Case study on advanced 3D finite element limit analysis of counter-acts installed at Ormen Lange

C L Olsen\textsuperscript{1,*} and K Krabbenhøft\textsuperscript{2}

\textsuperscript{1}Subsea 7 Norway AS, Norway
\textsuperscript{2}University of Liverpool, United Kingdom

*christian.lindeolsen@subsea7.com

Abstract. The design of counter-acts for the Ormen Lange Northern Field Development has previously been considered in other publications. Counter-acts were used to ensure pipeline stability during pipe-lay along route curves. The counter-acts were large diameter steel cylinders installed with self-weight penetration. The in-place design was completed with use of advanced Finite Element Analysis (FEA) program Abaqus and validated in parallel by the finite difference (FD) program, FLAC. This paper will present a comparison of the previous work to advanced 3D Finite Element Limit Analysis (FELA) with use of the software OPTUM G3. 3D FELA is newly developed for geotechnical design. The paper will show the advantage of the FELA which is based on the principles of limit analysis. The counter-act design is particularly complex and given the cylindrical shape with no internal base plate. This will challenge the element types in the FELA model. Further, the soil conditions are amongst the softest clay encountered in Norway further increasing the complexity of the design.

1. Introduction
During the Ormen Lange Northern Field Development, 36 counter-acts were installed to ensure the pipelines would not slide during pipelay. The counter-acts were cylinders installed with self-weight penetration into the extremely soft clay. The design of the counter-acts is published in [1].

The ultimate capacity of an open cylinder installed in very soft clay is a complex geotechnical numerical problem. The complexity increases as the interfaces are modelled with zero strength and tension cut off. The problem was original solved using advanced FEA and FD software.

In this paper, the counter-act design is completed in a newly developed FELA software, OPTUM G3. The problem is solved with use of a recent developed element type, the mixed element. The mixed element is based on the requirements of the upper and lower bound theorems and is found to be very accurate.

2. Case study
The case study is for the capacity design of counter-acts used for pipeline installation analyses performed for the Ormen Lange North project. The counter-acts are used to ensure the pipeline does not slide on the seabed during installation, see Figure 1.
At the Ormen Lange field, the seabed conditions are challenging since the field is located in the Storegga slide, see Ref. [2]. The seabed topography is undulating with slopes which locally are found to be steeper than 60°.

The stratigraphy along the pipeline routes comprising a post slide deposit of very soft to soft Holocene clay (Unit I) overlaying the slide deposit of stiff to very stiff clay till deposits (Unit II), see Ref. [3] and [4]. For the case study, only unit I soil is considered with an undrained shear strength of $s_{uc} = 1 + 1.6z$ (kPa). The recommended sensitivity is $S_t = 6$ for Unit I. Anisotropy ratios for Unit I and Unit II soil are given by:

\[
\frac{s_{ud}}{s_{uc}} = 0.8 \\
\frac{s_{ue}}{s_{uc}} = 0.6
\]

where:
- $s_{uc}$ = undrained shear strength in compression.
- $s_{ud}$ = undrained shear strength direct simple shear.
- $s_{ue}$ = undrained shear strength in extension.

2.1. **Counter act and load**

The counter-acts designed for the installation of the Ormen Lange North project were a steel cylinder with a diameter of 4 m, 6 m tall and a plate thickness of 25 mm. The submerged weight was 13.2 tons. An inner mechanism was designed to prevent over-penetration in the case of unexpected low undrained shear strength.

The in-place load on the counter-act is from the pipeline as the pipeline is pulled in a curve. The load is applied at an elevation of 0.2 m above the seabed and is purely horizontal.

