Undrained bearing capacity of skirted mudmats on inclined seabeds

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Subsea 7

1. Introduction

- Shallow skirted foundations known as mudmats are commonly used to support subsea structures such as pipeline end terminations.
- Mudmats sometimes need to be placed on sloping seabeds with inclinations of 5° or more.
- Mudmat design is generally based on classical bearing capacity theory stemming from the Brinch Hansen method. This approach can be conservative for mudmats under inclined or eccentric loading; it also assumes that the seabed is level.
- Here finite element limit analysis (FELA) is used to investigate how the undrained bearing capacity of a skirted mudmat is affected by seabed inclination.
- The main study focuses on combined vertical and horizontal loading of footings on inclined ground.
- The FELA methodology is also applied to a case study based on a recent mudmat design.

2. Methodology

Failure envelopes in terms of normalised loads were generated using **OxLim**, a **FELA** program developed at the University of Oxford[1,2,3].

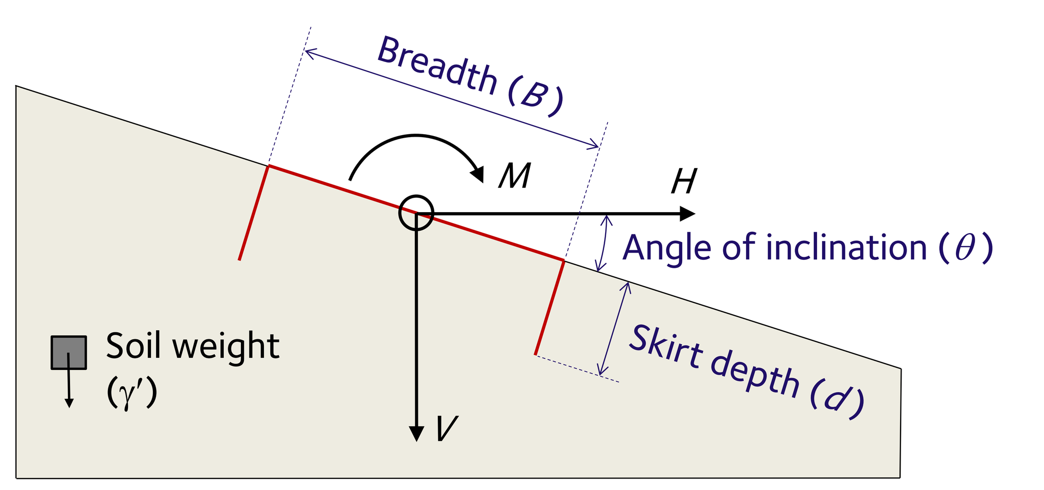
Numerous loading combinations were analysed, with each load-controlled 'probe' producing a single point on the relevant failure envelope.

The geometry was idealised as 2D (**plane strain**).

The soil was modelled as a **purely cohesive**, **rigid–plastic** material with **undrained** shear strength s_u.

The **shear strength** along the **footing/soil interface** was modelled as a **roughness factor** (α) times s_u.

The **tensile capacity** of the footing/soil interface was modelled either as **infinite** ($T = \infty$) or by imposing a **tension cutoff** ($T = 0$).



Notation and sign convention

OxLim

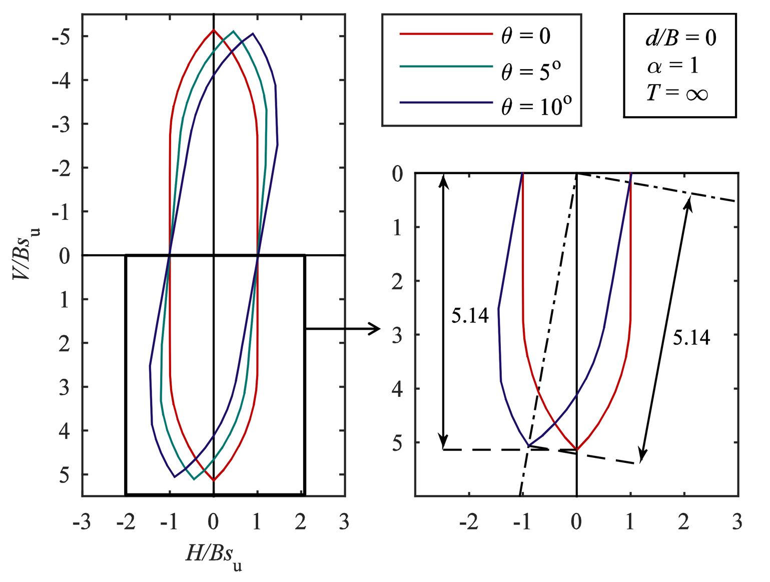
Lower bound (LB) and **upper bound** (UB) plasticity solutions are obtained by solving two separate large-scale numerical optimization problems[1,2].

