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# 3D Numerical Analysis of Installation Effects of Displacement Piles in Dikes

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***Abstract*** **-** This study investigates the installation effects of displacement piles used as a dike reinforcement method through advanced finite element modelling in PLAXIS 3D. The analysis builds on a previously developed PLAXIS 2D model, which used an equivalent diameter approach to approximate the pile wall effect. While 2D plane strain models offer computational efficiency and generally conservative estimates, they cannot fully capture three-dimensional effects such as out-of-plane deformations, spatial stress redistribution, and pile group interactions. A detailed 3D model was developed using the same geometry and soil parameters as the 2D model, based on the Bergambacht dike case. A volumetric strain method was employed to simulate the soil displacement caused by pile installation. The results indicate that the 3D model predicts displacements comparable to those of the 2D model at the toe of the dike. Beyond this point towards the polder side, the displacements gradually decrease, reaching values up to 20% lower than the 2D model within the first 12 meters, after which the results converge. The study concludes that the 2D equivalent diameter approach is considered a conservative approach and is suitable for preliminary design and assessment when buildings are located more than five meters from the dike toe. For closer structures or more refined evaluations, 3D modelling is recommended. The findings underline the importance of calibrating structural responses, particularly for embedded beam elements, using pile load test data to ensure reliable results.

***Keywords*****:** dike reinforcement, pile wall, ground displacement piles, finite element method.

## 1. Introduction

Reinforcement of flood defence dikes with pile walls has become an increasingly common solution in densely populated areas, where traditional widening methods are often impractical [1, 2]. Previous studies have demonstrated that displacement piles can significantly enhance dike stability but may also induce substantial soil displacements during installation, posing risks to adjacent buildings. These investigations, however, have largely relied on two-dimensional finite element analyses, which approximate the soil-structure interaction and require correction factors to account for inherently three-dimensional effects [3].

While 2D models provide valuable insights, they are limited in their ability to capture the full spatial distribution of stresses, displacements, and pore pressure changes around individual piles or pile groups. In reality, pile installation and subsequent soil deformation are three-dimensional processes, where soil can move and redistribute around the pile circumference, potentially reducing or amplifying installation-induced effects compared to 2D assumptions.

This paper therefore extends previous work by developing a comprehensive 3D numerical model of dike reinforcement with displacement piles. The model enables a more realistic representation of pile-soil interaction, pile spacing effects, and the influence of discontinuous pile rows. By comparing 2D and 3D results for the same dike case study, this research aims to quantify the limitations of plane strain assumptions and provide improved guidance on safe pile installation near existing buildings.

## 2. Schematization and soil properties

In a previous study, we investigated the effect of installing displacement piles in dikes using PLAXIS 2D [4]. The model schematization shown in Figure 1 was based on the Bergambacht dike case, where extensive laboratory testing was conducted to determine the necessary soil properties. The Soft Soil Creep (SSC) model was used to simulate the time-dependent

behaviour of clay and peat [5], while the Hardening Soil (HS) model was applied to the underlying Pleistocene sand layer. Soil properties are summarized in Table 1. To investigate the installation effect of displacement piles, an approach was utilized in which a lateral volumetric strain is applied to the soil. After reaching the state of the existing dike and building, a thin concrete column in the ground is activated (Figure 1), and then a volumetric strain in the lateral direction ($\varepsilon_{xx}$) is applied to push the surrounding soil outward.

The shortcoming of this approach is that it approximates the 3D pile wall configuration (diameter and spacing) with an equivalent diameter ($D_{eq}$) of the wall in the plain strain model. The value of the applied volumetric strain was calculated for a pile wall with pile diameter $D$=50 cm and centre-to-centre spacing of $l_t$=100 cm as follows:

$$f_{opening} = \frac{l_t}{l_t - l_0} * \frac{4}{\pi} = \frac{100}{100 - 50} * \frac{4}{\pi} = 2.55 \quad (1)$$

$$D_{eq} = \frac{D}{f_{opening}} = \frac{50}{2.55} = 19.6\ cm \quad (2)$$

Where $l_0$ is the distance between the inner edges of the piles as shown in Figure 1. The ratio 4/π represents the ratio of the area of a circle inscribed in a square to the area of the square.

