Critical Hydraulic Head Loss Inducing Sandy Cofferdam Failure by Numerical Approach

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Abstract:

On excavating soil with cofferdam in areas with a high ground water level, seepage of water around cofferdam is a problem. When the hydraulic head difference between the up- and downstream sides, H, is too large, seepage failure occurs at the front of the cofferdam wall. The seepage flow influences the stability of the wall where bulk heave, piping, liquefaction or failure by reduction of the earth pressure may occur. Several methods of calculating the stability against seepage failure of the soil have been proposed in the literature, leading sometimes to great differences on the hydraulic head loss inducing failure. Moreover, it is observed that failure mechanisms, highly depending on the limit hydraulic and mechanic conditions, may occur with hydraulic head loss less than the values corresponding to bottom failure. In this paper, the FLAC Code using an explicit finite difference method is used to compute the critical height of water on the upstream side of sheet pile wall embedded in homogeneous and isotropic semi-infinite soil medium that would cause failure.

Key words: Numerical modeling, seepage, cofferdam, failure, heaving.

1. Introduction

The design of cofferdams and deep sheeted excavations is often dominated by the water flow around the sheet piles or propped walls. The seepage flow, induced by lowering the groundwater table, influences the overall stability of the wall and the excavation bottom where bulk heaving or boiling may occur.

There are many published methods [1,2,3,4] for the assessment of bottom stability against seepage failure of soil based on a safety factor with respect to the failure by boiling or heaving, but failure sometimes occurs even in deep excavation designed by these methods [5].

Based on laboratory model tests, Kastner [6] has shown that the instability of the sheet pile wall in the presence of seepage flow may also occur as a result of the reduction of the passive earth pressures in front of the wall. This observation has been confirmed by the variational limit equilibrium method [7] and translational mechanism using numerical modeling method [8].

Other failure mechanisms, highly depending on hydraulic and mechanic boundary conditions, may occur with hydraulic head loss less than the values corresponding to bottom failure. Using the method of characteristics for effective stresses, Houslby in the discussion published by [9] has examined in two different ways the critical head loss that would cause instability by translation and rotation about the toe of the sheet pile wall. The results of the two calculations show that the second mechanism is more critical.

To investigate the critical height of water on the upstream side of sheet pile wall embedded in homogeneous and isotropic semi-infinite soil medium that would cause instability by rotation

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which represent a more realistic mechanism for wall, numerical analysis has been carried out using the code FLAC [10]. After brief review of the literature on the stability of cofferdams and deep excavations subjected to seepage flow of water around the walls, a description of the numerical modeling procedure is presented. An interpretation and discussion of the numerical results obtained from the present analysis are concluded this paper.

2. Overview of previous work

Several methods have been proposed for assessing the risk of failure due to seepage forces. The influence of seepage flow on the stability of retaining excavations was first addressed by [1]. From model tests, he found that within an excavation, the zone of danger of bottom heave is confined to a soil prism adjacent to the wall. Terzaghi approach's gives a value of *H/D* against seepage failure by heaving (Fig. 1) equal to 2.82, while the boiling phenomenon which appears for a critical hydraulic gradient at point E, occurs with a theoretical value of the hydraulic head loss equal to $H/D = 3.14 = \pi$.