2.2. **Models**

To determine the lateral capacity of the counter-acts in place, the finite element analysis (FEA) software Abaqus was used to assess all cases of embedment, seabed slope and counter-act tilt. Selected cases were analyzed with finite difference (FD) program FLAC to validate the Abaqus findings. Both the software packages are advanced three dimensional continuum numerical modelling software. The Abaqus model for a flat seabed is given in Figure 2.
Given the variation in seabed inclination, the depth to the “impenetrable” Unit II soil and the anticipated variation in angle of counter-act installation, a series of cases were considered varying the following parameters:

- Penetration: 1.5 m, 2.0 m, 3.5 m or 4.5 m.
- Seabed inclination: 0°, 10° or 15°.
- Counter-act inclination: 0° or 10°.
- Load applied 0.2 m or 1 m above the seabed level.

There were some differences between Abaqus and the program FLAC used to perform validation calculations. In the Abaqus model, the counter-act is modelled as a shell while the counter-act in the FLAC validation calculation is modelled as a solid component due to complications modelling a shell in FLAC. The counter-acts are installed with self-weight penetration, meaning that just after installation, the dead weight is carried by the resistance of the soil. Therefore, the interface strength is modelled as 0.0 kPa with a tension cut off in combination with no dead weight of the counter-act in the analysis.

Differences between the Abaqus and control calculations are found in some calculations, which can be attributed to differences in the modelling techniques. These discrepancies result in different failure modes when small penetration lengths are assessed where the Abaqus calculation results in a rotational failure mode, while the failure mode in the control calculation is a sliding failure. As the turn points consist of a hollow cylinder, modelling it as a shell is expected to present the most accurate solution.

The allowable lateral capacity is defined as the Ultimate Limit State (ULS) capacity divided by a factor. The factor in the case study was selected as 1.4 as a general factor of safety.

2.3. Results

The results presented in Ref. [1] relevant to this paper considers only the horizontal capacity of the counter-act. The failure of the counter-act was defined as the point at which plastic deformation occurred when considering the design undrained shear strength (Ref. [1]). In some cases, for very soft clay, the ultimate limit may be difficult to determine since the load displacement curve may not have a clear point of failure. An unpublished example from the project is given in Figure 3. During the project, failure was defined at 120 mm displacement.
The horizontal capacities presented in Ref. [1] were presented with the factor of 1.4 applied. Given that the scope of this paper is the ultimate capacity, the relevant results from Ref. [1] are presented as unfactored in Figure 4.

3. Finite element limit analysis

In the present paper, Finite Element Limit Analysis (FELA) is used for the purpose of computing load carrying capacities. Compared conventional FE analysis which requires the computation of the full load-displacement response to failure, FELA computes the load carrying capacity in a direct manner without the need to trace the load-displacement response. FELA is based on the known theorems of limit analysis first developed in the 1950s (see e.g. [5]). The basic premises are that the material is perfectly plasticity and that the deformations at the point of failure are sufficiently small for the usual small-deformation continuum mechanics framework to apply. Under these assumptions, it is possible to compute not only estimates of limit loads but also rigorous upper and lower bounds on these.

The lower bound theorem states that if a stress field that satisfies the equilibrium equations and the yield conditions can be found, the structure will not collapse. The task of determining the best lower bound thus becomes one of determining the maximum load magnitude for which an equilibrium stress distribution satisfying the yield conditions exists.
The upper bound theorem states that for a postulated collapse mechanism, the ratio between the external and internal rates of work will be greater than or equal to the actual ratio found at collapse. This implies that the external load is greater than or equal to the actual collapse load. With the upper bound theorem, the task thus becomes one of determining the collapse mechanics that leads to the smallest possible work ratio and thereby the smallest possible upper bound estimate of the limit load.

The upper and lower bound theorems may be implemented in a finite element framework where the relevant degrees-of-freedom are either the stresses (lower bound) or the displacements (upper bound). The finite element discretization generates a discrete optimization problem that may be solved efficiently using modern mathematical programming methods, notably conic programming methods (e.g. [6]). A review of FELA, including discussion of discretization and solvers can be found in [7].