Automated adaptive remeshing[3] based on the spatial variation of shear strain ensures fast convergence of the LB and UB solutions. It also facilitates **visual inspection of the failure mechanism**.

For undrained problems in plane strain, the **collapse load** can easily be **bracketed to within ±1%**, giving a solution that is essentially 'exact' (in the framework of classical rigid–plastic limit analysis).

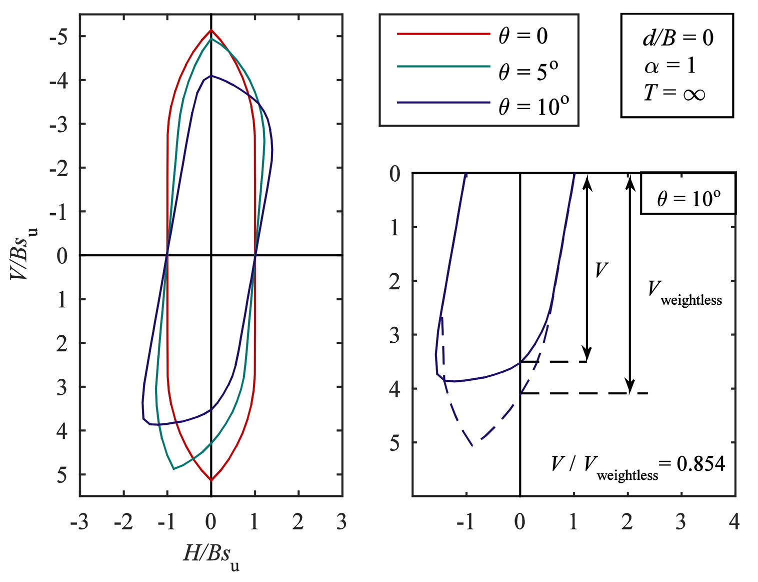
3. Results

Combined (V, H) loading on inclined **weightless soil** can be analysed by considering the same footing on flat ground, with the loads applied in a **suitably rotated axis system**.



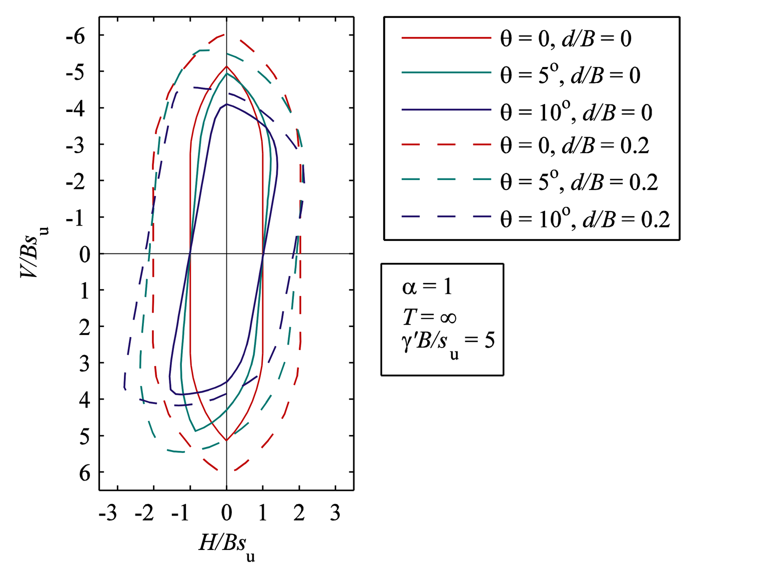
Footing on weightless soil

On inclined soil with **self-weight**, the body force γ' acts vertically (not normal to the slope). This **modifies the rotated failure envelope** when compared with the weightless case.