Since the concrete column width in the model is set to $d$=10 cm, and the required lateral soil displacement is 19.6 cm, then the prescribed volumetric strain is given by:

$$\varepsilon_{xx} = \frac{D_{eq}}{d} * 100 = 196\ \% \quad (3)$$

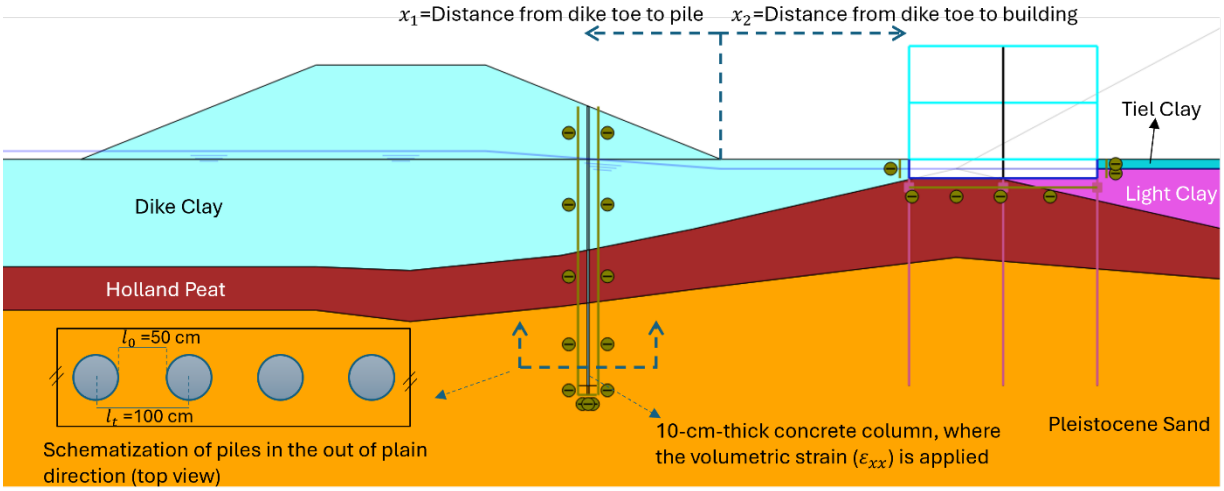



Fig. 1: 2D plain strain model for investigating the installation effect of displacement piles [4].

This installation effect was found to induce significant horizontal displacements in nearby structures, particularly when piles are placed close to buildings or when larger diameters are used. For buildings located less than 15 meters from the dike toe (for this case study), only smaller-diameter piles or greater installation distances could keep displacements within the acceptable threshold.

In this study, a 3D model is developed using the same geometry and soil properties as in the PLAXIS 2D model, to investigate effects that cannot be captured by a 2D plane strain analysis, and to assess whether the equivalent diameter used for the pile wall provides a good approximation of the problem.

Table 1: Soft Soil Creep model properties.

| Parameter | Name | Dike Clay | Holland Peat | Light Clay | Tiel Clay | Pleistocene Sand | Unit |
|---|---|---|---|---|---|---|---|
| **Saturated unit weight** | $\gamma_{sat}$ | 18.45 | 10.3 | 11.86 | 14.23 | 20 | kN/m$^3$ |
| **Modified compression index** | $\lambda^*$ | 0.0654 | 0.247 | 0.178 | 0.127 | - | - |
| **Modified swelling index** | $\kappa^*$ | 0.0077 | 0.0307 | 0.0378 | 0.0204 | - | - |
| **Modified creep index** | $\mu^*$ | 0.0039 | 0.0164 | 0.0119 | 0.0094 | - | - |
| **Poisson ratio** | $\nu_{ur}$ | 0.2 | 0.15 | 0.15 | 0.25 | 0.2 | - |
| **Secant stiffness (triaxial)** | $E_{50}$ | - | - | - | - | 35000 | kN/m$^2$ |
| **Tangent stiffness (oedometer)** | $E_{Oed}$ | - | - | - | - | 35000 | kN/m$^2$ |
| **Unloading/reloading stiffness** | $E_{ur}$ | - | - | - | - | 100000 | kN/m$^2$ |
| **Stress dependency power** | m | - | - | - | - | 0.5 | - |
| **Failure ratio** | $R_f$ | - | - | - | - | 0.9 | - |
| **Cohesion** | $c'$ | 2 | 1 | 1 | 1 | 0.1 | kN/m$^2$ |
| **Friction angle** | $\phi'$ | 27.3 | 29.78 | 31.23 | 18.9 | 32.5 | º |
| **Dilatancy angle** | $\psi'$ | 0 | 0 | 0 | 0 | 0 | º |
| **Interface reduction factor** | $R_{int}$ | 0.73 | 0.67 | 0.67 | 0.67 | 0.62 | - |
| **$K_0$ determination** | $K_0^{nc}$ | 0.4 | 0.34 | 0.64 | 0.6 | 0.426 | - |
| **Pre-Overburden pressure** | POP | 30 | 10 | 10 | 27 | - | kN/m$^2$ |
| **Over-consolidation ratio** | OCR | - | - | - | - | 1.1 | - |

