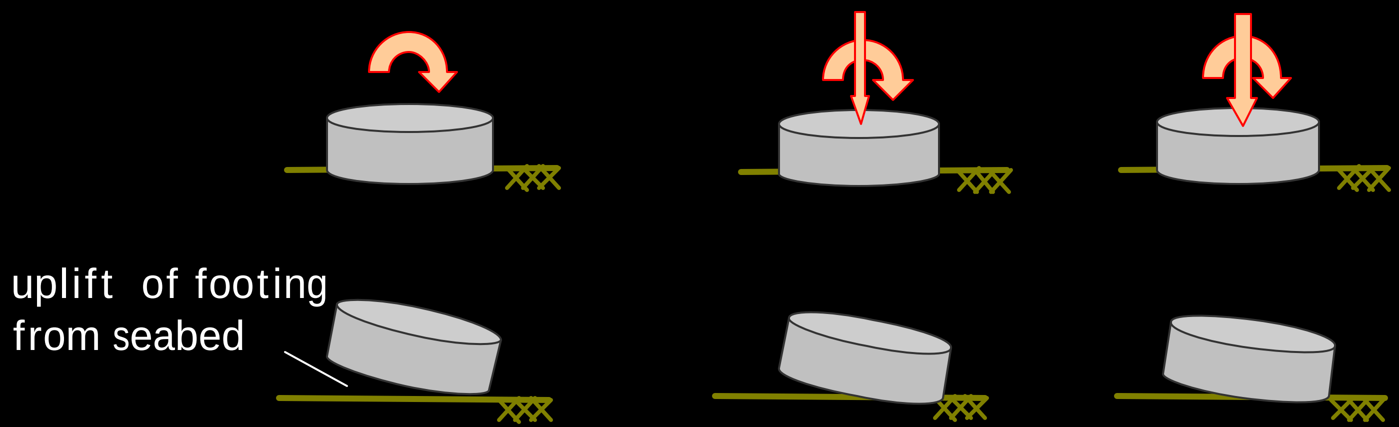
# >> 5 COMPARISON - ISO vs FEA RESULTS



>> UPLIFT

- uplift of footing from the seabed under moment loading at low vertical loads




- the reduced bearing area due to uplift causes reduced capacity
- vertical loads in excess of $0.5V_{ult}$ are sufficient to maintain foundation contact with the seabed
- ... but many offshore foundation systems would operate at working loads less than half their ultimate vertical capacity >>

