Experimental and Numerical Investigations of the Dowel Effect of Pile Grates in Quay Wall Structures

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Abstract: The typical quay wall structures consist of combined sheet pile walls, pile grates and horizontal anchors in north Germany. Measurements have shown that the earth pressure on the sheet pile wall is shielded due to the dowel effect of the pile grates. The shielded earth pressure is transferred through the slab sections (reinforces concrete superstructure) to the anchor system. In the current design recommendation a higher frictions angle is used to take the dowel effect into account. Firstly, 1g small scaled model tests have been conducted to obtain a better understanding of the failure mechanisms of the soil with regard to pile grates. Soil arches behind piles are observed in the model tests. In additional, the development of the shear bands is illustrated by using the Particle Image Velocimetry (PIV) technique. The numerical simulations using the Coupled Eulerian-Lagrangian (CEL) method have been carried out to estimate the resulted earth pressure on the sheet pile wall with proto type scale with regard to the shielding effect of the pile grates. The failure mechanisms shown by the numerical simulations match well with the observations from the model tests. The parametric studies have been performed to estimate the influences of the diameter of the piles, the height of the sheet pile wall, the block length and the pile-wall distance on the dowel effect.

Keywords: Quay wall structure, dowel effect, sand, arching, active earth pressure, Coupled Eulerian-Lagrangian, model test.

1. Introduction

A typical section of a quay structure in north Germany is shown in Fig. 1. Such a construction consists of combined sheet pile walls (consisting of king piles and intermediate piles), vertical piles (generally three rows) and inclined anchors. Measurements and FE-analyses [1] have shown that the earth pressure is shielded from the combined sheet piling due to the dowel effect of the pile rows (shown in red in Fig.1). The earth pressure, which is reduced by the pile rows, is transferred through the slab section (reinforced concrete superstructure) to the anchor system. In current building practice, an increased friction angle is considered to take the dowel effect into account. However, no evidence can be found that the dowel effect has an influence on the friction angle of the soils. The current knowledge of calculating the shielding effect is insufficient. Further research is needed to accurately estimate the shielding effect, so that the combined sheet pile wall can be designed more economically and the anchor system can be designed more securely.

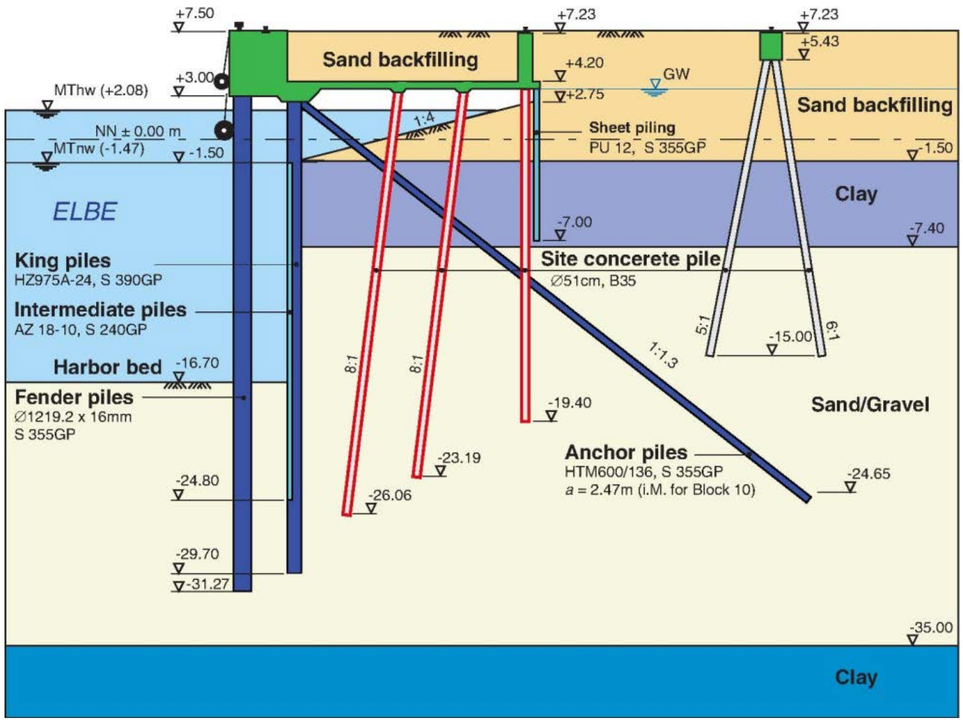


Figure 1. Section of the quay structure Containerterminal Alterwerder (CTA) in Hamburg, Germany [1]