OPTUM G3 implements both the upper and lower bound FELA. In addition, rather than computing rigorous upper and lower bounds, it is possible to construct finite element discretizations which blend the requirements of the upper and lower bound theorems. Experience shows that these so-called mixed formulations tend to be very accurate, even for relatively coarse meshes. The results presented in this paper are all of the mixed type.

4. Method
The Finite Element Limit Analysis (FELA) software OPTUM G3 (version 2021 2.1.1) is selected to compare the results from Ref. [1] presented in Figure 4. The advantage with a FELA software is that it determines the ultimate capacity and not the full load displacement curve, hence, the run time is significantly reduced. Another advantage with OPTUM G3 is that the mesh is adaptable over a selected number of iterations. The software will refine the mesh where the previous calculation detected failure. Typically, 3 iterations are required to obtain a precise result.

At the time of the Ormen Lange North project, no FELA 3D software were available; hence the finite element and finite difference software were selected. The seabed is modelled as flat or with a 10 deg inclination. The following cases were considered:

- Flat seabed – counter-act embedment 1.5 m, 2.0 m, 3.5 m and 4.5 m.
- 10deg inclined seabed, counter-act embedment 1.5 m, 3.5 m and 4.5 m.

The model space used is given as a 25 x 25 x 10 m soil volume. This is equivalent to a 3 x diameter in each direction of the model. The full three-dimensional model is used as opposed to half of the model given the symmetry considerations. The model for a flat seabed is presented in Figure 5.

The Mohr Coulomb soil model was used in [1]; however, there were no increase in strength as a function of the effective stresses; hence, [1] used a Tresca model, see [8]. Therefore, to model the soil properties, the Tresca model is used in the OPTUM G3. The undrained shear strength is applied an average anisotropy factor of 0.8 to reduce the strength according to the anisotropy. The undrained shear strength profile for the lower bound is therefore $s_{u,avg} = 0.8 + 1.28z$ (kPa). For the model with inclined
seabed, it was not possible to apply the soil strength as linearly increasing, therefore, a series of layers with an equivalent constant strength was used, as illustrated in Figure 6.

To model the counter-act, the rigid shell element is used. OPTUM G3 does not have a curved shell element; hence, the cylinder is modelled as a prism. A prism with 24 surfaces is found sufficient to model the problem. The prism model of the counter-act is illustrated in Figure 7 for the 10 deg sloping seabed embedded 4.5m. Note the interfaces are modelled for each equivalent constant strength layer.

At the time of installation, the self-weight of the counter-act is in equilibrium with the soil resistance. Clay is disturbed during skirt penetration and will start to regain strength immediately after installation, see [1] and [9]. However, the interface is modelled with a strength of 0.0, tension cut off and the deadweight is not included in the calculation which is a conservative approach since there was time between counter-act installation and pipe lay.

5. Results

Numerical simulations were completed with use of the mixed element type in OPTUM G3. The adaptive iteration function was used with 3 iterations and a target of 10,000 elements. The average total run time is 4 minutes 32 seconds each model.

The deformed meshes for flat and inclined seabed and 4.5 m counter-act are illustrated as shear dissipation in a cross section through the middle of the counter-act, see Figure 8. In both cases, it
becomes obvious that the tension cut off has an impact on the results, given the crack on the tension side of the counter-act and the soil.

![Deformed mesh and shear dissipation 4.5 m counter-act.](image1)

The total displacements are illustrated in Figure 9 for the 4.5 m penetrated counter-acts for both flat and inclined seabed. It is evident that the failure mechanism is a rotational failure with the centre of rotation under the counter-act.

![Deformed mesh total displacements 4.5 m counter-act.](image2)

The failure mechanism from the previous work (Ref. [1]) for a 4.5 m penetrated counter-act and 10° inclined seabed is compared to the OPTUM G3 results in Figure 10. Note that the illustration from Abaqus was previous unpublished. In both cases, it is seen that there is no tension and the failure mechanism is a rotational failure with a centre of rotation under the counter-act.

