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ASSESSMENT OF SHEET PILE AND COFFERDAM REINFORCED DYKES IN PLAXIS 2D BASED ON THE DUTCH GUIDELINES

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The rise in sea levels and changes in safety standards necessitate reinforcing earthen dykes to comply with the permissible probability of failure. Traditional methods of raising and widening dykes, such as berms, present significant challenges in densely populated areas due to space constraints. As an alternative, integrating structures like sheet piles into dykes offers a viable solution. However, despite conservative design guidelines for these solutions, excessive deformations near the toes of dykes have been observed in several instances, resulting in damage to nearby properties.

In this paper, we utilize the finite element method to model the soil-structure interaction in dykes reinforced with unanchored sheet piles and cofferdams (two sheet pile walls connected with anchors). We focus on hypothetical cases typically found in the Netherlands, while using typical Dutch soft (organic) soil data as obtained from the Eemdijk test. The models focus on determining the long-term deformations near the dyke during high water levels, and the factor of safety for macro-stability based on deterministic approach and the semi-probabilistic method outlined in the Dutch guidelines (POVM, 2020a). The model shows the benefit of constructing a cofferdam as dyke reinforcement when it is not possible to use inclined anchors. The use of cofferdams as an independent structure decreased lateral displacement at the top of the wall by 40% and increased the stability by 16% when compared to unanchored sheet pile wall. The effect of stress path dependent shear strength on the factor of safety is demonstrated. Additional deformations resulting from soil predrilling and liquefaction during installation are also evaluated. These effects are reflected in the properties of the interface elements, represented by its strength reduction factor. The influence was most prominent at the inner toe, where lateral displacements doubled when decreasing the interface strength reduction factor from 0.8 (no predrilling) to 0.5 (with predrilling).

Keywords: dyke reinforcement, sheet pile walls, cofferdams.

1. Introduction

In the Netherlands, approximately 1,500 kilometers of flood defenses are projected to need reinforcement by 2050 (National Delta Programme, 2023). This includes both dykes (levees) and dunes, which are vital to protecting the country from flooding due to its low-lying geography. The primary flood defenses must meet the safety standards. Dyke reinforcement is necessary when existing structures do not provide sufficient protection against macro- stability failure mechanisms, which can result in devastating societal and economic damage. A common method of reinforcement involves raising and widening dykes with berms. However, this approach is not always feasible, particularly when buildings are constructed close to the dyke's inner toe, obstructing the use of berms. As a result, alternative structures, such as anchored and unanchored sheet piles, diaphragm walls, soil mix, combined walls, and cofferdams (two sheet pile walls connected with anchors) can be integrated into dykes to enhance stability.

The complexity of the problem does not allow for the implementation of analytical methods during the design process. The Finite Element Method (FEM) offers a suitable alternative, as advanced soil models can capture complex aspects of soil behavior. The Cross-Project Exploration of Macro Stability (Project over stijgende Verkenning Macrostabiliteit (POVM, 2020a)) sets the guidelines for designing and assessing a longitudinal structure that ensures that the relevant flood defense meets the required target reliability for macro stability. Even though the implementation of such solutions follows a strict and cautious design process, excessive deformations have been reported near the toe of dykes in several instances, resulting in damage to nearby properties.

This paper investigates the benefits of using a cofferdam wall compared to a sheet pile wall, focusing on deformation at the toe and crest of the dyke and the resulting increase in the factor of safety.

Additionally, an investigation is conducted to analyze the influence of strength anisotropy on the factor of safety using the NGI-ADP-SHANSEP constitutive model in the finite element method (Panagoulias & Brinkgreve, 2017). This model accounts for the dependency of the shear strength on the stress path, with distinction between Active, Direct simple shear and Passive undrained shear strength. The Active shear strength S_u^A is determined based on the SHANSEP formulation. The influence of the lateral earth pressure coefficient K_0^{nc} in the Soft Soil Creep (SSC) model is also studied to account for time-dependent behaviour (creep). The impact of predrilling or soil liquefaction is accounted for by reducing the interface element strength reduction factor R_{int}. Both characteristic and design values of soil properties are incorporated into the FEM model, following the recommendations of (POVM, 2020b).