Many experiments, e.g. [2-6], have been carried out to measure the static earth pressure on a wall. A retaining wall facility was built at the National Chiao Tung University (NCTU) [7]. The strain-gauge-type transducers (Kyowa PGM-02KG with 19.6 kN/m^2 capacity) were used to measure the active earth pressures. The shielding effect of row piles behind sheet piling of a quay wall construction has been investigated by Förster [8] through model tests with sand. Based on the theory of plastic deformation an equation to estimate the lateral force acting on the stabilizing piles was obtained by Ito and Matsui [9]. Chen and Martin [10] conducted finite difference analyses using the program FLAC to investigate the mechanisms of the mobilization of resistance for landslide stabilizing piles regarding the arching effect in sand. Experiments [11-14] have been carried out to investigate the stabilizing effect of piles in sand on a sliding slope. Valuable experiments [11-14] have been carried out to investigate the influence of the pile diameter as well as pile-pile distance on the force acting on the pile. In the current German norm (DIN) or design recommendations (e.g. EAU 2004), the shielding effect of row pile has not been taken into consideration by designing a sheet piling.

2. Model tests

A 1g small scale (1:50) model retaining wall, which is similar to the test stand in NCTU, is built in the Institute of Geotechnical Engineering and Construction Management of the Hamburg University of Technology (TUHH). The test stand is shown in Fig. 2.

The model retaining wall is operated by 3 drives, therefore varied wall motions (parallel movement, rotation about wall base, wall top and wall side) are possible. Each drive consists of two brushless DC-servomotors with integrated speed controller (FAULHABER, 3242G024BX4), which are controlled by a computer with the program LabVIEW from NATIONAL INSTRUMENTS. With this program the velocity of the wall movement can be controlled. In this study only the earth pressure caused by a parallel movement of the retaining wall is investigated, so that the velocity of the 6 motors is kept constant for all experiments.

The soil bin has inside dimensions of 82cm x 92cm x 100cm (see Fig. 2) and is separated with a 4.5cm thick transparent acrylic wall from the other. For the experiment concerning active earth pressure in this study, only the first soil bin is used, since the second soil bin is planned for the passive earth pressure experiments in the future. The side walls of the soil bins are made of 4.5cm thick transparent acrylic plates, so that the movement of the sand can be observed from the outside. The bottom of the soil bin is made of a PVC plate with a thickness of 2.0cm.

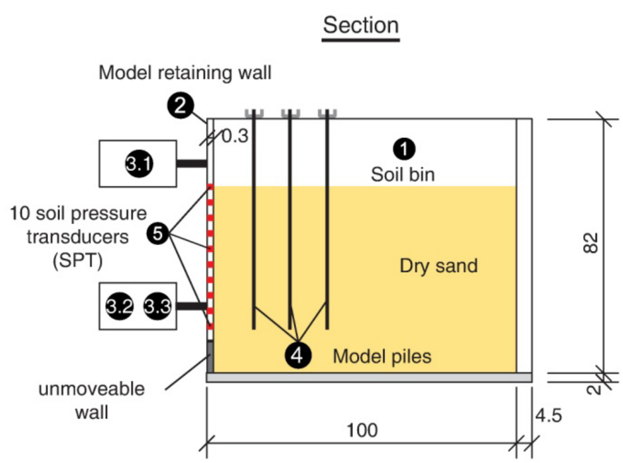


Figure 2. Test stand of the 1g model test to investigate the earth pressure on the model retaining wall, unit [cm]

The model retaining wall is made of a 3mm thick steel plate reinforced with stiffener plates. The flexible wall is 92cm wide and 72cm high. A 10cm high fixed steel plate is located below the flexible wall. The fixed plate holds a 10cm sand layer to reduce the base effect from the soil bin's bottom.

The model piles are made of steel and have a diameter of 1cm (corresponding a prototype pile with 50cm diameter). The model piles are fastened with M10 nuts at a pile carrier fixed on the soil bin.