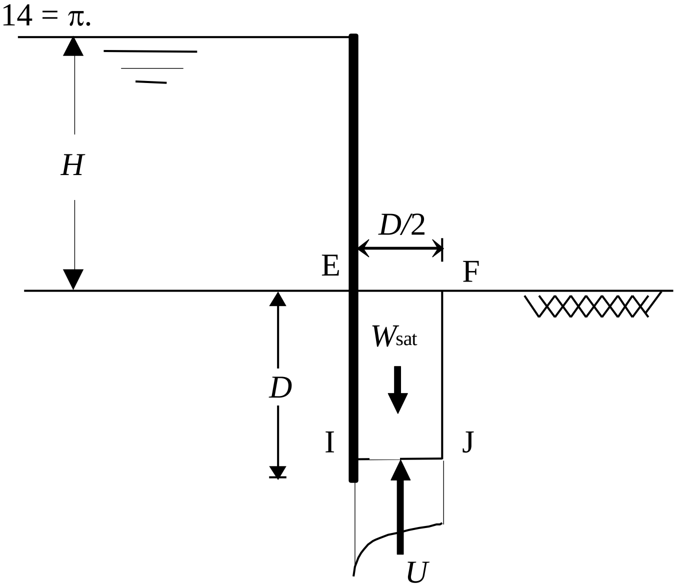

Figure 1. Failure by heaving [1]

Soubra et al. [7] published results of the passive earth pressure coefficients in the presence of hydraulic gradients using the variational approach applied to the limit equilibrium method. Their results show a quasi-linear decrease in the passive earth pressure coefficients K_p for the hydraulic head loss (*H/D*) values varying from 0 to 2.5, for the case of a single sheet pile wall driven into a homogeneous and isotropic semi infinite soil medium. The passive earth pressures are sensitive to the soil–structure interface friction δ but vanish completely at the same value of $H/D = 2.78$ for different interface friction angles. The authors concluded that the angle of friction at the soil–structure has no effect on the *H/D* value causing failure by heaving.
Using the explicit finite difference method implemented in FLAC code and considering a fixed wall which may represent sheet pile with strutted, Benmebarek et al. [11] have identified different failure mechanisms at bottom excavation occurring for critical hydraulic head loss in the

range 2.63-3.16 which depend on the soil and soil/wall interface conditions as described in the literature [1,2,3,4].
From numerical experiments by FLAC code and using translational mechanism, Benmebarek et al. [8] have published numerical computation results of the decreasing passive and increasing active earth pressures by seepage flow around sheet pile for associative and non-associative material. For the passive earth pressures, the comparison with the upper bound solutions given by Soubra for associative material and the stress-caracteristic solutions obtained by Houlsby given in discussion [9] shows a very satisfactory agreement.
Houlsby has presented the critical height of water on the upstream side of the sheet pile wall by both the translation mechanism and the rotation mechanism. The results show clearly that the rotation mechanism involving the equating moments about the toe of the sheet pile wall represent a more realistic mechanism.

From these overviews, it appears that seepage failure at sheet pile wall can arise from different failure mechanisms. The aim of this study is to propose a numerical procedure in order to evaluate the critical height of water on the upstream side of the sheet pile wall without strut.
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3. Numerical modeling

A sheet pile wall with penetration depth equal to D in homogeneous isotropic semi-infinite soil is considered as shown in Fig. 2. The wall is subjected to gradual increasing the hydraulic head loss H until instability occurs using numerical simulation with FLAC code.
The soil behavior is modeled by the elastic-perfectly plastic nonassociative Mohr–Coulomb model encoded in FLAC code. All subsequent results are given for γ_{sat}/γ_w = 2, elastic bulk modulus K = 30 MPa and shear modulus G = 11.25 MPa.