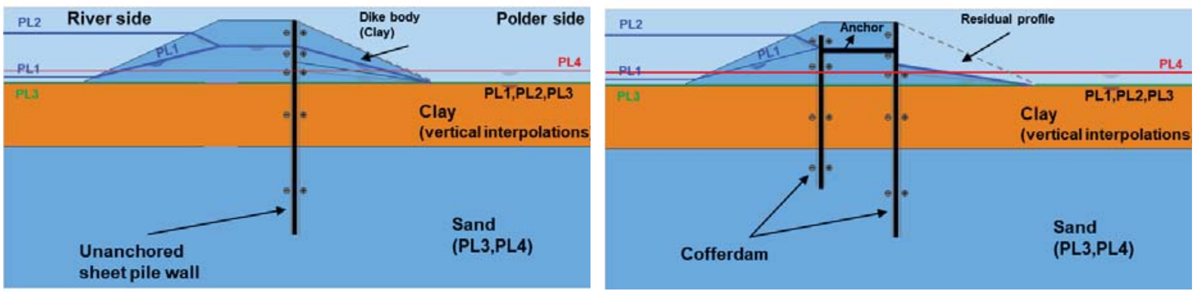
2. Schematization and calculation steps:

The model represents a typical soil configuration found in the Netherlands, with a dyke constructed on a Holocene clay layer overlaying a Pleistocene sand layer. For simplicity and the purposes of this study, the clay layer is assumed to be homogeneous and have a uniform thickness of five meters. The inclination of both the inner and outer slopes is 1:2.2, with a crest height of five meters.

The average (PL1) and extreme (PL2) water levels are +1.0 and +4.0 meters above the toe, respectively. The schematization of the pore pressure distribution follows the guidelines in (TAW, 2004) for case 1A (clay dyke on compressible soil). The hydraulic head profile in the sand layer (aquifer) is often determined based on field measurements. For this study, the head for the Pleistocene layer under daily conditions (PL3) and extreme conditions (PL4) has been chosen to be +0.0 m and +1 m above the toe, respectively. The pore pressure distribution in the clay layer under the dyke is vertically interpolated from the pressure at the boundaries of the layer, as shown in Figure 1.

The Soft Soil Creep (SSC) model is applied to the dyke material and the overlying clay layer. Before calculating the factor of safety, the SSC model is switched to the NGI-ADP-SHANSEP model. The sand layer is modelled throughout the analysis using the Hardening Soil (HS) model. The calculation phases follow the steps described in (POVM, 2020b). The initial phase (1a) models the existing dyke and generates the initial stresses using the K_0 procedure. Stresses are redistributed and their directions are adjusted to achieve equilibrium in the plastic-nil phase (1b). The subsidence of the soft soil prior to the application of reinforcement is accounted for in step (1c). A 10-year period is assigned in the plastic calculation to accumulate creep strains in the SSC model.

In step (2), the reinforcement is activated along with the interface elements. A pre-stress force of 100 kN/m is applied to the anchor in this phase. In step (3a), the effect of soil settlement over the structure's 100-year lifetime on the structural forces is assessed. The prestress force is adjusted in step (3b) to account for the additional force in the anchor due to soil subsidence. In step (4a), extreme hydraulic loads, are applied (PL2 and PL4 in Fig 1). Next, in step (4b), the SSC model is switched to the NGI-ADP-SHANSEP model, and the traffic load (13 kN/m² over a width of 2.5 meters) is activated. At this stage, the soil behaviour is assumed to be fully drained in all soil layers to reflect long-term behaviour. Finally, in step (5), the global safety factor is calculated using the strength reduction method.



a. Unanchored sheet pile with full dyke profile. b. Cofferdam with residual profile (independent structure).

Fig. 1 Model schematization and phreatic levels

3. Soil and structure properties

The parameters for the Hardening Soil (HS), Sof Soil Creep (SSC), and NGI-ADP-SHANSEP models were derived from the clay and sand layers in the full-scale Eemdijk test (Lengkeek, 2022). The extensive laboratory testing program at the Eemdijk site enabled an accurate parameter determination. Layer I is an organic clay layer, identified by the high organic content (loss on ignition N=20%). While layer II is silty sand with medium density.

Soil model parameters were obtained and calibrated by numerically simulating soil lab tests and comparing the results with the real laboratory test data. The derived mechanical parameters are shown in Table1.

Table 1. Parameters of the SSC and HS soil models.

