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Recent developments on the use of cylindrical steel structures in marine construction

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ABSTRACT: Steel cylindrical structures are widely used for a number of applications. These include supporting offshore wind turbines, masts, oil and gas platforms, and anchors. These structures are economical, applicable and ecofriendly. These structures have been modified into large cylindrical cut-off walls and work platforms to temporarily support construction in marine settings. The cylindrical cut-off walls temporarily enclose off the working area to enable a dry interior, while the work platforms support construction equipment. This study investigated the stability of a large cylindrical cut-off wall by performing a series of finite element analyses of the downstream and upstream ground in medium dense sand. The study varied cylinder diameters, upstream head and embedment depth. The stability was influenced by the flow condition subjected to the cut-off wall. The axisymmetric flow condition was found to be the governing flow condition for the cut-off wall. This flow condition was applied to estimate the exit gradients inside the cut-off wall, which can be used to estimate the factor of safety against piping. Equations have been proposed to guide the evaluations for a stable large cylindrical cut-off wall.

1 INTRODUCTION

In the last few decades, there has been an increasing number of structures constructed in marine environments. These include foundations for bridges, masts, towers and observation decks. Conventional methods have been used to temporarily enclose the working space; the most common one being driven sheet pile cofferdams. Conventional technology results in high construction cost due to the long sheet pile penetrating time and the technicality associated with joint sealing to prevent leakages through joints. In addition, conventional methods pose a high risk to human life and equipment due to the likely collapse of the enclosed ground.

A cylindrical cut-off wall (Figure 1) is a promising technology to temporarily enclose workspaces in marine environments. This technology is economical in terms of installation, easy to apply and causes minimal damage to marine life. The construction sequence is as follows.

A top covered cylindrical ring is lowered to touch the seabed. Suction is then applied inside the closed ring, which draws cylindrical cut-off wall down to the desired depth. The top cover is then removed, and cylindrical ring-segments are subsequently added to raise the cut-off wall above water level. The cut-off wall can be disassembled after works completion and reused. This technology is fast, applicable and cost effective.

Figure 1. Structure of steel cylindrical cut-off wall

Depending on the shape, cut-off walls are mainly subjected to three flow conditions namely: two-dimensional flow, two-dimensionally concentrated flow, and axisymmetric flow.

The stability of the downstream soil is affected by the cut-off wall penetration depth. As the cut-off wall embedment depth increases, the flow length becomes longer and the seepage flow decreases (Sedghi et al. 2010; Yousefi et al. 2016). The ratio of the horizontal permeability coefficient to the vertical permeability coefficient increases, the hydraulic pressure acting on the cut-off wall increases and the flow velocity increases (Koltuk & Iyisan 2013).

The axisymmetric flow condition, common in circular shapes, concentrates flow inward (Tanaka et al. 2000).

Flow into the cut-off wall occurs because the upstream head rises higher than the downstream head. The increase of the upstream head beyond a critical value leads to boiling of the enclosed ground and consequently erosion of the soil particles (Terzaghi 1943). The stability of downstream soils can be evaluated through the factor of safety (McNamee 1949; Terzaghi 1943).

The previous findings discussed above were mainly limited to excavations, embankments, dams, levees, and coastal embankments (Ojha et al. 2003; Lopez et al. 2014). They may not give realistic seepage predictions in large steel cylindrical cut-off walls.

The current study focused on a large cylindrical cut-off wall with an aim of devising easy approaches to evaluating the stability of the enclosed soil to ensure a safe work environment.

2 NUMERICAL MODELLING

2.1 *Analysis conditions*

Table 1 shows the analysis cases considered and Figure 2 defines the parameters used in the study.

