Influence of Surrounding Soil Conditions and Joint Sealing on Seepage Resistance of a Sheet Pile Wall, Three Dimensional Numerical Analyses

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Abstract. The aim of this article is to present 3D numerical calculations results of the seepage resistance of sheet pile (SP) wall with sealed joints. In the present work the leakage through SP wall was determined for one joint of full length. In the analysed example, the SP wall passed through one kind of soil but some conditions (permeability of joint and of surrounding soil) changed depending on the adopted assumptions.

To find the distribution of the total head in the calculation area Laplace equation was used. To determine the velocity field Darcy's law was adopted. In the first step, the discharge flowing through the single joint of SP wall based on 3D numerical simulations was determined. In the next step, the joint resistance was estimated and the discharge was found analytically. The results obtained using these two methods were compared. And the conclusions are as follows: it seems possible to estimate the „joint permeability” coefficient using numerical methods, in some conditions the analytical results are far away from numerical ones, due to the nonlinear pressure distribution along the joint, it is necessary to collect in-situ data to confirm the usefulness and reliability of obtained solutions and to proposed more complete methods of determination of SP wall seepage resistance.

1. Introduction
The seepage resistance of sheet pile (SP) wall depends on: the nominal shape of the lock, which affects the length of the seepage path and distribution of pressure; the width of a single sheet pile, which determines the spacing of the locks; the permeability of surrounding soil; pressure distribution acting on the wall; the stress state on the contact surface of the lock (it can change in the trench housing, it is susceptible to differences in the ground conditions and the quality of the pile driving).

In engineering practice, the water volume flowing through SP joint is an important information, necessary to design an appropriate drainage system or joints sealing. There are some numerical results and analytical method based on the concept of joint resistance [1], [2], [3] proposed to calculate the water discharge flowing through the lock.

This article presents the results of numerical 3D modelling of flow through the one full length SP joint. For the same conditions as in the numerical calculations the discharge was found also analytically based on the concept presented in [1], [2], [3], and the results from both methods were compared.
2. Purpose of the research and adopted assumptions

The research aimed: to determine by analytical and numerical method the amount of water flowing through a single joint of sheet pile wall and to compare the obtained results.

In the analytical and numerical studies, the same calculation scheme was adopted, i.e. it was assumed that a building pit was protected by the steel sheet pile (SSP) wall as in figure 1. The wall was made of steel profiles AZ 18-700 (figure 2).

![Figure 1. Cross-section through a building pit](source: http://www.grodzice.pl/bazacad.html)

![Figure 2. AZ 18-700 profile](source: http://www.grodzice.pl/bazacad.html)

The bottom of the excavation is in the ground, which can be considered impervious, and therefore there is no groundwater flow under the wall or directly below the bottom of the excavation. The excavation has been drained, whereas the groundwater outside the excavation is maintained at a constant \( H \) [m] level (counting from the bottom of the excavation, which is the datum). Hence the water flow through SSP wall is steady. The assumption that groundwater table is flat and constant is the same as in the analytical method described in [1], [2], [3].

The soil outside the excavation is homogeneous and isotropic and it is characterised by the permeability coefficient \( k \) [m/s]. (Acceptance of stratified soil is not a problem, but complicates the interpretation of the numerical results).

It has been assumed that the SSP wall joint is filled by the less or more permeable material (bitumen seal or soil), characterised by the permeability coefficient \( k_z \), and further, similar as authors [4], have been assumed that Darcy’s law remains valid.

In relation to the analytical method presented in [1], [2], [3] (and also shortly described in the next
section), the authors defined explicitly the tightness parameter of joint \( \rho_z \) (in the concept of joint resistance known as the inverse joint resistance) and next the discharge of water flowing into the excavation was calculated. What is important, in the inlet to the lock, along the joint, the hydrostatic pressure distribution was assumed (which is consistent with already mentioned references). Calculations of discharge flowing through the joint to the building pit were made for \( H = 1; 2; 3.02; 4; 5 \) [m] for each variant presented in table 1.