Both the active earth pressure and the active force on the retaining wall are measured. Ten strain-gauge-type soil pressure transducers (SPT) have been arranged within the central zone of the model retaining wall. Extremely sensitive transducers (Kyowa, PGM-02KG) are used to measure the active earth pressure. The soil pressure transducers are very stiff and installed flush with the surface of the wall to eliminate the local soil arching effect in the near field of the SPT. Three force transducers (Hottinger Baldwin Messtechnik, U10M/25kN) are installed in driving casings to measure the active force. These force transducers are developed for the test with small displacement and even suitable for dynamic applications. The measured earth pressures and earth forces are transferred through the data acquisition system (Hottinger Baldwin Messtechnik, MGCplus) to the PC.

Figure 3. (a) Feeding device; (b) Filling of the bin [16]

The ISS0 sand (Industry Special Sand, washed and sieved) is used in the experiments. The sand is filled into the soil bin by using the feeding device shown in Fig.3 (a). The drop height of the sand is control by using the space plumb. The height of the spread cone to the sand surface is kept constant in one test to obtain a homogeneous sand sample. The drop height is varied from 30cm to 90cm in the tests to assess loose samples as well as dense samples.

3. Results of the selected model tests

A shielding effect of pile rows is present in granular soil. The measure earth pressure coefficients in the case without piles (in red) are larger than those in the case with piles (blue and green), see Fig. 4. The number of pile rows has no influence on the shielding effect.

Soil arches can be observed behind the piles (see Fig. 5). The soil arches distribute the earth pressure to the piles, so that the earth pressure on the retaining wall is reduced.

Table 1. Summary of small scaled model tests carried out by [16] and [17]; *n*: number of pile rows; *b*: pile-wall distance; b_1:pile-pile distance; *L*: block length; *H*: height of backfilling; I_D: density index of sand

Model tests	n [-]	b [cm]	b_1 [cm]	L [cm]	H [cm]	I_D [-]
V1						0.35
V2		without pile			50	0.71
V3						0.43
V4						0.43
M1		9		4		0.45
M2	1	10	-	4	50	0.45
M3		10		2		0.36
M4		6		4		0.45
M5		10		4		0.42
M6	3	10	10	4	50	0.43
M7		14		4		0.41
M8		10		6		0.41

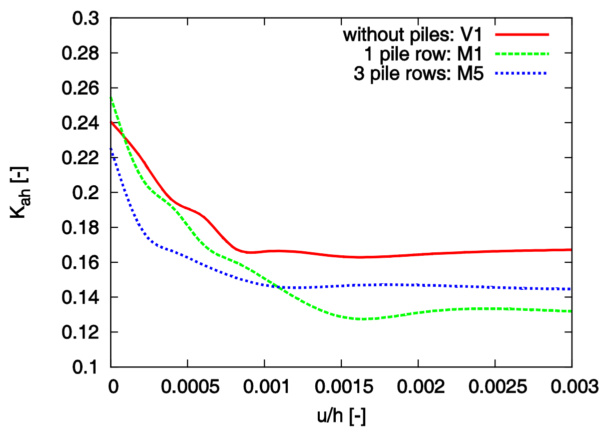


Figure 4. Relationship between Kah and the relative wall movement u/H due to parallel translation of the wall