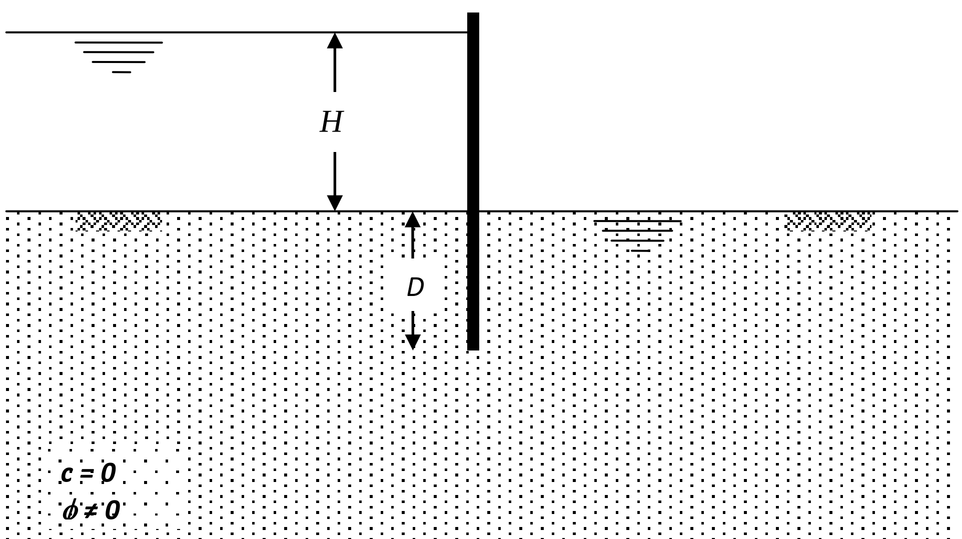


Figure 2. Case study

Fig. 3 shows the mesh (80x40 elements) and mechanical boundary conditions retained for this analysis. The mesh size is fine near the wall where deformations and flow gradients are concentrated. In order to minimize boundary effects, the length from the wall and the depth of the mesh are respectively located at six and five times the wall penetration. As a general rule for the boundary conditions, the bottom boundary is assumed to be fixed, the right and left lateral boundaries are fixed in the horizontal directions. The sheet piles wall is modeled by structural beam elements connected to the soil grid via interface elements described by Coulomb law and attached on both sides of the beam elements. The wall thus acts as an impermeable member. The interface has a friction angle δ, a cohesion c=0 kPa, a normal stiffness K_n=10^9 Pa/m, and a shear stiffness K_s=10^9 Pa/m.