### Table 1. Calculation variants.

| variant | \( k_z \) [m/s] (joint) | \( k \) [m/s] (soil) |
|---------|-----------------|-----------------|
| 1       | \( 1 \cdot 10^{-6} \) | \( 1 \cdot 10^{-4} \) |
| 2       | \( 1 \cdot 10^{-5} \) | \( 1 \cdot 10^{-4} \) |
| 3       | \( 1 \cdot 10^{-4} \) | \( 1 \cdot 10^{-4} \) |
| 4       | \( 1 \cdot 10^{-4} \) | \( 1 \cdot 10^{-5} \) |
| 5       | \( 1 \cdot 10^{-4} \) | \( 1 \cdot 10^{-6} \) |

For numerical calculations, every assumption remains valid except the pressure distribution. In this case the pressure distribution along the joint is not taken a priori but is determined by the adopted mathematical model.

3. Analytical method

According to the accepted assumptions, the starting point is Darcy's law, which allows to determine the flow velocity of water through the joint of SSP wall. With reference to figure 3 it can defined the "elementary" discharge:

\[
q(z) = \frac{k_z (H - z)}{L} \cdot b_z \cdot dz
\]

where:

- \( k_z \) [m/s] and \( H \) [m] are already defined in the previous section, \( z \) [m] is an elevation head of the selected cross-section, thus \( (H-z) \) [m] is the hydraulic head in the selected cross-section and it is equal to the total head difference between the inlet and outlet of the joint at level \( z \), \( L \) [m] - is the shortest filtration path between the inlet and the outlet of the joint, and the width of the joint at the outlet is \( b_z \) [m] (see figure 3).

After integration of equation (1) from 0 to \( H \) the total flow through the joint was obtained:

\[
Q_a = \frac{1}{2} \cdot b_z \cdot k_z \cdot H^2
\]

From the form of equation (2), it can be inferred that:

\[
\rho_z = b_z \cdot \frac{k_z}{L}
\]

Equation (3) is the estimation of the tightness parameter of joint \( \rho_z \) [m/s].
4. Description of the numerical method

To determine the discharge flowing through the joint the analytical method is based on the supposition that the vertical distribution of pressure along the inlet of the joint is hydrostatic. How good is this supposition? To verify this and to determine the discharge the numerical 3D calculations were performed. To define the total head distribution in the area of interest (figure 4) the Laplace equation was used:

\[ \text{div}(k \cdot \text{grad}(h)) = 0 \]  

(4)

where:

- \( h = z + H \) is the total head, \( k \) is the appropriate permeability coefficient depending on the medium (ones for surrounding soil or for material in the joint).

The adoption of equation (4) is of course a simplification but it allows at least to compare the numerical and the analytical results.

The calculation area was 0.337 m long in the \( x \) direction, about 0.53 m long in the \( y \) direction and its height varied from 1 m to 5 m. The example of computing area was shown in figure 4. In this figure, the blue area represents the surrounding soil and the yellow area represents the joint of SSP wall. The blue plane \((x, z)\) at the front represents the SSP wall.

The following boundary conditions were established (see figure 4):

- the plane \((x, y)\) for \( z = 0 \) is impermeable (the bottom),
- at the level of \( z = H \) the total head \( h = H \) (the top),
- the planes \((y, z)\) and the plane \((x, z)\) at the back are permeable (sides and back),
- the plane \((x, z)\) at the front is impermeable except the inlet and "joint channel", nevertheless the walls of the "joint channel" are also impermeable (see figure 3 and figure 4).
- in the plane \((x, z)\) at the outlet the total head \( h = z \).

This boundary problem was solved in Flex PDE [5], which uses the finite element method.