Parameter	Name	Clay	Sand	Unit
Soil model	-	Soft Soil Creep	Hardening Soil	-
Modified compression index	λ^*	0.118	-	-
Modified swelling index	κ^*	0.051	-	-
Modified creep index	μ^*	0.004	-	-
Poisson ratio	ν_{ur}	0.176	0.2	-
Secant stiffness (triaxial)	E_{50}	-	24,000	kN/m^2
Tangent stiffness (oedometer)	E_{Oed}	-	21,200	kN/m^2
Unloading/reloading stiffness	E_{ur}	-	72,000	kN/m^2
Stress dependency power	m	-	0.575	-
Failure ratio	R_f	-	0.9	
Cohesion	c'	2	0.1	kN/m^2
Friction angle	ϕ'	30	35	^{o}
Dilatancy angle	ψ'	0	7	^{o}
Interface reduction factor	R_{int}	0.8	0.8	-
K_0 determination	K_0^{nc}	0.5	0.5	-
Pre-overburden Pressure	POP	13	30	kN/m^2

The sheet piles profile used in this study is the AZ36-700N, their properties can be taken directly from the catalogues. The sheet piles are modelled with plate elements with the following properties: $EA = 4.088 * 10^6$ kN/m and $EI = 172.5 * 10^3$ kN.m^2/m. The anchors are at a depth of two meters with 2.8 meters spacing and stiffness EA of $1.16 * 10^8$ kN.

Measures can be taken to reduce the damage caused by vibrations during the insertion of sheet piles. Techniques such as pre-drilling and fluidization can significantly influence the shear strength and stiffness of the soil surrounding the pile, with a suggested reduction in the friction factor of 50–60% (POVM, 2020a). The effect of this reduction on dyke deformations is analyzed using a range of R_{int} values from 0.5 to 1. A value of 1 indicates that no reduction is applied to the shear strength from the adjacent soil layer.

(Brinkgreve, 2004) studied the effect of the parameter M in the SSC model on the deformation of the soft soil layer due to embankment construction. The parameter represents the slope of the line that determines the steepness of the yield cap (ellipse), and thereby the direction of creep strains, which in turn determines the coefficient of lateral earth pressure K_0^{nc}. In his model a decrease in M to match the critical line resulted in a considerable increase in settlement and horizontal deformations. Here, we investigate whether this parameter affects the deformations in the case when the dyke is already constructed, and the extreme water level is applied. Two values are investigated, the default value calculated in Plaxis M=1.467 based on K_0^{nc} = 0.5, and the value corresponding to the slope of the critical line M=1.2 which aligns with a normally consolidated lateral earth pressure of $K_0^{nc} = 0.59$.

3. Results

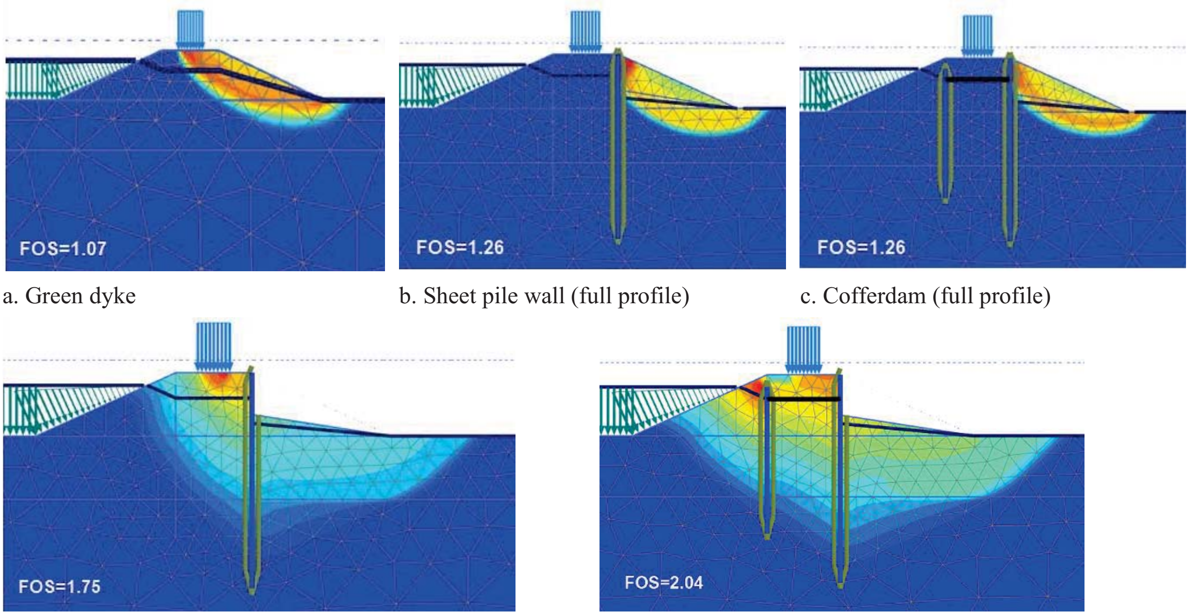
First, the stability of the so called ‘green dyke’ (unreinforced) is evaluated under extreme water levels using characteristic soil properties. The most critical slip plane occurs on the polder side, with a factor of safety (FOS) of 1.07. When compared with the green dyke, the introduction of sheet piles or cofferdam walls increases the FOS to 1.26 in both cases. This indicates no additional stability provided by the second anchored wall in the cofferdam due to the failure of the inner slope of the dyke as shown in Figure 2a, b and c.