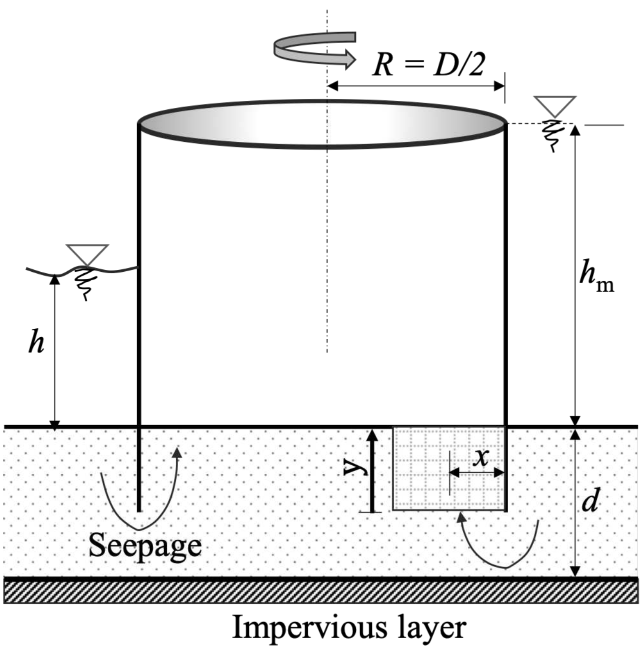

Figure 2. Definition of parameters

These included the cut-off wall diameter, R (m), embedment depth, d (m), upstream water head, h (m), and maximum upstream head (hm = 20 m). The thickness of the soil layer, D was taken to be 40 m. Nondimensional quantities d/D, h/hm, and R/hm were used (Munson et al. 2002).

Table 1. Analysis conditions

Parameter	Dimension
Depth, *d/D*	0.1, 0.2, 0.3, 0.4, 0.6, 0.8
Wall radius, *R/hm*	0.2, 0.4, 0.6, 0.8
Water head, *h/hm*	0.25, 0.5, 0.75, 1.0

2.2 *Finite element modelling*

Numerical modelling was performed using ABAQUS (2012), It is assumed that the external water level is always constant and steady state flow occurs under the axisymmetric conditions. The ground was assumed to be a uniform homogeneous medium dense sand with soil properties shown in Table 2. The ground was modeled using 4-node axisymmetric quadrilateral, bilinear displacement, bilinear pore pressure (CAX4P) elements. The cut-off wall was modelled as a V-shaped cut with impervious surfaces. The lateral sides of the model were made impermeable by default. To induce flow, the surface of the ground inside the cut-off wall was assigned zero pore water pressure. The bottom boundary of the sand layer was assigned an impervious boundary condition to simulate impervious rock strata.

The flow analysis was performed while changing the value of the upstream head. The mesh size gradually decreased from the lateral boundary to the vicinity of the model i.e. the mesh density increased near the cut-off wall where the flow was concentrated.

The thickness of the cutoff wall was set to 0.03 m, and, since only the flow analysis was performed, the deformation was assumed to be constant.

Table 2. Soil properties (EAU, 2004)

Parameter	Value
Buoyant unit weight, γ' (kN/m^3)	19
Internal friction angle, φ' (°)	35
Poisson's ratio, ν	0.25
Cohesion, c (kN/m^2)	0.1
Hydraulic conductivity, k (m/s)	$1x10^{-4}$

2.3 *Validation*

The simulation was validated by simulating a published case of sheet pile walling shown in Figure 3 (Craig 2004) and pore pressure values along the sheet pile wall compared.

The relative error between the FE analysis and Craig's analytical solution (Figure 4) was 0.4% which is reasonably small (< 10%). Therefore, the numerical modelling of seepage analysis was considered to be reliable. Seepage flow into the circular cut-off wall is axisymmetric, implying that, an axisymmetric flow condition applies to the cylindrical cut-off wall.

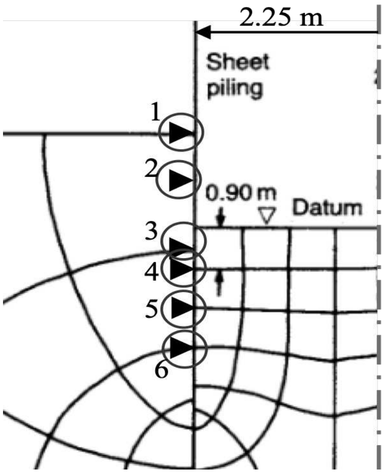

Figure 3. Theoretical data (Craig 2004)