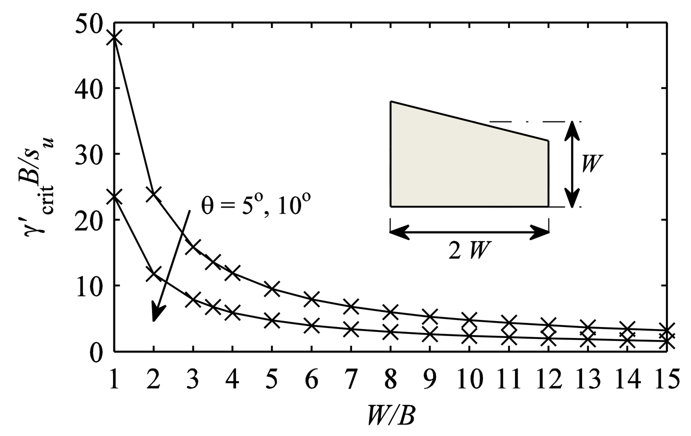
Footing on soil with weight ($\gamma' B / s_u = 5$)

When **skirts** are introduced, the **increase in horizontal capacity** is greater when pushing the footing into the slope than when pulling it away from the slope.



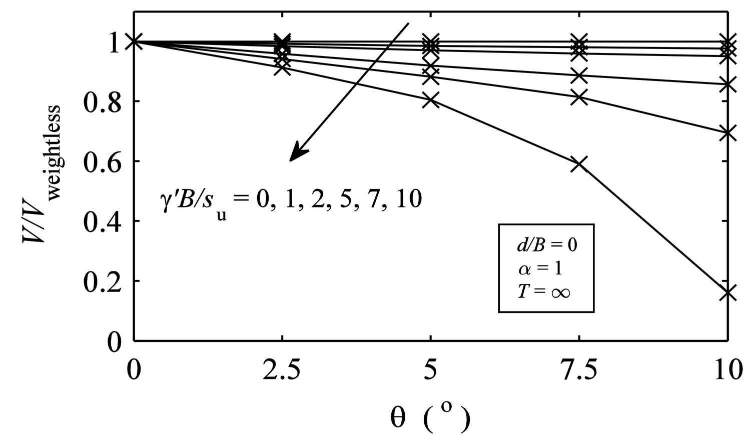
Effect of perimeter skirts

When **soil weight** is introduced, the extent of the FELA model is limited by **global undrained slope failure**.



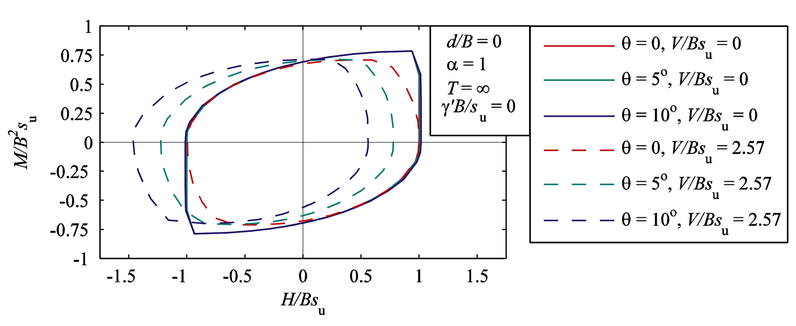
Limiting soil weight as a function of analysis domain size

Steeper inclinations and larger values of the factor $\gamma' B / s_u$ cause **greater reductions** in vertical capacity.



Reduction in capacity under pure vertical loading

The (H, M) failure envelope is only marginally affected by ground inclination. With a vertical dead load applied, the **horizontal capacity away from the slope is reduced**.