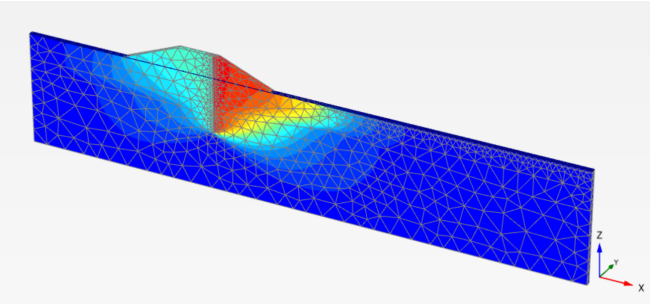
## 3. Effect of the mesh

The 2D plane strain model uses 15-node triangular elements, which provide fourth-order interpolation for displacements, with numerical integration carried out at twelve Gauss points (stress points) [6]. On the other hand, PLAXIS 3D uses 10-node tetrahedral elements, which allow for the modelling of more complex geometries and 3D effects, such as spatial stress distribution, out-of-plane deformation, and pile group interactions [6].

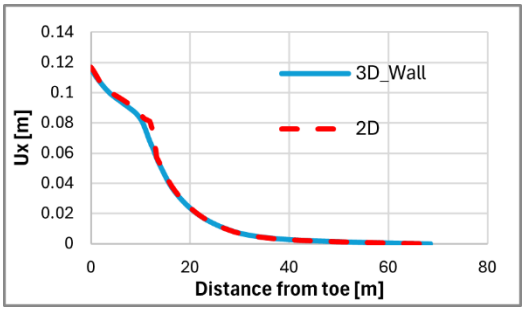
As a first step, to investigate the influence of the difference in elements type in the two models, and without considering the effect of spatial stress distribution and out of plane deformations, a one-meter-wide 3D model which is identical to the 2D plain strain model was built (Figure 2a). The model also includes a 10 cm wide concrete wall where similar volumetric strains are applied as the 2D model ($\varepsilon_{xx}$ =196%).

The lateral displacements are compared between the two models from the toe of the dike up to 69 meters toward the polder side, at a depth of 0.5 meters below the surface. The displacements are in the green field in both cases (the adjacent building is not modelled).

The results show very good agreement between the 2D and 3D models, indicating that the differences in mesh and element type have only a minor influence on the outcome as seen in Figure 2b.



a. Total displacements in the 3D model after applying the 196% volumetric strains to the 10 cm concrete wall.




b. Comparison between the 2D model and 3D one-meter-wide model

Fig. 2: one-meter dike 3D model with concrete wall of 10 cm width for studying the influence of the mesh

## 4. Effect of out of plane deformations in the 3D model

After finding that the mesh and element type have only a marginal effect on the outcome, the pile wall is modelled more accurately in Plaxis 3D. The model includes a pile wall that consists of 40 piles with the configuration shown in Figure 3 with a diameter of 50 cm and centre-to-centre spacing of 100 cm. Following the same approach used in the 2D model, by applying volumetric strain to a thin concrete pile of 10 cm, leads to severe convergence issues in the 3D model when applying high volumetric strains. In PLAXIS 3D, using a small mesh size in a large model is generally not recommended due to several key concerns related to computational efficiency and numerical stability. Therefore, several initial pile diameters ($d$) are tested and compared to find the smallest element size possible that ensures convergence in the calculations. Only half of the pile wall is modelled assuming that the x-z plane is a plane of symmetry. The model extends 60 meters in the y-direction, and 20 piles are modelled as volume elements. The distance from the first pile to the minimum boundary in the y-y direction is 50 cm, and the distance from the last pile to the maximum boundary in the y-y direction is 30 meters. The applied volumetric strain to the piles depends on the initial pile diameter and it should lead to a displacement equal to the pile diameter ($D$=50 cm) in both the x-x and y-y directions. The volumetric strain is calculated from Equation 3. For a realistic construction staging, each pile was implemented in a separate phase by first changing the volume material to concrete and then applying the volumetric strain. Construction starts with the pile closest to the boundary at y=0.5 m. This approach was also compared to a scenario where the volumetric strain was applied to all piles simultaneously.