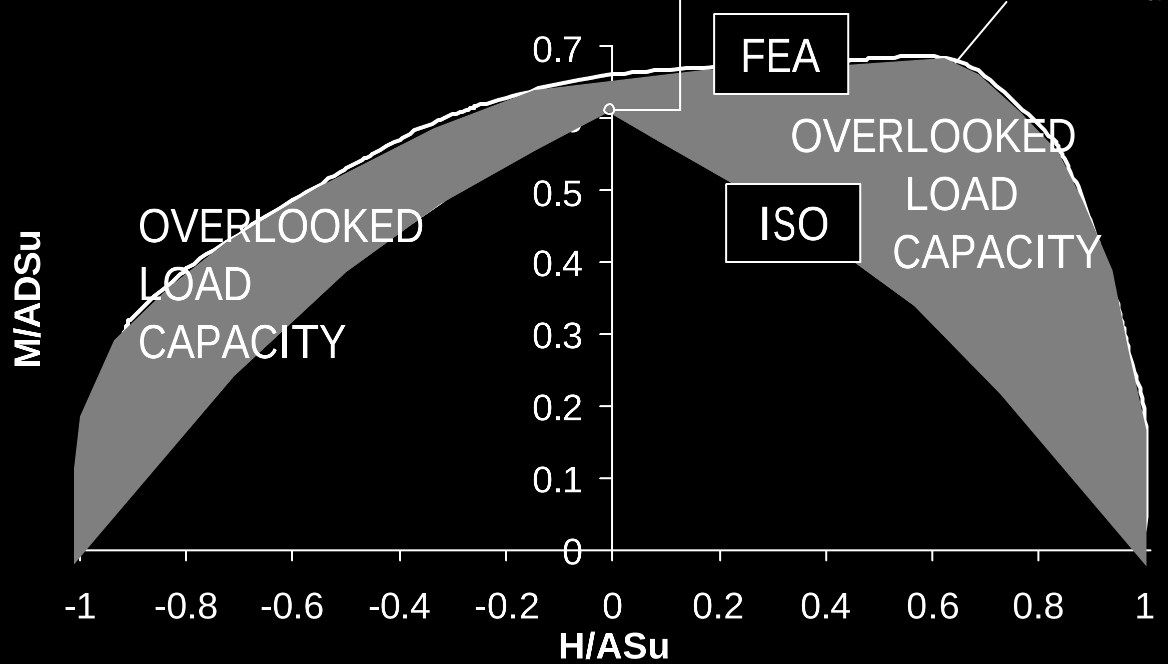
# >> 5 COMPARISON - ISO vs FEA RESULTS

>> $V=0.5V_{ult}$

- i.e. like comparison: no uplift

ISO: $M_{max}=M_{ult}$ at $H=0$

FEA: $M_{max}$ ($>M_{ult}$), $H>0$

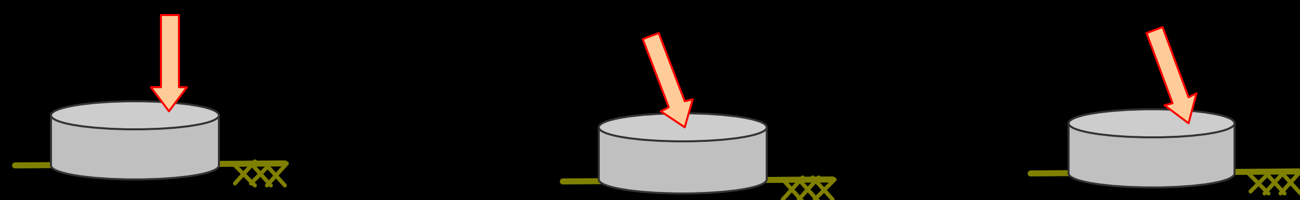



- inadequcy of superposition of VH and VM solutions (quasi-linearity)
- neglect of difference between VHM and V-HM modes (symmetry) >>

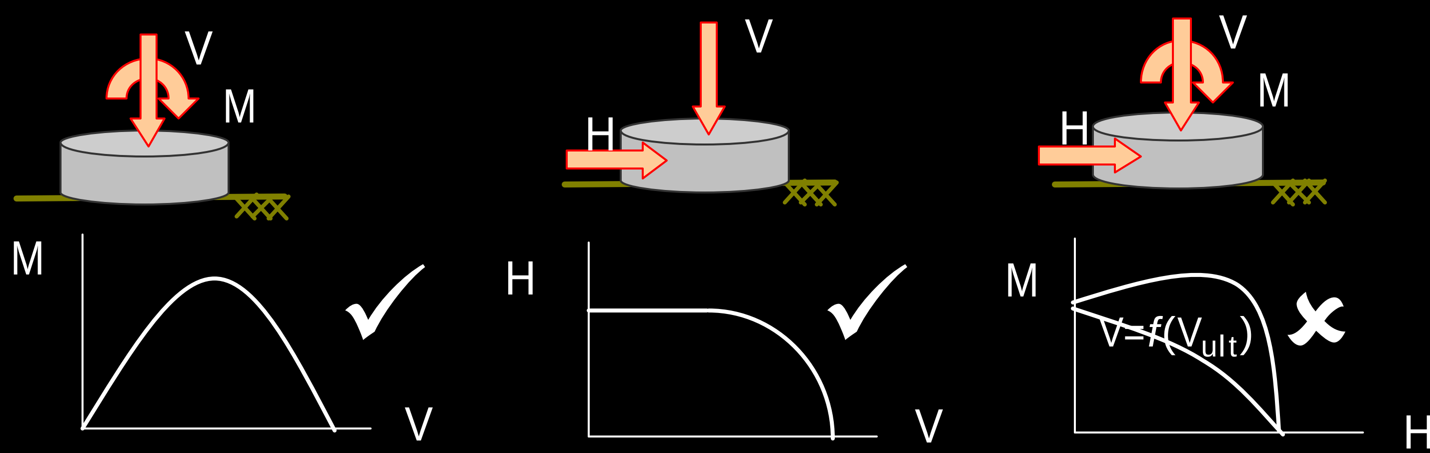
# >> 5 COMPARISON - ISO vs FEA RESULTS

>> ECCENTRIC *OR* INCLINED LOADS (VM *or* VH)