(H, M) failure envelopes for two levels of vertical loading

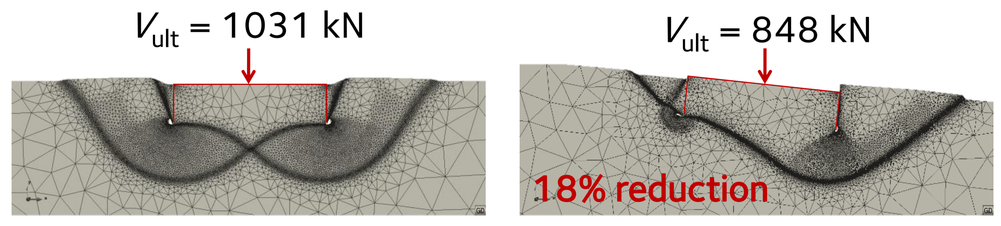
4. Case study

Site-specific analyses for a skirted mudmat on a sloping seabed confirm that the **vertical capacity is significantly reduced** by a slight incline.

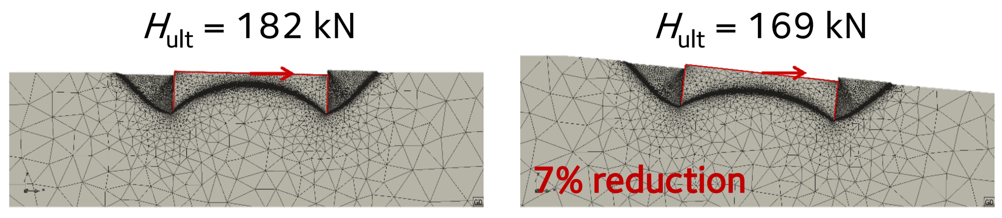
Case study input parameters	
Breadth of footing	5 m
Length of footing (out of plane)	10 m
Skirt embedment depth	1.3 m
Skirt thickness	0.025 m
Submerged unit weight	3 kN/m³
Mudline strength	0.77 kPa
Vertical strength gradient	1.05 kPa/m
Seabed inclination	0 & 5°

Failure mechanisms are easily identified by inspecting the adaptively refined OxLim meshes.

V_{ult} = 1031 kN $\quad$ V_{ult} = 848 kN

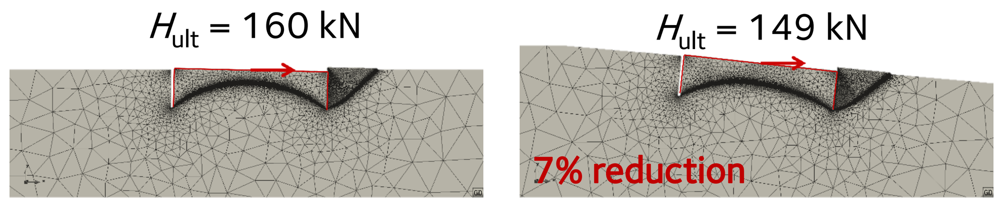


H_{ult} = 182 kN $\quad$ H_{ult} = 169 kN



Full interface tension capacity ($T = \infty$)

H_{ult} = 160 kN $\quad$ H_{ult} = 149 kN



Zero interface tension capacity ($T = 0$)

5. Conclusions

- If soil self-weight is neglected, a footing on sloping ground can be analysed as an equivalent footing on flat ground, with the applied loads suitably rotated.
- When soil self-weight is included, direct numerical analysis is required. The vertical bearing capacity can be significantly less than that on flat ground.
- The addition of perimeter skirts can offset this reduction, while also providing much improved horizontal capacity.
- Analysis of a case study based on a recent skirted mudmat design showed that a seabed inclination of just 5° led to reductions of 18% in vertical capacity and 7% in horizontal capacity.

References

[1] Makrodimopoulos, A. & Martin, C.M. 2006. Lower bound limit analysis of cohesive-frictional materials using second-order cone programming. *Int. J. Numer. Meth. Eng.* 66(4): 604-34.

[2] Makrodimopoulos, A. & Martin, C.M. 2007. Upper bound limit analysis using simplex strain elements and second-order cone programming. *Int. J. Numer. Anal. Meth. Geomech.* 31(6): 835-65.

[3] Martin, C.M. 2011. The use of adaptive finite-element limit analysis to reveal slip-line fields. *Géotechnique Letters* 1:23-29.

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