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# Numerical Investigation of Compensated Suction Caissons in Soft Soil

K. Choosrithong*, M. Todnem
*Subsea7 Norway AS, Stavanger, Norway*

**kamchai.choosrithong@subsea7.com (corresponding author)*

**ABSTRACT:** A novel suction caisson concept, namely the compensated suction caisson, is investigated to minimize settlement for templates where the settlements are critical. The compensated suction caissons involve the excavation of soil inside the caissons to reduce the net increase in load applied by the foundation to the underlying soft soil. The removal of soil reduces the vertical effective stress in the soil, thus putting it in an overconsolidated state and reducing its compressibility. The subsequent loadings of the foundation will therefore tend to cause less settlement than if no excavation of the soil had been carried out. It has been shown that the use of compensation, via excavation of the soil and embedment of the base slab, can lead to significant reduction in settlement compared to conventional suction caissons. A series of finite element analyses has been conducted to investigate effect of the caisson geometry on the undrained foundation capacity under combined vertical-horizontal-moment loading and the mechanisms occurring at failure. The results show a significant increase in foundation bearing capacity for the compensated suction caissons.

**Keywords:** Compensated Suction Caisson; Soft clay; Numerical Modelling; Offshore

## 1 INTRODUCTION

A suction caisson has been extensively used in offshore facilities for supporting or anchoring large offshore installations e.g. drilling templates, platforms, wind turbines, and jacket structures (see e.g. Gourvenec, 2007 and Skau et. Al., 2019). A suction caisson is usually fabricated from steel consisting of a base plate (lid) resting on seabed with a skirt penetrated into the soil. It is first penetrated into the seabed under self-weight and further penetration proceeds by applying pressure (suction) inside the skirts by pumping out water. Additional downward force occurs due to the differential pressure over the lid.


*Figure 1 – Typical foundation structure for template*

In the offshore oil and gas industry, due to increasing water depth (greater than 100 m) and increasing foundation size in future projects, there is an increasing interest for alternative foundation concepts, in particular when the foundation engages in soft soil. Figure 1 shows an illustration of the caisson foundation supporting a drilling template. The suction caisson can be used in two foundation configurations – in a multiple-suction caisson support template structure (see Figure 1)or a single caisson support template structure. The foundation structures are exposed to loads from template and surface conductor load (drilling operation). The bending moment around the horizontal axis and vertical load are of paramount importance for the single- and multiple-caisson support structure.

Accurate prediction of the foundation response is important in the design as it influences the stability of the foundation and operability of the wellhead. The load sharing between the lid and skirt are crucial in the development of settlements during drilling and long-term. Generally, the internal soil plug is subjected to a uniformly distributed additional stress underneath the lid. For soft soil, this additional stress due to large load is unfavourable to the settlement control and load-bearing capacity due to a relatively low strength and stiffness of the soil. The challenge rises when the allowable settlement is limited throughout operation to maintain the connection from other subsea equipment to the supported structure.

Therefore, the compensated suction caisson concept is introduced by excavating soil inside the caissons and casting a base slab on top of the soil plug, after caissons are installed, to reduce the net increase in vertical downforce applied by the foundation to the underlying soft soil. It is also anticipated that the mobilisation of skin friction inside and outside the caisson is beneficial to reduce the additional stress in the soil plug inside and thus to reduce the settlement.

This paper presents the concept and results of numerical investigation for the compensated suction caisson supporting a template structure in soft offshore clay. The undrained capacity has been analysed through the effect of embedment depth. Long-term settlement analysis is calculated only by considering vertical loading. It is noted that the dynamic loads can significantly impact the soil stiffness degradation and the deformation response of foundations. The cumulative displacement generated by the cyclic load adversely effects the behavior and stability of offshore structures. Nervertheless, this study assumes a simplified static loading condition.

## 2 COMPENSATED SUCTION CAISSON

Figure 2 shows the schematic of installation and construction sequences for a compensated suction caisson. The caisson is firstly installed and partially penetrated into seabed due to self-weight and momentum of the pile. A suction pump has been activated. This creates an underpressure within the caisson (Figure 2a) that draws the pile deeper into seabed and the underpressure will also cause the soil plug to heave above the level of the surrounding seabed.