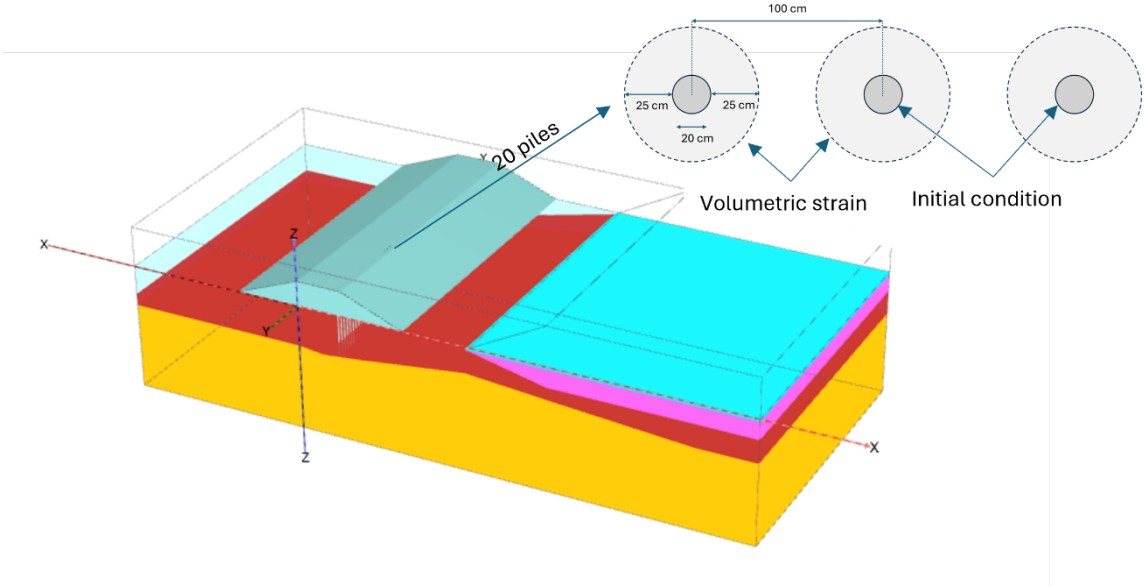



Fig. 3: Pile wall in dike in Plaxis 3D

Both greenfield conditions and the case with a building are assessed. Similarly, half of the building is modelled using plate elements for the walls, floors, and raft foundation. The building is 10 meters long (in the x-x direction) and 5 meters wide (in the y-y direction). Interface elements are applied to the basement plates that are in contact with the soil. Plate element properties are shown in Table 2. The building is supported on piles modelled with embedded beams, having a solid circular cross-section with a diameter of 30 cm, spacing of 100 cm, and stiffness $E$=10*10$^6$ kN/m$^2$. The skin friction is layer-dependent, with a maximum base resistance of 500 kN.

Table 2: Material properties of the building's plate.