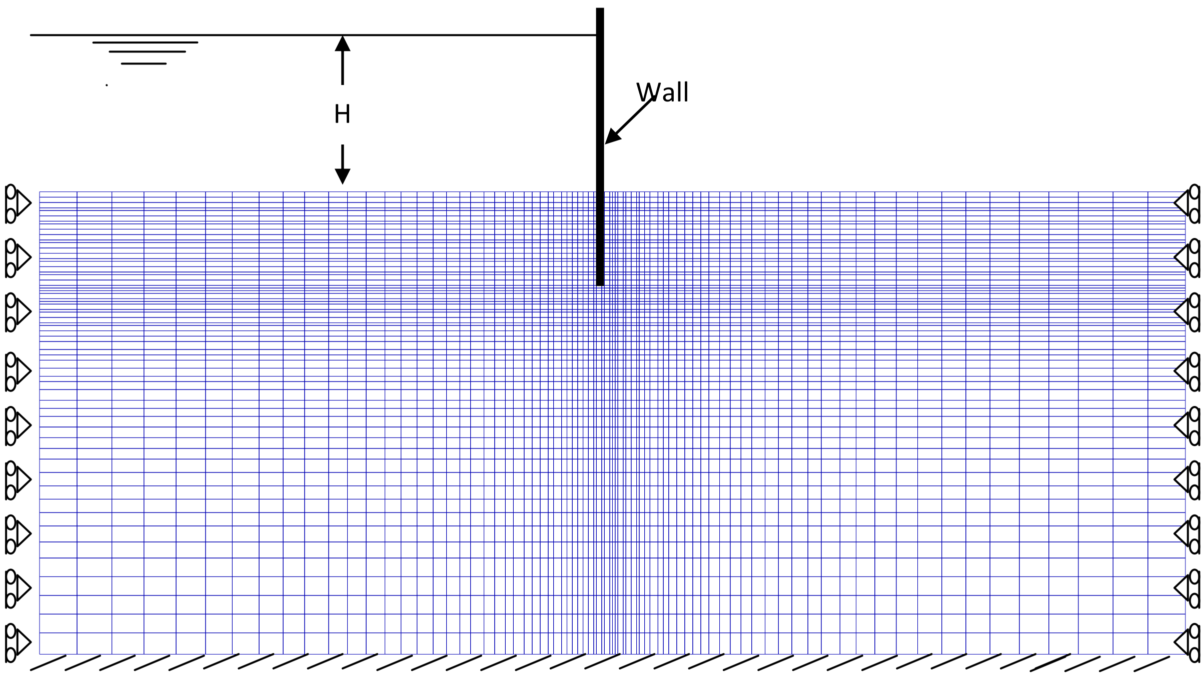


Figure 3. Mesh used and mechanical boundary conditions

Accordingly, in order to develop an acceptable analysis scheme for later computations, preliminary simulations have been carried out by testing the influence of the mesh dimensions, the element size, the boundary conditions and the earth pressure coefficient at rest K_0 as well. The results confirm that variation in practical range of the elastic soil parameters and earth pressure coefficient at rest K_0 do not have any significant influence on the critical hydraulic pressure loss, as the numerical estimation of the bearing foundation capacity factor N_c [12,13].

To identify the critical height of water on the upstream side of the sheet pile wall for the rotation mechanism, the following three simulation procedure steps are adopted:

1. In the first step the initial pore water pressures and initial effective stresses were established assuming that:
   - The groundwater level is located at the ground surface on both sides of the sheet pile (i.e. there is no seepage flow during this stage);
   - the ratio of effective horizontal stress to effective vertical stress at rest K_0 is taken 0.5;

At this stage some stepping is required to bring the model to equilibrium. This is because additional stiffnesses from the structural beam elements representing the wall and interface elements produce an imbalance that necessitates some stepping to equilibrate the model.

2. A hydraulic head loss H is applied to the sheet pile wall as shown in Fig. 2 with boundary conditions in terms of pore pressures as shown in Fig. 4. The corresponding field describing the distribution of the pore water pressures is calculated using the groundwater flow option in FLAC.
3. The mechanical response is investigated for the pore pressure distribution established in the previous step.

Steps 2 and 3 are repeated with gradual increasing of the hydraulic head loss until instability of the wall.