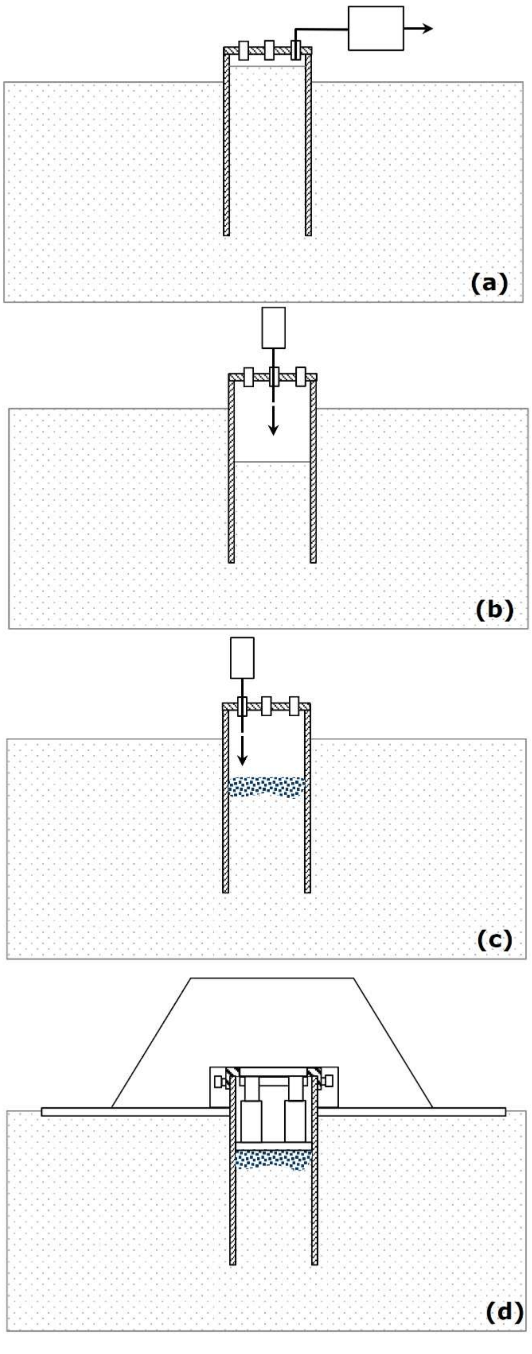


*Figure 2. Installation sequences*

Figure 2b demonstrates an excavation tool by using contra-flowing along an elongated wand to erode and fluidise the soil. The fluidised soil mixed with the water is expelled through the outlet channel. When excavation is complete, a layer of grout or cementitious material is placed on top of the excavated plug (Figure 2c). A subsea structure such as a template is subsequently lowered and seated on top of the caisson, which then serves as the foundation of the structure (Figure 2d).

## 3 NUMERICAL MODELLING

The numerical modelling considered in this paper represents an alternative design concept for a typical project on the Norwegian Continental Shelf.

### 3.1 Site condition and geotechnical properties

The soil profile consists of homogeneous, uniform, slightly overconsolidated clay. The undrained shear strength significantly increases with depth as illustrated in
Figure 3. The simulated undrained shear strength profile is based on laboratory calibration.

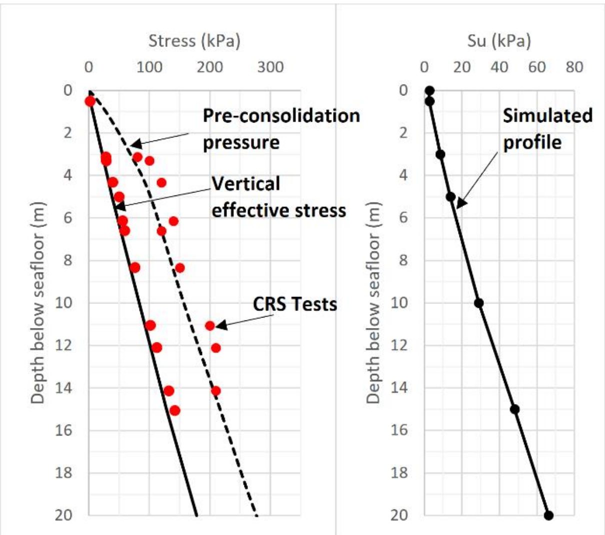


*Figure 3. Soil profile*

The double hardening plasticity (HS model) was used in the analysis. The model is based on the effective stress framework and the undrained shear strength is a consequence of the model adopted. The reference stiffnesses were calculated based on experiments and CPTu tests. The oedometric, secant and unloading stiffnesses are calculated as followed:

$$E_{oed} = E_{oed}^{ref} \cdot \left(\frac{c \cdot cot\varphi + \sigma_1'}{c \cdot cot\varphi + p_{ref}}\right)^m \quad (1)$$

$$E_{50} = E_{50}^{ref} \cdot \left(\frac{c \cdot cot\varphi + \sigma_3'}{c \cdot cot\varphi + p_{ref}}\right)^m \quad (2)$$

$$E_{ur} = E_{ur}^{ref} \cdot \left(\frac{c \cdot cot\varphi + \sigma_3'}{c \cdot cot\varphi + p_{ref}}\right)^m \quad (3)$$

The stiffness ratio of $E_{oed}^{ref}/E_{50}^{ref}/E_{ur}^{ref}$ is 1/1/8.

*Table 1. Input parameters for HS model.*

| Parameters | 0 m-10 m | From 10 m |
|---|---|---|
| $\gamma'$ [kN/m$^3$] | 8 | 10 |
| $E_{oed}^{ref}$ [kN/m$^2$] | 2155 | 5000 |
| $\varphi'$ [∘] | 28 | 28 |
| $c'$ [kN/m$^2$] | 1.6 | 1.06 |
| $m$ [-] | 0.8 | 0.8 |
| $K_0$ [-] | 0.75 | 0.65 |
| $OCR$ [-] | 3 | 2 |
| $R_{int}$ [-] | 0.7 | 0.7 |

Note: $\gamma'$= effective unit weight, $\varphi'$= friction angle, $c'$= effect cohesion, $m$= stress dependency, $K_0$ = earth pressure coefficient, $OCR$= Over consolidation ratio, $R_{int}$= interface parameter

### 3.2 Finite element model

The finite element software PLAXIS 3D (PLAXIS, 2020) was used in the numerical study. The soil was modelled with 10-noded tetrahedral elements, and structural with 6-noded quadratic triangular plate elements. Interface elements were applied between structure and soil with strength reduction. Half of the physical problem was modelled utilizing symmetry to reduce computational cost.

A 5 m diameter caisson with 7.5m deep skirts was considered in this study. Figure 4 shows a finite element model. The caisson was modelled using plate element with thickness of 20 mm and assumed to have Young's modulus E = 2.2E8 kPa. A grout thickness of 20 cm was assumed based on experience and the grout stiffness was assumed to be 9 times the initial soil stiffness ($G_{grout} = 9G_{soil}$) (Skau et. al., 2019).

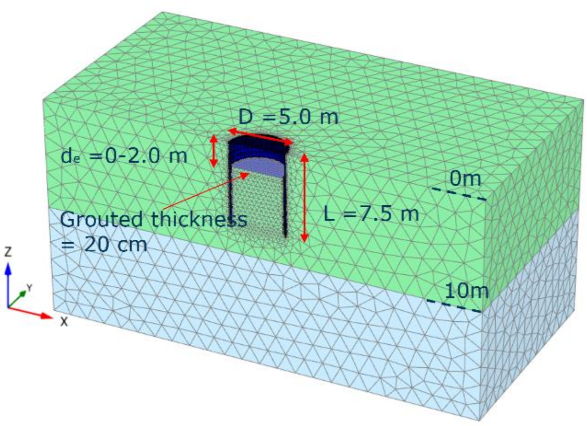


*Figure 4. FEM mesh and geometry*

The simulations considered in the analyses are as follows:

- Generation of initial stress
- Wished-in-place installation to avoid installation effects, assuming full soil strength gain along the suction pile-soil interface.
- Lowering water level suction caisson
- Excavation
- Casting of grout base slab
- Application of loading

The suction caisson was investigated under combined vertical-horizontal-moment loading as illustrated in Figure 5. The so-called "single swipe test" has been used for applying the load on suction caissons. It is first pushed vertically to a prescribed embedment, after which the vertical is held constant while the foundation is swiped horizontally.