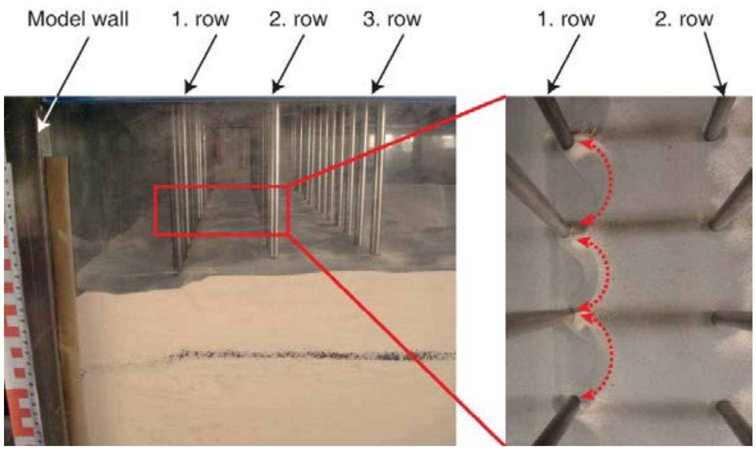
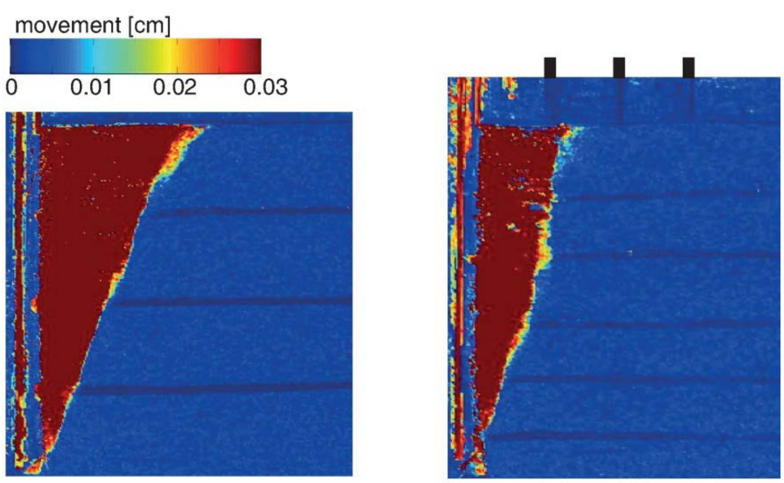


Figure 5. Side (left) and top view (right) of test M6 after a parallel translation of u/H = 0.012 [17]

The Particle Image Velocimetry (PIV) approach is used to illustrate the development of the shear band. The contour plots of the soil movement in test V3 and M6 are shown in Fig. 6. A wedge-shaped soil body can be observed in Fig. 6(a) for the test without piles, whereas a soil body with nearly trapezoidal shape can be observed in Fig. 6(b) for the test with 3 pile rows. The shielding effect is mostly influenced by the first pile row.



(a) V3: without pile (b) M6: with 3 pile rows

Figure 6. Contour plots of the soil movement at critical state with PIV approach: (a) Test V3 without pile; (b) Test M6 with 3 pile rows [17]

4. Numerical model

In numerical analyses the Coupled Eulerian Lagrangian (CEL) method [18] is used to overcome the mesh distortion problem. Several benchmark calculations in Qiu et al. [19] reveal that the CEL method is well suited to solve numerical problems involving large deformations. The geometry and boundary conditions of the FE-models for back-calculation of the model tests are shown in Fig. 7. The CEL modeling is carried out in 3D models, because the 3D element E3D8R is the only available Eulerian elements in Abaqus. Due to symmetry only one half of the block length ($L/2$) is simulated to save the computational time.
The sheet pile wall is simulated as a discrete rigid body and is moved parallel away from the backfilling. The pile rows are simulated as elastic bodies to investigate the influence of the stiffness of pile rows on the shielding effect.

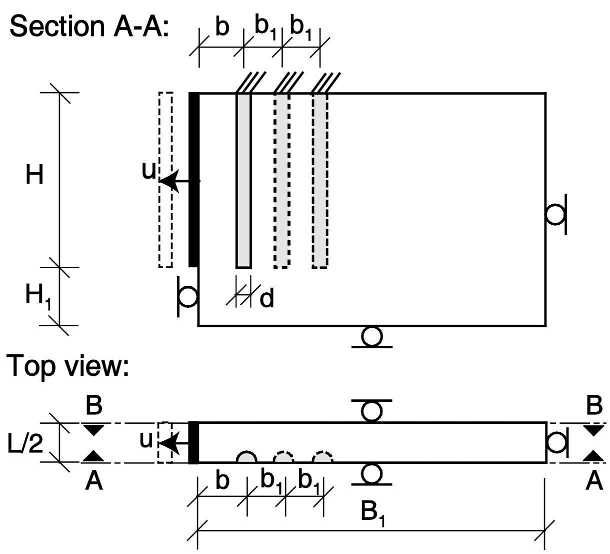


Figure 7. Geometry and boundary conditions of the FE-simulations used for analyzing the earth pressure on a retaining wall

The hypoplastic constitutive model after von Wolffersdorff [20] is used to describe the behavior of sand. The hypoplastic model is well suited to model the nonlinear and inelastic behavior of dry granular soils. Typical soil characteristics like dilatancy, contractancy, different stiffnesses for loading and unloading and the dependency of stiffness on pressure and void ratio can be modeled.