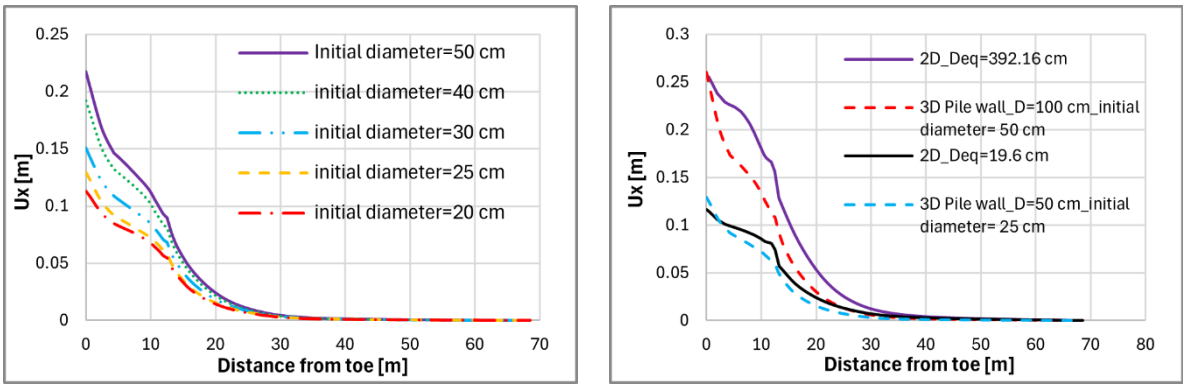
| Parameter | Name | Building plate | Basement plate | Unit |
|---|---|---|---|---|
| **Material type** | - | Elastic | Elastic | - |
| **Weight** | $w$ | 10 | 20 | kN/m/m |
| **Isotropic** | - | Yes | Yes | |
| **Axial stiffness1** | $EA_1$ | $10^6$ | $10^6$ | kN/m |
| **Bending stiffness** | $EI$ | $13 * 10^3$ | $13 * 10^3$ | $kNm^2/m$ |
| **Poisson ratio** | $\nu$ | 0 | 0 | - |

## 5. Results

The smallest initial pile diameter that produced good mesh quality and avoided divergence issues in the model was 20 cm. The initial diameters compared in the model are 50, 40, 30, 25, and 20 cm with volumetric strains applied in the x-x and y-y directions of 100, 125, 166.67, 200 and 250% respectively, as calculated from Equation 3 to reach a displacement of 50 cm.

Using a small initial diameter simulates the displacement of the soil at the pile location more accurately, as the soil at the centre of the pile is displaced by the full pile radius ($R$), while displacement decreases with distance from the pile centre due to soil compaction and a reduction in void ratio. However, this approach has a limitation: the final diameter of the pile is not accurately represented, especially that the updated mesh is not considered in the analysis, allowing for greater spreading in the y–y direction than would occur in reality. The second approach starts with an initial diameter equal to the final pile diameter in the wall. Although this approach provides a more accurate representation of the final geometry in the mesh, it results in significantly higher displacements. This occurs because the soil within the pile location is not allowed to compact (with soil at the edge of the pile being displaced by $R$=25 cm), and the proximity to previously installed piles restricts realistic lateral spreading of the soil in the y–y directions. As a result, exaggerated deformations occur in the x–x direction. Figure 4a shows the horizontal displacements in the x-x direction from the dike toe up to 69 meters away, measured at x=0 (the middle of the pile wall) at a depth of 0.5 meters below the surface for different initial diameters. The comparison shows how horizontal displacements at the toe of the dike increase with larger initial pile diameters in the model. This effect becomes small for initial diameters below 25 cm. Therefore, selecting an initial diameter equal to half the final pile diameter appears to be a reasonable choice that approximates the physical behaviour without compromising numerical stability in the model.

Figure 4b shows a comparison between the 3D model with the configuration shown in Figure 1 with an initial diameter of 25 cm and volumetric strain of 200%, and the 2D plane strain model with the initial diameter of 10 cm and the equivalent diameter calculated from Equation 2 that leads to a volumetric strain of 196%. The results show good agreement between the two models at the toe of the dike. Between 2 and 13 meters from the toe, however, the 2D model appears to overestimate the displacements by up to 16%. Beyond this range, the results converge again, indicating that the 2D equivalent diameter approach provides a conservative estimate of horizontal displacements. Similarly, Figure 4b shows the same comparison for a pile wall with a diameter of 100 cm and centre to centre distance of 200 cm. The equivalent diameter for the plane strain 2D model is 392.16 cm. The initial diameter in the 3D model is half the pile diameter ($d$=50 cm) and the applied volumetric strain is 200%. A similar trend is observed as the previous configuration. However, in this case, the 2D model overestimates the horizontal displacements by up to 30 %.




a. Horizontal displacements with the increasing initial diameter at the toe of the dike at y=0