Finally, based first on Darcy’s law:

\[ v = -k \cdot \text{grad}(h) \]  

(5)

the distribution of the velocity of the flow was found and later using the flow rate equation:
the discharge flowing over one joint per unit of time was calculated.

\[ Q_a = \iiint_{\text{outer}} \left( k \cdot \frac{dh}{dy} \right) dA \]  

\[ (6) \]

5. Results and discussions

The numerical tests were performed in 5 variants (Table 1), where each variant differed by a combination of parameters \( k_z \) and \( k \). The calculations of discharge flowing through the joint of SSP wall were made for AZ 18-700 profile (Figure 2 and Figure 3), where the joint parameters are as follows: \( b_z = 3.4 \, [\text{mm}] \), \( L = 111 \, [\text{mm}] \) (see section 3 for parameter definitions). The groundwater level outside the excavation \( H \) was equal to: 1.0; 2.0; 3.0; 4.0; 5.0 [m] in each computation variant.

From formula (3), the tightness parameter of the joint \( \rho_z \) was calculated, and it is equal to \( 3.063 \times 10^{-6} \, \text{m/s} \) for \( k_z = 1 \times 10^{-4} \, \text{m/s} \), and \( 3.063 \times 10^{-8} \, \text{m/s} \) for \( k_z = 1 \times 10^{-6} \, \text{m/s} \). (It should be mentioned that the preliminary results of this issue can be also find in [6]). In the next step using equation (2) and (6) the discharges \( Q_a \) ("analytical discharge") and \( Q_n \) ("numerical discharge") were determined and shown in Figure 5. In this figure, it can be observed the good accordance of the results for the first two variants. This is because the hydraulic head distribution at the inlet of the joint is almost hydrostatic (see Figure 6 and Figure 7 variant 1), which remains in line with the assumption adopted in the analytical method. And further the hydraulic head is hydrostatic because almost all pressure difference \( (h-z) \) responsible for the flow is distributed in filler material which is much less permeable than surrounding soil. However, when the permeability of filler material \( (k_z) \) and the surrounding soil \( (k) \) are the same the values of discharges differ considerably, and for \( H = 5 \, Q_n \) is about 4 times greater than \( Q_a \). In this case, the distribution of the hydraulic head (figure 6 and figure 7 variant 3) deviates
Figure 5. The discharge $Q_a$ ("analytical") and $Q_n$ ("numerical") for five variants
from the hydrostatic distribution and this discrepancy increases with rising the groundwater table. And hence, the analytical method gives an inflated output values.

The case where $k_z > k$ (variant 4 and 5 in figure 5) seems to be the most interesting. The plots indicate that discharges $Q_a$ and $Q_n$ differ significantly. This is due to the fact that the analytical method does not take into account the permeability of the surrounding soil. It should be noted that in variants 4 and 5, $Q_a$ was calculated based on $k$ and not $k_z$ (equation 2). This is because in these two last variants the flow is determined by the medium with lower permeability which in this issue is the soil. This argument is confirmed by figure 6 and figure 7, variant 5. The hydraulic head at the inlet to the joint ($z = 0$) is only about 0.2 m regardless of the groundwater level $H$. Moreover, the hydraulic head in function of $z$ decreases rapidly and on $z = 1.2$ m ($h-z$) is about 1 cm. And such a hydraulic head distribution causes that the flow through the joint is approximately constant as it can be observed in figure 5 variant 5 and partially in variant 4.

**Figure 6.** The evolution of the hydraulic head ($h-z$); variant: 1, 3, 5 by $H$ equal to: 1, 3, 5 m
Figure 7. The field of the total head $h$ in the joint and in the soil by the inlet; $H=5\text{m}$, cross-section on $z=0$; a) variant 1, b) variant 3, c) variant 5
6. Conclusions
In the article, the results of numerical calculations of three-dimensional water flow through the joint of a SSP wall was presented. In the modelling, the actual geometry of the joint was taken into account.

Obtained results show that in the general case the hydraulic head distribution at the inlet to the joint is not hydrostatic. To properly determine the discharge flowing through the joint the "permeability" of the joint and permeability of the surrounding soil should be taken into account. The analytical method is based on the permeability of filler material of the joint and for this reason it works well only if the material permeability is much less than the permeability of the soil.

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