In the hypoplastic model the objective stress rate tensor $\overset{\circ}{\mathbf{T}}'$ is defined as a tensor-valued function $\mathbf{h}$ of the effective Cauchy stress $\mathbf{T}'$, the deformation rate $\mathbf{D}$ and the void ratio e:

$$\overset{\circ}{\mathbf{T}}' = \mathbf{h}(\mathbf{T}', \mathbf{D}, e)\,.$$

Kelm [21] implemented the hypoplastic model in form of a VUMAT-subroutine in Abaqus/Explicit. This VUMAT-subroutine has been used to solve many geotechnical boundary value problems [19, 22, 23, 24] The explicit implementation of the visco-hypoplastic model in form of a VUMAT-subroutine has been carried out by Qiu and Grabe [25] to model the cone and strip footing penetration into clay under drained and undrained conditions. The hypoplastic parameters to simulate the sand can be found in Tab. 2. The effective unit weight of the backfill is set to γ' = 10 kN/m^3. The sand is in a medium dense state and has a density index I_D = 0.5 (e_0 = 0.69). After [26] the initial lateral stress coefficient K_0 is set to 0.5. The contact between the soil material in the Eulerian domain and the model piles as well as the model retaining wall meshed with Lagrangian elements is described using the general contact algorithm. The friction behavior between the soil and the structures is described using the linear-elastic, ideal plastic formulation stated by COULOMB. The friction angle δ between soil and structures is set to 20, which leads to a friction coefficient of tan δ = 0.36.

Table 2. Hypoplastic parameters of Karlsruhe sand after [27]

Parameter	Description	Unit	Value
φ_c	Critical state friction angle	[°]	30
h_s	Granular hardness	[MPa]	5800
n	Exponent	[-]	0.28
e_{d0}	Minimum void ratio	[-]	0.53
e_{i0}	Critical void ratio	[-]	0.84
e_{c0}	Maximum void ratio	[-]	1.00
α	Exponent	[-]	0.13
β	Exponent	[-]	1.05

5. Results of the numerical modeling

The shear band patterns for the simulation with a wall height of H = 25m are shown in Fig. 8(a). After the limit state is reached (u/H = 0.004), a clearer continuous shear plane can be observed. The soil wedge has a nearly wedge-shaped as suggested by COULOMB. The slip plane angle ν is 50°, which is smaller than the theoretical value ν = 56°.

Fig. 8(b) shows the shear band pattern in the case with three piles, which is very similar to the pattern shown in Fig. 6(b). Instead of a triangle shape wedge, the soil wedge has a nearly trapezoidal shape at critical state. The trapeze has a width of b = 5m, in which b is the distance from the wall to first pile row. The slip plane angle ν is 60°, which is larger than the calculated value ν = 50° for the case without pile.

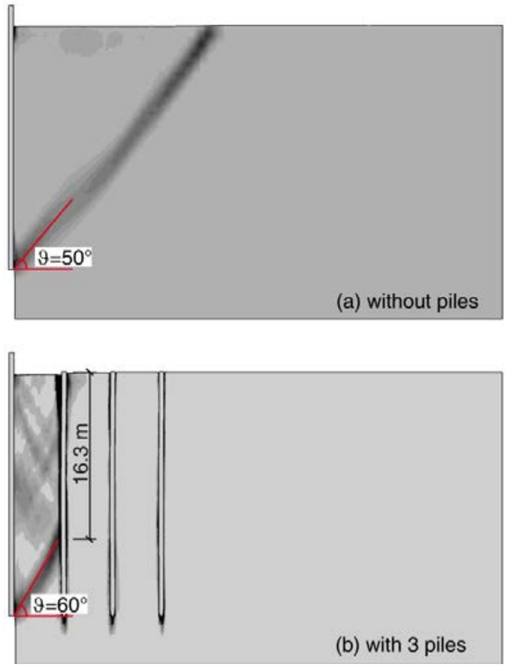


Figure 8. Development of shear band due to parallel movement of the wall; H=25m, L=2m, d=0.5m, b=b_1=5m; (a) without piles, (b) with 3 piles [28]

The deformed piles at the limit state for the case with three elastic pile rows are shown in Fig. 9. The first pile row moves 0.085m in the center of the pile due to a translation of the wall of u = 0.15m. The movement of the piles reduces to 0.044m in the second row and 0.028m in the third row.