![Total displacements 4.5 m penetrated counter-act and 10deg inclined seabed.](image3)
The unfactored capacities are plotted for the OPTUM G3 models and compared to the corresponding findings in Figure 11 and presented in Table 1. The average percent difference relative to the original results is 5.7%. The best fit is for flat seabed and 4.5 m penetrated counter-act with a percent difference of 0.3% and the worst fit is for the 10° inclined seabed and a 1.5 m penetrated counter-act with a percent difference of -14.9%.

**Figure 11.** Unfactored capacity.

**Table 1.** Unfactored capacity.

| Embedment (m) | Seabed 0°, counter-act 0° | Seabed 10°, Counter-act 0° |
|---------------|---------------------------|----------------------------|
|               | [1] OPTUM G3              | [1] OPTUM G3               |
| 1.5           | 25                        | 11                         |
| 2             | 39                        | NA                         |
| 3.5           | 97                        | 64                         |
| 4.5           | 139                       | 84                         |

6. Discussion
The geotechnical design of counter-acts used for pipeline installation was published in [1]. The design was completed with use of advanced three dimensional FEA and FD software. The counter-act is an open steel cylinder which is loaded horizontally as the pipeline is pulled in a curve around the counter-act.

This paper has focused on the capacity of the counter-act. The design is complex given the strength at the interface is modelled as 0 kPa with a tension cut off. The open cylinder is difficult to model in geotechnical software since the lack of a horizontal plate may cause numerical instability.

The capacity of the counter-acts is modelled with use of the three dimensional FELA software OPTUM G3. An element type combining a lower and upper bound limit analysis called the mixed element is used to assess the capacity. In some of the capacity calculations, the seabed is inclined. This is solved in OPTUM G3 with a series of soil layers each with an equivalent constant shear strength.

The run time in OPTUM G3 is fast compared to conventional three dimensional FEA with a run time under 5 minutes. The results compare well with the previous published work with an average difference of 5.7%, see Table 1. Some of the variation may be explained by the difficulties in identifying the accurate capacity on the load displacement curve from the original work. In OPTUM G3, the equivalent
constant shear strength layered model may have been slightly inaccurate, since the shallowest counter-act on the 10\(^\circ\) slope has the largest relative difference, see Table 1.

The OPTUM G3 mixed element is found to be very accurate for complex three dimensional problems for modelling undrained behaviour. The difference in capacities are within normal anticipated variation between geotechnical software.

7. Acknowledgement

The authors would like to acknowledge Subsea 7 for permission to publish the results presented in the paper.

References
[1] Olsen C, Brown N, Rosborg A and Sørensen C S 2014 Lessons Learned - Counter-acts Used To Install Pipelines Offshore In Very Soft Clay, OTC.
[2] Bryn P, Berg K, Fosberg C F, Solheim A and Kvalstad T J 2005 Explaining the Storegga Slide, Marine and Petroleum Geology. Volume 22, Issues 1–2, January–February 2005, Pages 11-19.
[3] Eklund T, Høgmoen K and Paulsen G 2007 Ormen Lange Pipelines Installation and Seabed Preparation, OTC.
[4] Eklund T and Paulsen G 2007 Ormen Lange Offshore Project Subsea Development Strategy and Execution, ISOPE.
[5] Drucker D C, Prager W and Greenberg H J 1952. Extended limit theorems for continuous media, Quarterly of Applied Mechanics, 9, 381-389.
[6] Andersen E D, Roos C and Terlaky T 2003. On implementing a primal-dual interior-point method for conic quadratic programming, Mathematical Programming, 95, 249-277.
[7] Sloan S W 2013. Geotechnical stability analysis, Geotechnique, 63(7), 531-572.
[8] Krabbenhoft K, Lymain A V and Krabbenhof J 2016 OPTUM G2 Materials.
[9] Jeanjean P 2006 Setup Characteristics of Suction Anchors for Soft Gulf of Mexico Clays: Experience From Field Installation and Retrieval, OTC.