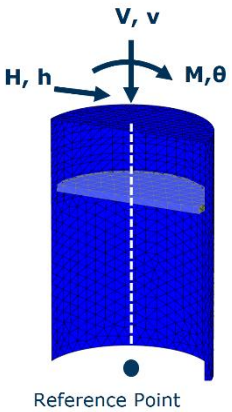


*Figure 5. Loading condition and reference point (+V denotes compression)*

### 3.2.1 Parametric study

A parametric study was carried out by investigating the response of the system to the excavated depth ($d_e$, see Figure 4). The $d_e$ varies from 0 to 2 m below the top plate. A practical point of view, it is suggested the $d_e$ should be excavated from the top of foundation by at least 20% of the height of the foundation. Additional checks should be carried out to ensure adequate seal for the suction caisson.

## 4 RESULT AND DISCUSSIONS

### 4.1 Response to vertical loading

Figure 6 shows the load-displacement curves. The bearing capacity is assessed by a displacement-controlled procedure. The load was applied on top of caisson for the case without excavation inside the suction caisson (de = 0 m and will report herein as "reference analysis", see Figure 4). For the compensated suction caissons, the loads will be applied on the top plate and at the grout slab simultaneously to assess the load-bearing capacity.

The reference analysis without excavation inside suction caisson ($d_e$ = 0 m, see Figure 4) shows a softer response, especially at larger mobilization levels. The contributions of excavated area and grout slab reveal a significant increase of vertical load by 15% at 100 mm (2% caisson diameter). This is due to the stiffer response of soil due to utilisation of the unloading stress path and the contribution of loading at the grout slab which prevents the failure of soil plug underneath.

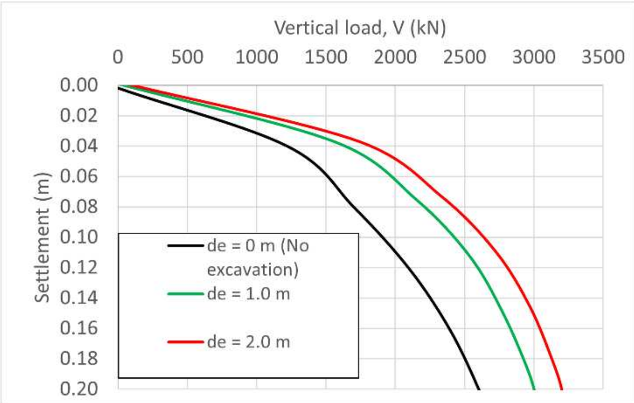


*Figure 6. Vertical load - settlement*

The long-term settlement has been investigated. The following load sequences are assumed:

- Template installation (Self weight 179 ton)
- 1-year consolidation
- Applied drilling load (460 ton)
- Assumed 60-day of drilling operation
- Removing drilling load
- 24-year consolidation

It is noted that the loading sequences do not represent the drilling operation plan and the intention is to demonstrate the development of vertical settlement over time. The FEM model and modelling procedures have been described in section 3.2

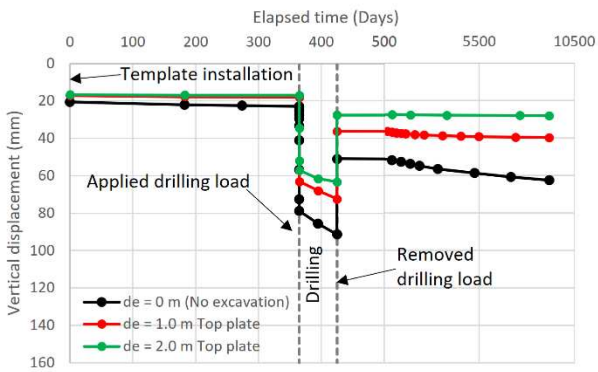


Figure 7 shows the responses of long-term settlement at top plate for each case. It is obviously shown that the cases of $d_e$ = 1.0 m and $d_e$ = 2.0 m shows a significant decreasing of settlement after applied drilling load (e.g. at 425 days) by 20% and 31%, respectively. The tendency of an increasing long-term settlement is observed for the reference analysis ($d_e$ = 0 m). This is due to the the increasing in load applied by the foundation top plate to the underlying soft soil.