The earth pressure coefficient K_{ah} = 0.177 is calculated from the simulation with three rigid piles, whereas K_{ah} = 0.227 is calculated from the simulation without piles (see Fig. 10(a)). A reduction factor η is defined as the ratio of the earth pressure on the sheet piling in the case with piles to without piles:

$$\eta = E_{ah,\,with\,piles} / E_{ah,without\,piles} \,.$$

Thus, η = 0.78 is calculated and the earth pressure on the wall is reduced *22%* due to the shielding effect of the piles. After a translation of about u/H = 0.0015, the friction angle between the backfilling and the wall is fully mobilized and remains constant by the given value of 20° (see Fig.

10(b)). The friction angle between the backfill and the wall depends on the physical properties, i.e. the roughness of the wall and grain shape of the backfill. The dowel effect of the piles reduces the earth pressure on the wall but has no influence on the wall friction angle.

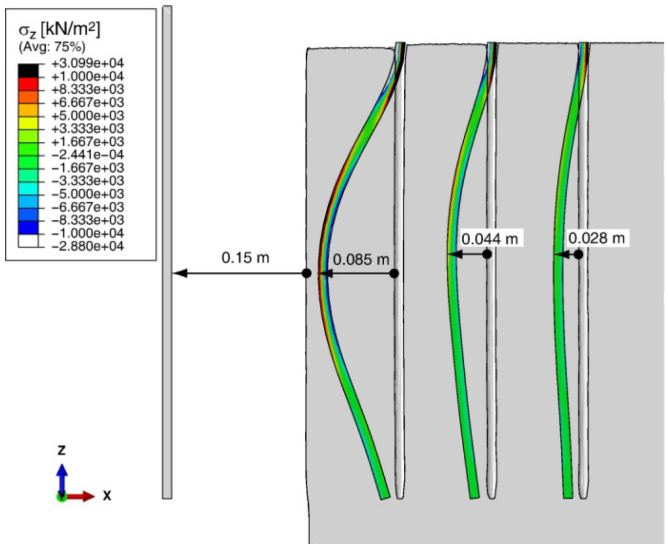


Figure 9. Deformed piles (deformations scale factor =50) due to parallel movement of the wall; H=25m, L=2m, d=0.5m, b=b1=5m, u/H=0.006, with 3 elastic pile rows

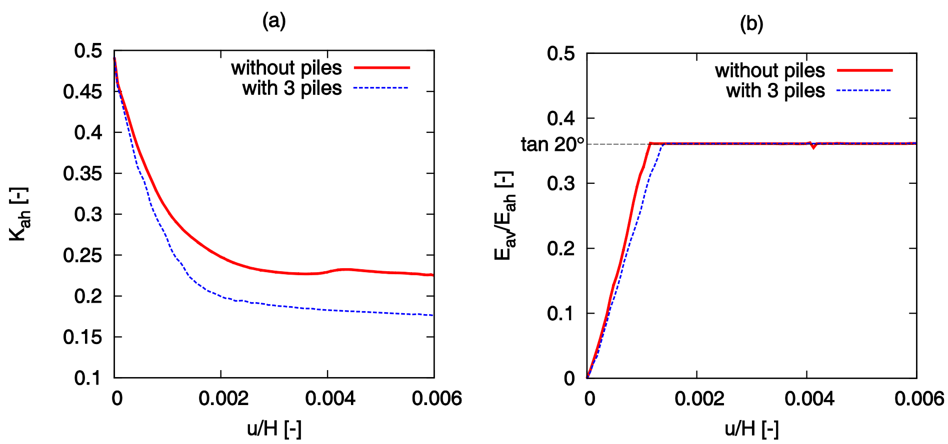


Figure 10. Deformed piles (Relationship between (a) K_{ah} and (b) E_{av}/E_{ah} and the relative wall translation u/H; H = 25 m, L = 2 m, d = 0.5 m, b = b_1 = 5 m