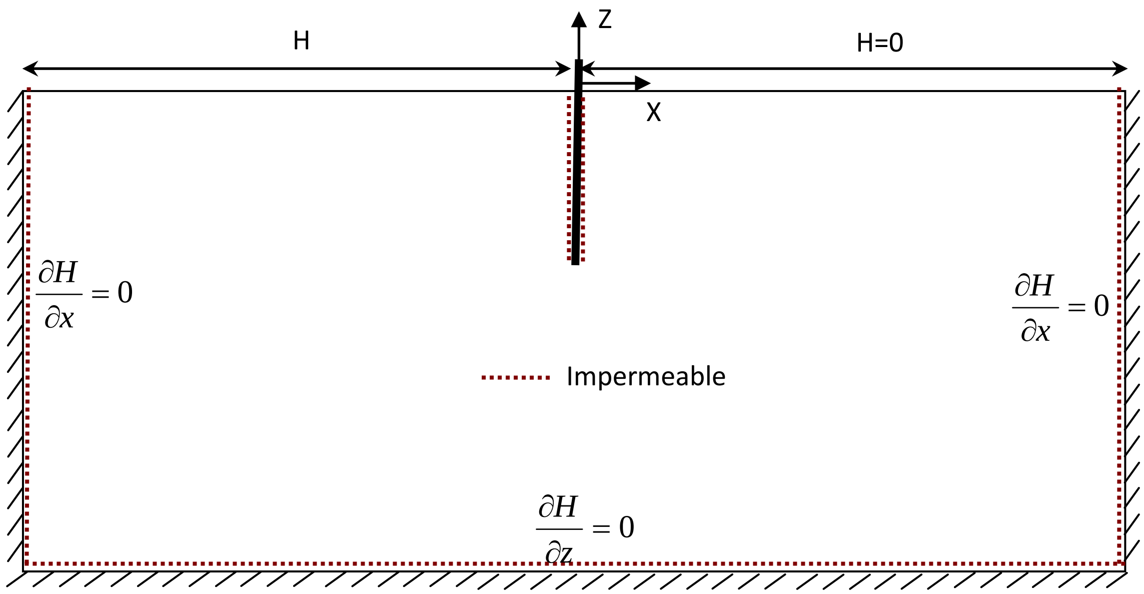


Figure 4. Hydraulic boundary conditions

4. Results and discussion

It should be mentioned, for the mechanical and hydraulic boundary conditions considered in this computations (Figs. 3, 4 and 5), that the all numerical results have shown that the instability is obtained by rotation mechanism. To investigate the critical height of water on the upstream side of sheet pile wall that would cause instability by rotation, table 1 gives the present critical height of water for five values of the internal friction angle ϕ (20°, 25°, 30°, 35° and 40°). For each internal friction angle, three values of dilation angle (ψ/ϕ= 0, 1/2 and 1) and four values of soil/wall interface friction (δ/ϕ= 0, 1/3, 2/3 and 1) are considered in this analysis. The results obtained by Houlsby given in discussion [9] are also reported in table 1 for comparison purpose with the present results in the case of $\psi=\phi$.

The comparison shows a perfect agreement for smooth walls (δ/ϕ=0) in spite of the use of

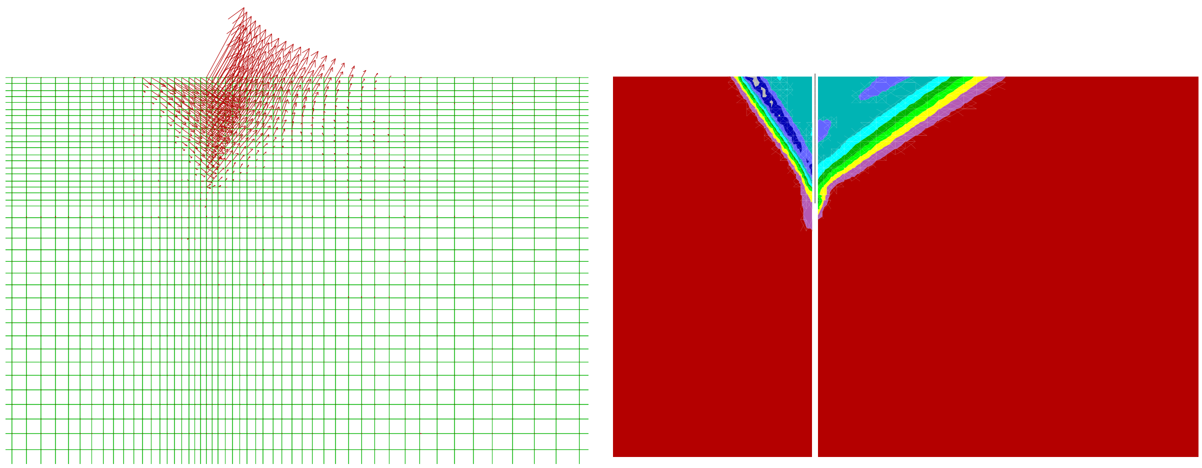
different approaches, and the difference does not exceed 1%.
As observed in Table 1, the critical hydraulic head loss *H/D* increases with the increasing of the soil-wall interface friction δ. For occurrence, for the present results, the increase from perfectly smooth (δ/ϕ=0) to perfectly rough (δ/ϕ=1) reaches 27%, 29% and 36% for ϕ equal 30, 35 and 40° respectively. However, Houlsby results presented in the discussion [9] reach 50% and 81% for ϕ equal 30° and 40° respectively. Hence, the present results are more critical.

Table 1. Critical hydraulic head loss H/D for various governing parameters ϕ, δ/ϕ and ψ/ϕ.