Guidelines recommend that in such cases, the wall should be capable of independently withstanding extreme loads in the absence of the outer slope soil. This condition is referred to as the residual profile, where two-thirds of the dyke's height on the polder side is removed. Under the residual profile scenario, the sheet pile wall increases the FOS to 1.75, while the cofferdam achieves an FOS of 2.04 (Figure 2d,e). The cofferdam structure reduces the wall's lateral displacements (at extreme water level) and bending moments by 37% and 50%, respectively, compared to an unanchored sheet pile wall.

The interface reduction factor R_{int} has marginal effect on the vertical deformations. However, the lateral deformations at the outer crest, inner crest, and toe increases with the decreasing value of R_{int}. This is primarily due to higher plastic strains developing in the interface elements as a result of reduced strength properties (c', φ') that define the Mohr-Coulomb failure surface. A similar pattern is observed for the maximum bending moment. Careful consideration is required when selecting the interface reduction factor, as it depends on the wall's material, installation method, and damage mitigation measures. This factor can be critical for the serviceability limit state, as illustrated in Figure 3.

In this case, where the dyke is already constructed, the effect of the steepness of the yield cap (M) on the settlement was marginal at the toes of the dyke. Nevertheless, the settlement at the outer crest and the lateral displacement at the inner toe increased by 1.8 times and 5.8 times, respectively, when changing M from the default value 1.467 to 1.2 for R_{int}=0.7. The decrease in M leads to an increase in lateral earth pressure, resulting in higher horizontal stresses, which explains the observed increase in lateral displacements at the inner toe. Additionally, higher plastic strains caused by the decreasing dimensions of the cap also contribute to the deformations.

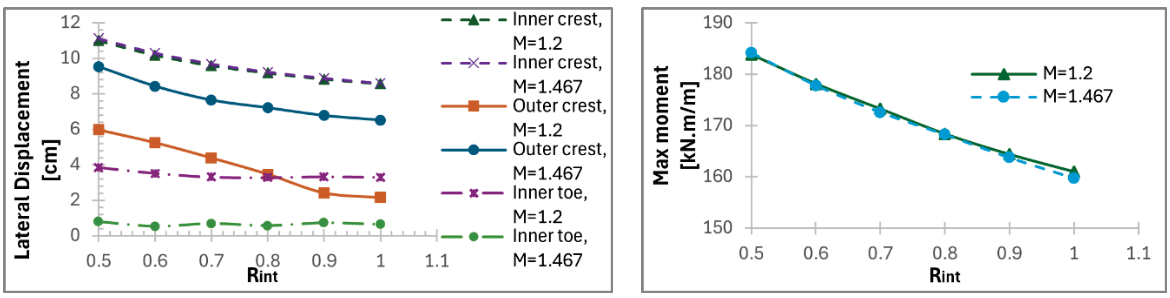
Using the NGI-ADP-SHANSEP model accounts for stress path dependency of shear strength along the studied slip plane (Panagoulias & Brinkgreve, 2017). Typical shear strength ratios are $S_u^{DSS}/S_u^A = 0.7$ (ratio of direct simple shear strength over plane strain active shear strength), and $S_u^P/S_u^A = 0.6$ (ratio of passive shear strength over active shear strength). This anisotropy significantly influences macro-stability assessments as shown in Figure 4a. Applying isotropic shear strength based on S_u^A resulted in a 10% higher factor of safety compared to that obtained with anisotropic shear strength. Such a design would be unconservative.



a. Green dyke b. Sheet pile wall (full profile) c. Cofferdam (full profile)

d. Sheet pile wall (residual profile) e. Cofferdam (residual profile)