- conventional theory is based on solutions for load inclination and vertical load eccentricity and breaks down under superposition



eccentrically applied vertical load | centrally applied inclined load | eccentrically applied inclined load

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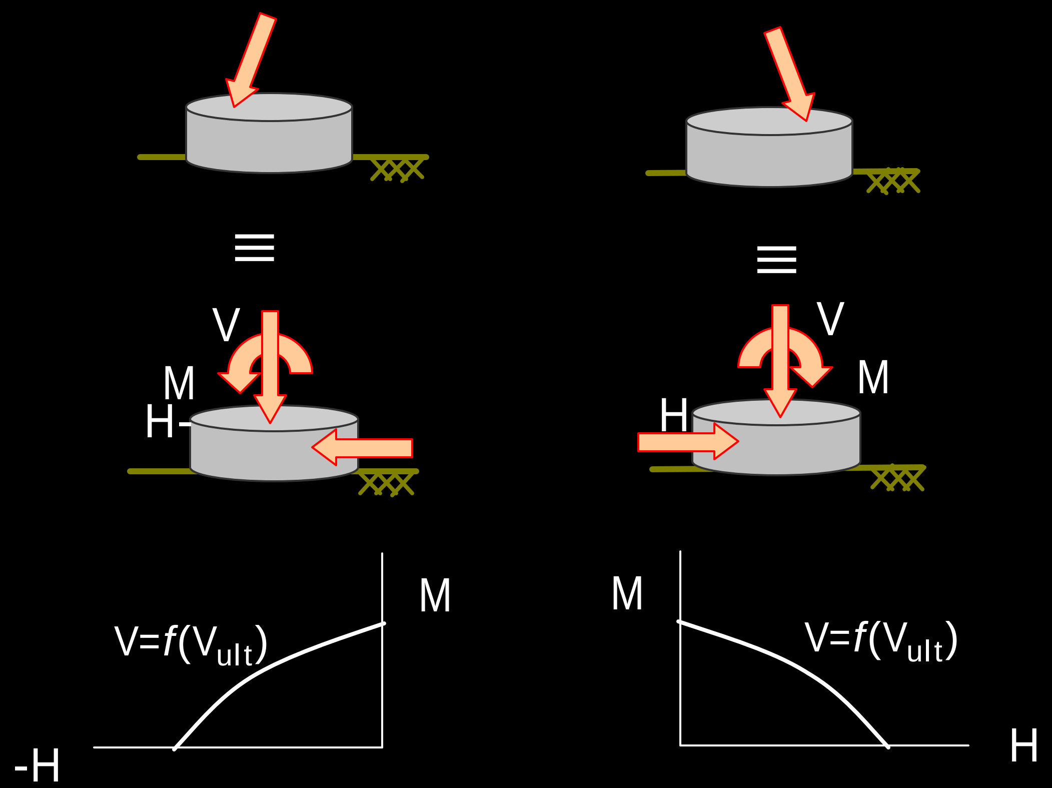
# >> 5 COMPARISON - ISO vs FEA RESULTS



>> SYMMETRY: VHM vs V-HM

- conventional method reflects locus from VHM quadrant for negative H




- VHM is NOT physically equivalent to V-HM

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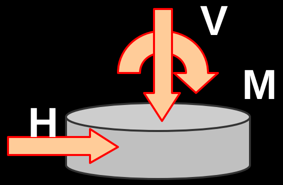
# >> 6 SUMMARY



## >> FOR THE CONDITIONS INVESTIGATED

(i.e. undrained bearing failure of a circular footing on a homogenous soil)




- conventional bearing capacity theory inadequately represents the <u>shape</u> of the failure loci and underestimates the <u>magnitude</u> of the bearing capacity of shallow foundations under general combined VMH loading

- superposition of solutions for inclined (VH) and eccentric (VM) loading failing to represent the response to <u>inclined eccentric (VMH) loading</u> in conjunction with the neglect of the differences between the <u>H & M modes of loading</u> (i.e. HM and –HM)

- conservatism is exacerbated for conditions of low vertical load as the conventional bearing capacity theory does not account for <u>tensile capacity</u> achieved with foundation skirts