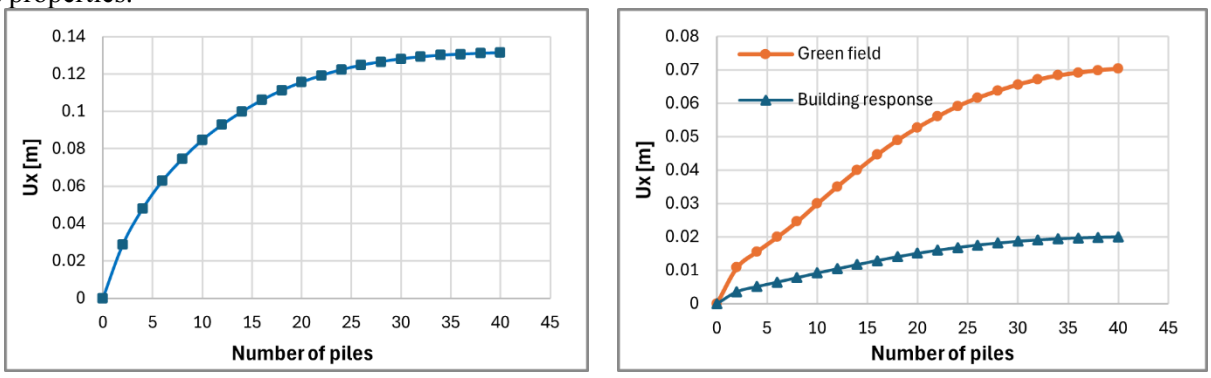
b. Comparison between the horizontal displacement in 2D and 3D analysis

Fig. 4: Horizontal displacement in the dike 3D model due to displacement piles

Since the pile wall was implemented in stages (adding each pile separately) we can examine the effect of the number of piles in the wall on lateral displacement. Figure 5a shows the displacement in the direction perpendicular to the dike at the inner toe. The measurement point is located at the minimum y-boundary, which corresponds to the middle of the pile wall due to symmetry. The results indicate that the maximum horizontal displacement is reached after implementing 15 piles in the model (equivalent to 30 piles in the full pile wall), beyond which any further increase is marginal.

In general, the 2D and 3D models show good agreement, with the 2D analysis providing conservative estimates in most cases, except when the building is located at the dike toe. Nevertheless, the use of displacement piles is not recommended when buildings are situated closer than 5 meters to the toe. Considering the significantly higher computational cost of 3D analyses, particularly for large-scale models, the 2D approach, using an equivalent pile wall diameter, offers a practical and sufficiently accurate alternative for preliminary assessments.

To study the effect of displacement piles on the adjacent building, a similar model was used with 20 piles. Only half of the building was modelled, assuming symmetry along the x–z plane. The maximum horizontal displacement of the building's foundations in the 3D model reached 2 cm, compared to 2.8 cm in the 2D plain strain model. This indicates that the 2D analysis yields a conservative estimate in this case. While the difference in the response of embedded beams to lateral stresses between 2D and 3D analyses is beyond the scope of this study, it is recommended to calibrate this response using pile load tests prior to assessing the effects of displacement pile installation, as the outcome is highly dependent on the structural element properties.




a. Horizontal displacements at the toe of the dike at y=0 with the increasing number of piles

b. Horizontal displacement 10 meters from the dike toe in the green field compared to the horizontal displacement of the building in the same location

Fig. 5: effect of number of piles in the wall in the green field and on the building response

## 6. Conclusion

This study investigates the effects of displacement pile installation in flood protection dikes using a detailed 3D finite element model in PLAXIS 3D, with reference to an equivalent 2D plane strain model previously developed in PLAXIS 2D. The analysis confirms that while 2D modelling with an equivalent pile wall diameter provides a practical and conservative approximation. However, certain 3D effects, such as spatial stress distribution, pile group interactions, and out-of-plane deformations, can only be captured using a full 3D approach.

The comparison between the 2D and 3D models reveals that differences due to mesh type and element formulation are minor. However, the 3D model shows slightly higher displacements near the pile wall. Further from the toe, the discrepancy between the models diminishes significantly and the 2D approach becomes more conservative with higher horizontal displacement. At approximately 40 meters from the toe, both models yield nearly identical displacement predictions.

Modelling the building scenario further highlights the conservative nature of the 2D approach, where horizontal displacements were nearly double those of the 3D model. Despite this, the 2D method remains a valuable tool for preliminary assessments, particularly when the distance between the building and the dike toe exceeds 5 meters.

Due to the computational complexity of 3D modelling, it is recommended to use the 2D method with an appropriately calculated equivalent pile wall diameter for initial designs. For more critical applications, 3D analysis is advised. Calibration of the structural elements, especially embedded beam behaviour under lateral stresses, based on pile load tests is essential for improving accuracy in both modelling approaches.

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

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