Parametric studied are conducted to investigate the influence of the diameter of piles *d*, the height of the wall *H*, the block length *L* and the pile wall distance *b* on the dowel effect (see Fig. 11). For the piles commonly used in harbor construction, the diameter d has almost no influence on the shielding effect. The reduction factor η reduces with the increasing of the wall height H. Reduction factors $\eta = 0.78$ and 0.82 can be calculated for $L = 1$ and 2m.

It shows that the block length L has little influence on the earth pressure shielding. The increasing of b from 3m to 7m leads to an increasing of the reduction factor by *31%*. It is one of the most important parameters to estimate the shielding effect.

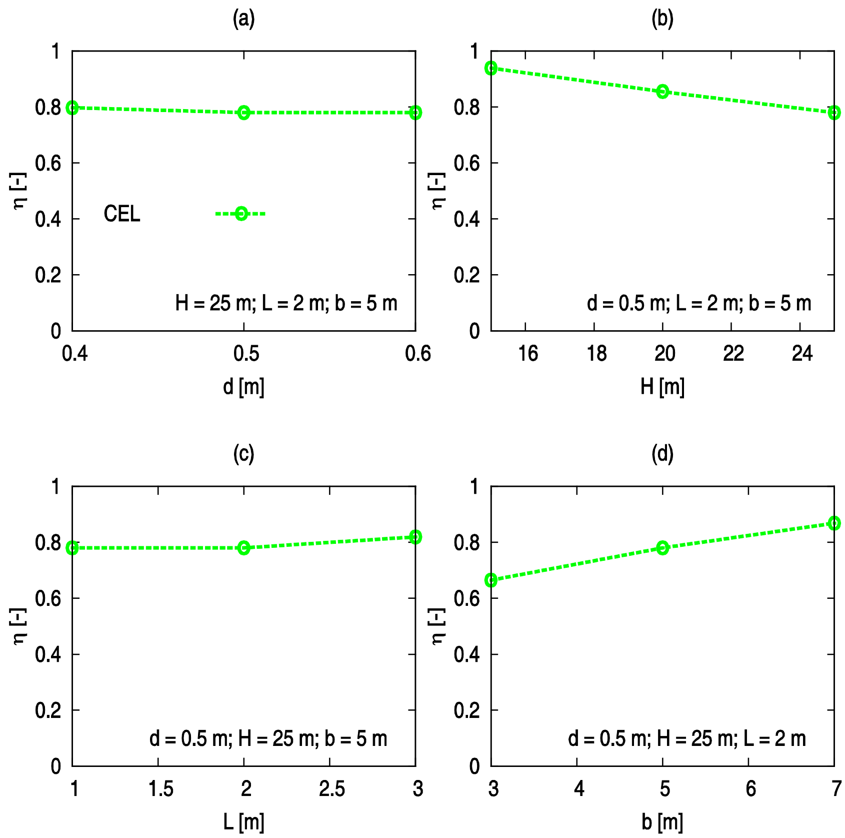


Figure 11. Reduction factor η as a function of (a) the section area of piles in one block *a*, (b) the quay wall *H* and (c) the block length *L*; the friction angle of sand *φ'*=30°, the wall friction angle *δ*=2/3*φ'*

6. Conclusion and outlook

Small scale model tests have been carried out to investigate the dowel effect of the pile row. The shielding effect has been confirmed. The failure mechanisms of the sand behind the model wall

have been observed by using the PIV technique. A wedge-shaped soil body can observed for the case without piles, a soil body with nearly trapezoidal shape can observed for the case with three piles. Because the earth pressure on the model wall is very small and the results are not suitable to be used to quantitatively evaluate the dowel effect due to scale effect. Numerical simulations with prototype scale have been conducted. It shows that the pile rows have great influence on the earth pressure on the wall but have no influence on the wall friction angle.
Based on the observed failure mechanisms and the results of parametric studies, an analytical method will be developed to estimate the earth pressure on a sheet pile wall with regard to the dowel effect of pile grated in quay wall structures.

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