ϕ	δ/ϕ	Present solution (FLAC) $(H/D)_{critic}$			Houlsby [9] $(H/D)_{critic}$
		$\psi = 0$	$\psi = \phi/2$	$\psi = \phi$	
20°	0	0,35	0,35	0,36	/
	1/3	0,40	0,40	0,40	/
	1/2	0,42	0,42	0,42	/
	2/3	0,42	0,43	0,43	/
	1	0,44	0,44	0,44	/
25°	0	0,42	0,43	0,43	/
	1/3	0,48	0,49	0,49	/
	1/2	0,50	0,51	0,52	/
	2/3	0,51	0,53	0,53	/
	1	0,53	0,54	0,54	/
30°	0	0,49	0,50	0,51	0,52
	1/3	0,57	0,59	0,60	/
	1/2	0,60	0,62	0,63	0,67
	2/3	0,61	0,64	0,65	/
	1	0,62	0,65	0,67	0,78
35°	0	0,56	0,60	0,61	/
	1/3	0,65	0,68	0,69	/
	1/2	0,67	0,72	0,74	/
	2/3	0,69	0,74	0,76	/
	1	0,70	0,75	0,77	/
40°	0	0,64	0,67	0,68	0,69
	1/3	0,74	0,80	0,81	/
	1/2	0,76	0,84	0,86	1,00
	2/3	0,77	0,89	0,92	/
	1	0,78	0,91	0,94	1,25

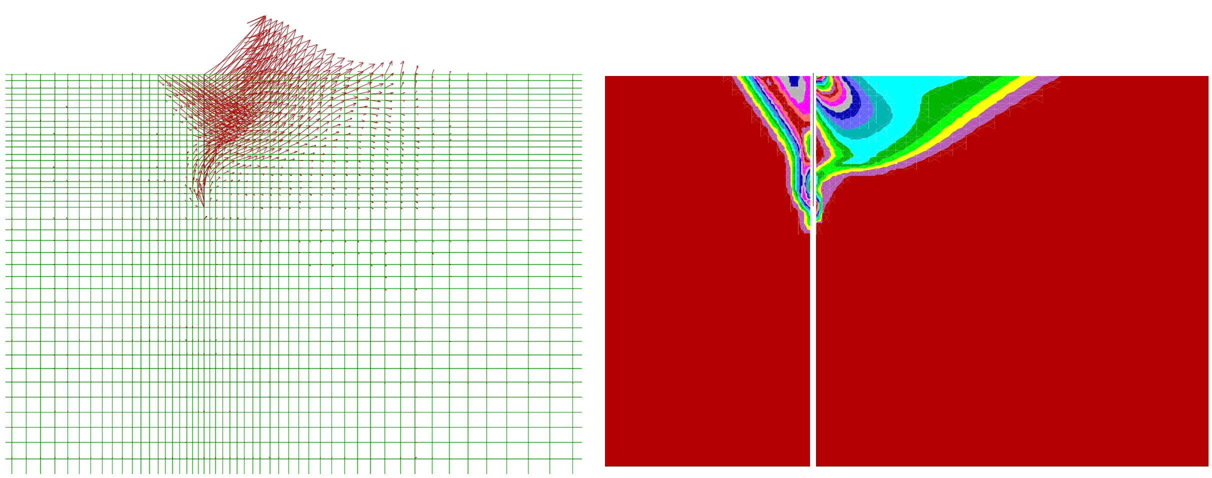
The numerical results of the soil dilation angle effect show a reduction in the critical hydraulic loss with a decrease in the dilation angle for large angle friction values. For instance, the reduction reaches 6%, 9% and 16.3% for ϕ equal 30°, 35° and 40° respectively.
The reduction is most significant for ψ/ϕ included in the interval [0, 1/2] than that for ψ/ϕ included in the interval [1/2, 1].

Figs. 6 and 7 show respectively for two values of the interface friction angle (δ/ϕ=0, 2/3) the failure mechanisms presented by the displacement field and the corresponding distribution of maximum shear strain rates at steady state plastic flow when ϕ= 40°, ψ/ϕ=1/2. These failure mechanisms are obtained when the hydraulic head loss *H/D* reaches respectively the critical values 0.68 and 0.89.