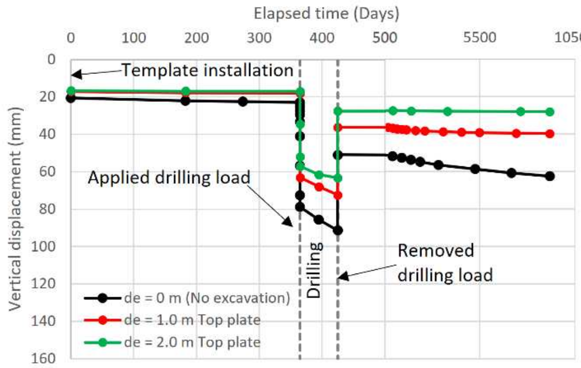


*Figure 7. Long-term settlement due to vertical loading*

## 4.2 Response to combined loading

The capacity envelope under combined loads was determined using the probe method (see e.g. Hung, and Kim (2014) and Suryasentana, 2020), which increases the displacement at a constant displacement ratio (e.g., h/v= constant). The loading path in the probe method criterion at a specific point, which indicated one point on the capacity envelope. The subsequent points along the capacity envelope were obtained by changing the displacement ratio.

The $V_{0,ref}$, $H_{0,ref}$ and $M_{0,ref}$ were determined using the tangent intersection method from the reference case without excavation inside the caisson ($d_e$ = 0m). The method plots two tangential lines along the initial and later portions of the load-displacement curve, and the load corresponding to the intersection point of these two lines is taken as the bearing capacity. Figure 8 demonstrates the V-H-M envelopes for case $d_e$ = 2.0 m.

Figure 8 compares the V-H-M envelops for each case. In Figure 8a, the bending moment is only marginally increased (at $H/H_{0,ref}$ = 0). The grout slab plays no role in improving the bending moment capacity when combined with horizontal load.

The response of VM is shownin Figure 8b. As expected, the analysis without excavation is significantly softer in vertical response. The combined vertical and moment loads for analyses of $d_e$= 1.0m and 2.0 m show a decreasing rate of moment capicity which is nearly coinciding response ($V/V_{0,ref}$ towards zero).

Similar observation is found at VH envelop (see Figure 8c). The horizontal load bearing capacity for suction caisson is lower than the reference analysis. This is due to the contribution of soil plug that play a crucial role in the reduction of horizontal capacity.

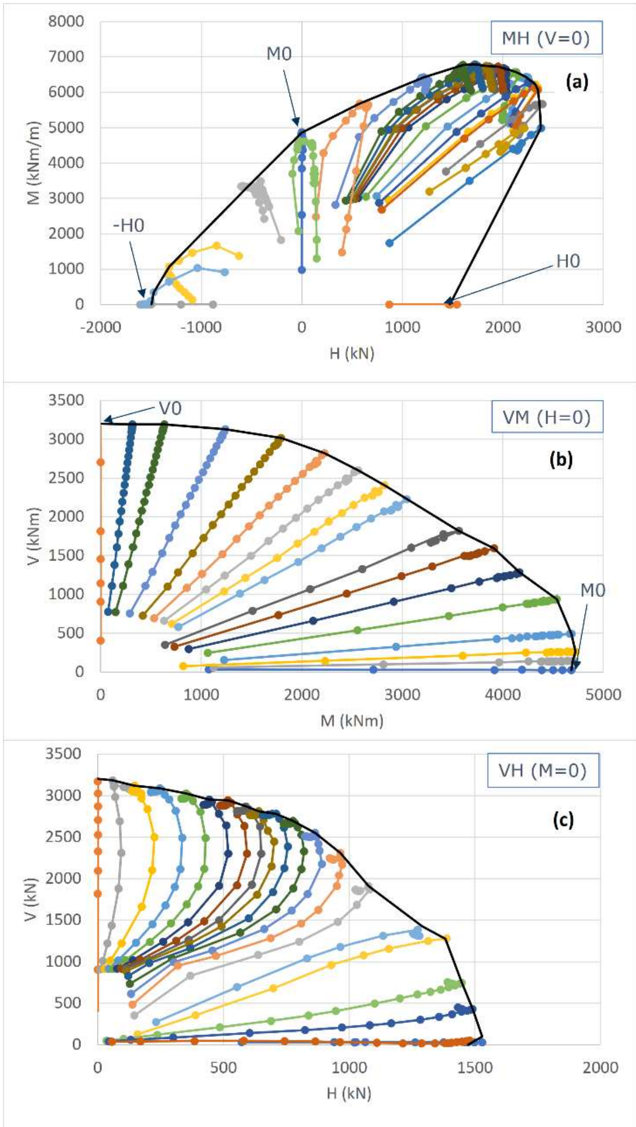


*Figure 8. Vertical load – Moment – Horizontal load envelopes for case $d_e$ = 2.0 m*