Fig. 2 Failure mechanisms for the studied cases

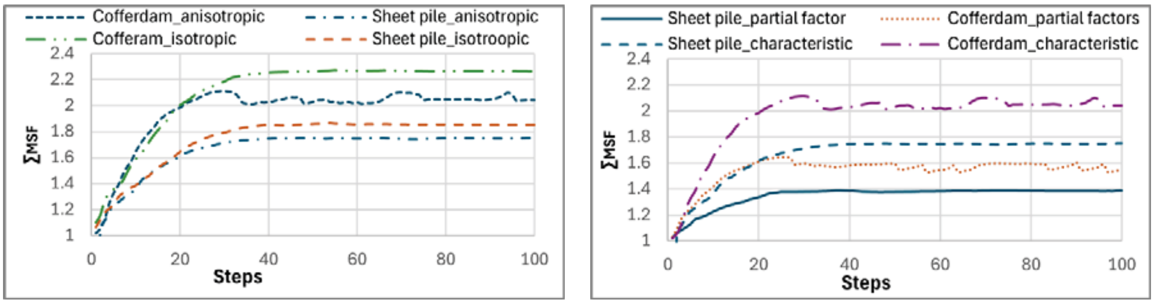


a. Lateral displacements at the inner and outer crest b. Impact on the maximum bending moment at the wall.

Fig. 3 Effect of the strength reduction factor on the dyke reinforced by cofferdam (residual profile).

The semi-probabilistic approach adopted by Eurocode and the guidelines (POVM, 2020a), applies partial safety factors on the strength parameters of the soil based on a permissible probability of failure of the dyke trajectory. With a reliability index $\beta = 5.02$, the calculated material and model partial safety factors are γ_n =1.16 and γ_d =1.06

respectively. Therefore, a partial factor of safety of 1.23 in total is applied to the shear strength parameters c', S_u, and tangent of φ'. The schematization factor for stability is 1.05 which is compared to the resulting global factor of safety from the safety analysis. Applying the partial factors of safety in the analysis resulted in an FOS of 1.39 for the sheet pile wall. Even though this satisfies the Ultimate Limit State (ULS), the lateral displacement at the top of wall reached 19 cm, exceeding the permissible displacement of 10 cm. Therefore, the use of anchors is necessary to reduce the lateral displacement. Anchoring the polder side wall with a shorter wall at the river side (cofferdam), increased stability factor to 1.55 and decreased the lateral displacement at the top of the wall to 12 cm. These displacements can be further reduced by increasing the prestress applied on the anchors after installation and increasing the length of the anchor wall. A prestress force of 200 kN/m and a wall length of 14 m satisfies the Serviceability Limit State, ensuring that displacements at the crest and toe of the dyke remain below the permissible limit of 10 cm with a deformation safety factor of 1.3 (POVM, 2020b).



a. Effect of reinforcement method and strength anisotropy b. Effect of design approach and partial factors of safety.

Fig. 4 Factor of safety calculated from step 5 in Plaxis for a residual profile case.

4.Conclusion

This study evaluated the macro-stability of sheet pile reinforced dykes using advanced constitutive models in the finite element method, focusing on Dutch guidelines. The results showed that incorporating cofferdams as an independent structure significantly improves dyke stability, especially when space limits the use of inclined anchors. Cofferdams increase the factor of safety (FOS) and reduce lateral deformations compared to unreinforced dykes. Using the semi-probabilistic approach outlined in Eurocode and Dutch guidelines, the analysis showed that while the FOS satisfied the Ultimate Limit State (ULS), lateral displacements exceed permissible limits for sheet piles without anchoring. Applying anchors and increasing the prestress force effectively reduces displacements, ensuring the dyke meets the Serviceability Limit State (SLS) requirements. This highlights the importance of advanced modeling in the design for dyke reinforcement.

The NGI_ADP_SHANSEP model revealed that accounting for shear strength anisotropy prevents an unconservative design compared to the use of isotropic strength models. Damage mitigation measures (e.g. predrilling) can be accounted for in the model by decreasing R_{int} (weaker shear zone around the structure). The interface reduction factor R_{int} plays a critical role in determining lateral deformations and bending moments more accurately. A decrease in R_{int} leads to significant increase in lateral deformations at the outer crest, inner crest, and toe of the dyke. Furthermore, the effect of the parameter M in the SSC model on the settlement was marginal at the toes of the dyke. Nevertheless, the settlement at the outer crest and the lateral displacement at the inner toe increased by 1.8 times and 5.8 times, respectively, when changing M from the default value 1.467 to 1.2 for R_{int}=0.7.

Declarations

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The datasets generated during and/or analysed during the current study will be available upon request.

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