(a) **(b)**

Figure 5. Displacement field (a) and the corresponding distribution of maximum shear strain rates (b) when ϕ= 40°, ψ/ϕ=1/2, δ/ϕ=0 and *H/D* = 0.68

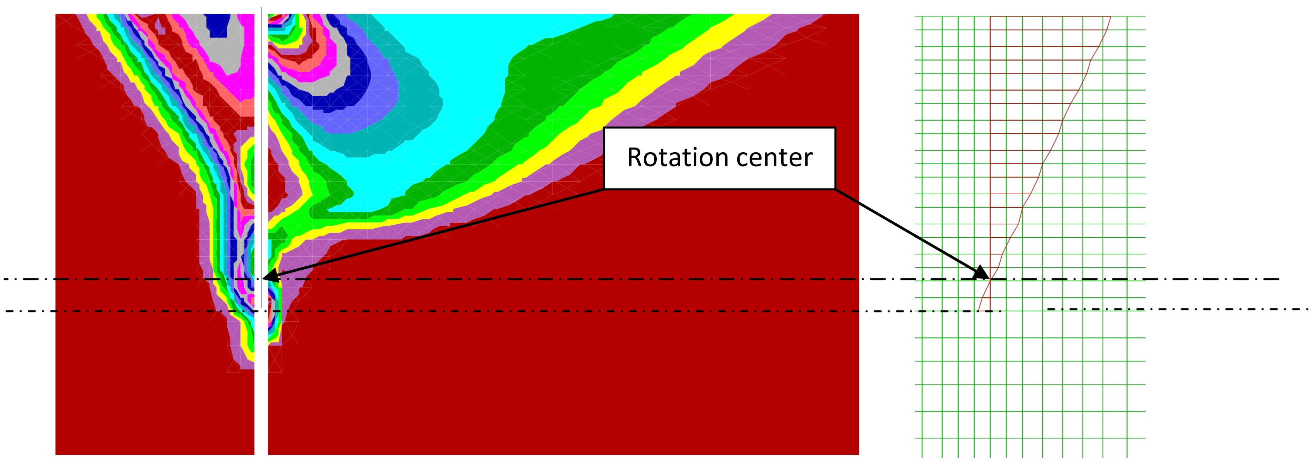


(a) **(b)**

Figure 6. Displacement field (a) and the corresponding distribution of maximum shear strain rates (b) when ϕ= 40°, ψ/ϕ=1/2, δ/ϕ=2/3 and *H/D* = 0.89

For δ/ϕ=0 the failure surface is similar to the planar surface proposed by Rankine [14]. However,

for δ/ϕ=2/3 in downstream, the mechanism is similar to the Prandtl mechanism[15] with a radial shear zone followed by Rankine passive wedge.
As illustrated by Fig. 8, it should be noted that the failure mechanism obtained is a rotational mechanism around a center slightly above the toe of the sheet pile wall about 10% of the penetration depth of the sheet pile. Hence the present approach is more rigorous than the Houlsby approach's.



(a) **(b)**

Figure 7. Distribution of maximum shear strain rates near the toe (a) and wall rotation displacement (b) when ϕ= 40°, ψ/ϕ=1/2, δ/ϕ=2/3 and H/D = 0.89

Conclusions

Numerical computation of the critical height of water on the upstream side of sheet pile wall embedded in homogeneous isotropic semi-infinite soil has been performed using FLAC code. The solutions presented are given for associative and non-associative material. The results of these simulations have shown the following:

- For ϕ=20°, 30°,35°, 40°, rotation failures occur for a critical height of water about H/D=0.36, 0.52, 0.61, 0.69 respectively which are greatly less than 2.82 corresponding to seepage failure by bottom heaving given by Terzaghi approach's.
- The critical height of water increases with the increasing the soil friction angle and the interface soil/wall friction.
- The comparison between the results of the method of characteristics published by Houlsby in discussion [9] and the present results for $\psi=\phi$ shows good agreement for perfectly smooth wall. However the present solutions are more critical for rough walls. For instance, the difference reaches 33% when ϕ=40° and δ/ϕ=1.
- The critical height of water on the upstream side of sheet pile wall decrease with a decreases in the soil dilation angle ψ for large ϕ.

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