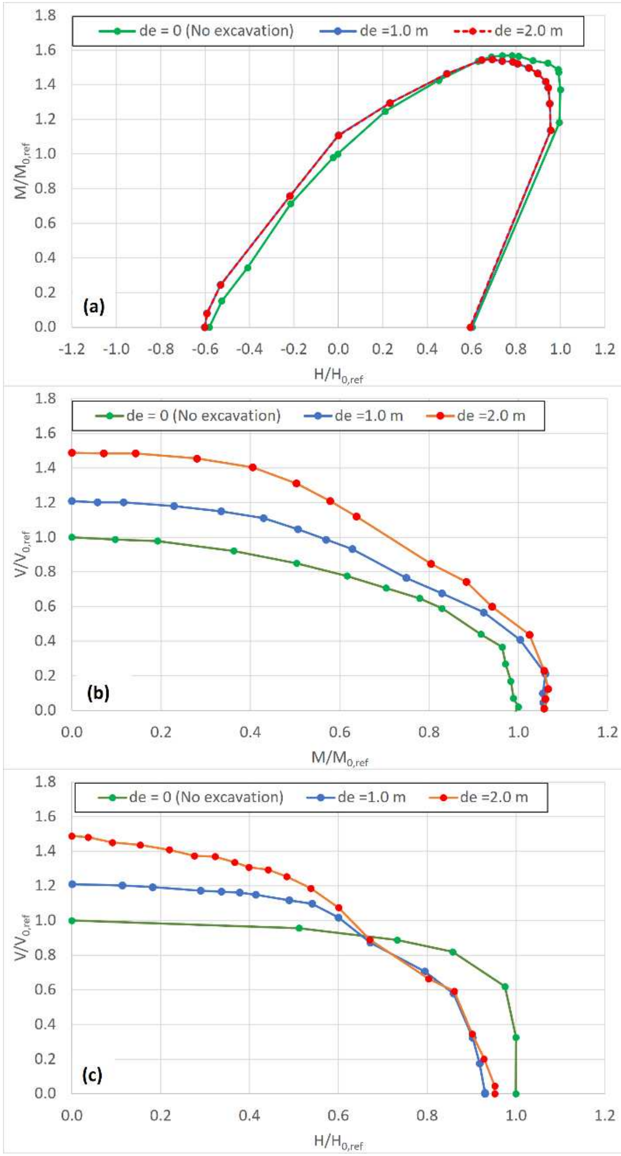


*Figure 9. Comparison of Vertical load – Moment – Horizontal load envelopes for each case*

## 5 CONCLUSIONS AND OUTLOOKS

The compensated suction caisson concept was introduced. The concept involves the excavation of soil inside the caissons and follow by casting a base slab on top of the soil plug. The preliminary investigation had been carried out by means of 3D FEA. It has been shown that the vertical load bearing capacity can be improved and initial settlement can be reduced due to the reduction in vertical effective stress within the soil plug and putting soil in unloading stage. However, the improvement of horizontal and bending moment capacity is not clearly observed during the combined loading. Therefore, the compensated suction caisson concept may be more applicable for structures that have a tight tolerance for vertical alignment in the structure-wellhead interface, or significant vertical loads that cause bearing capacity challenges. The concept will also be favourable in areas with limited penetration depth due to presence of harder soil units.

Further detailed analyses have to be carried out such as skirt thickness, aspect ratio (length and diameter), and long-term cyclic soil-structure interaction by iterative process in order to investigate the sensitivity and geometrical effect of structure from excavation depth ($d_e$) inside the caisson. Influences of mechanical behaviour of grouted material (e.g., unit weight, compressive strength, tensile strength, and post peak behaviour such as strain-softening behaviour) should also be addressed in the detailed analyses.

## AUTHOR CONTRIBUTION STATEMENT

**Kamchai Choosrithong**: Data curation, Formal Analysis, Writing- Original draft. **Magnus Todnem**: Supervision, Visualization Investigation, Writing- Reviewing and Editing,

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