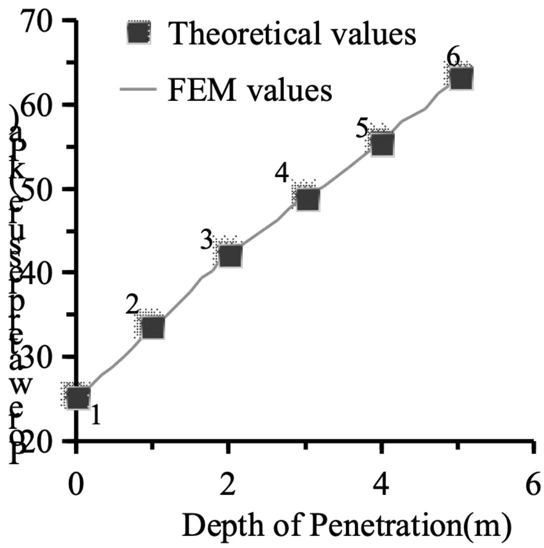

Figure 4. Comparison of FEM values with theoretical values

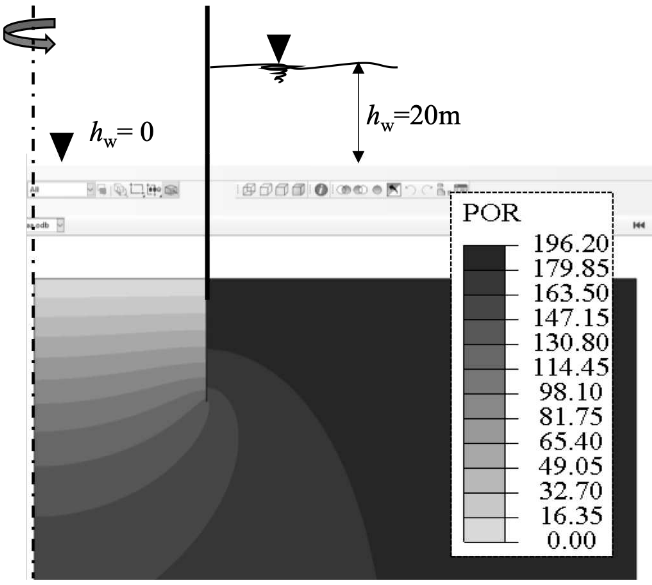

Figure 5. Equipotential lines (R=16m, d=12m)

Figure 5 and Figure 6, respectively show an example of equipotential lines and seepage flow lines in the upstream and downstream faces of the cut-off wall. The water pressure was applied to estimate the exit gradients inside the cut-off wall.

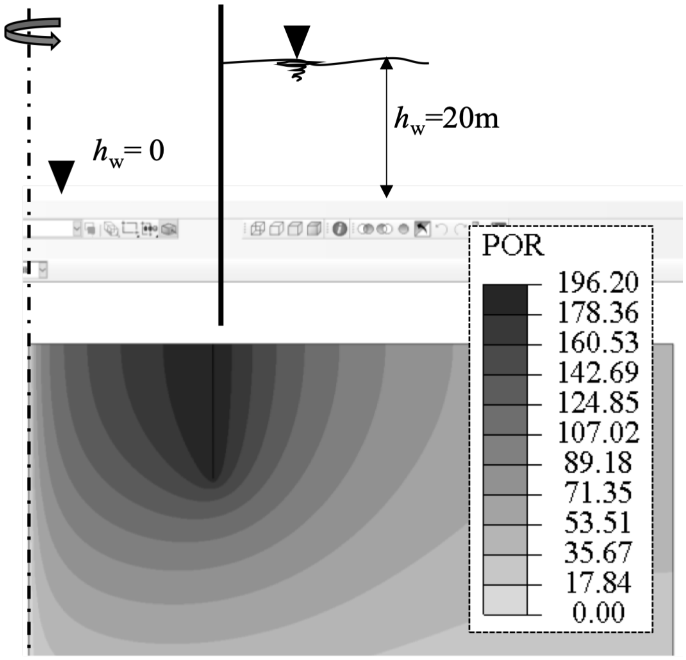

Figure 6. Flow lines (R=16m, d=12m)

3 RESULTS AND DISCUSSIONS

3.1 *Seepage velocities*

Seepage velocities vary according to the flow condition induced by the cut-off wall. Figure 7 shows an example to illustrate seepage velocity under axisymmetric flow condition. All cases showed similar trends. x is the lateral distance of the soil elements from the inner face of the cut-off wall. The seepage velocity, v_n in the downstream soil was calculated by dividing the flow velocity by an average porosity value of 37.5% for sand (Yu et al., 2015). The closer to the wall, the faster the seepage rate. Seepage flow velocities are largest in the inner ground adjacent to the wall tip.

The seepage flow velocity under the axisymmetric condition was respectively about 1.5 times and 2 times larger than that estimated by Ssenyondo et al. (2017) for two dimensionally concentrated (2-DC) flow condition and two-dimensional (2-D) flow condition. It implies that downstream soils under axisymmetric flow conditions are the most vulnerable to boiling or piping since they are subjected to the largest seepage flow velocities. Figure 8 shows the percentage reduction in seepage due to the increase in bucket diameter and penetration depth.

Seepage inside the cut-off wall decreased significantly with the cut-off wall penetration depth compared with the increase in cut-off wall diameter. The seepage reduction was estimated from the quantity of water discharged inside the cut-off wall.

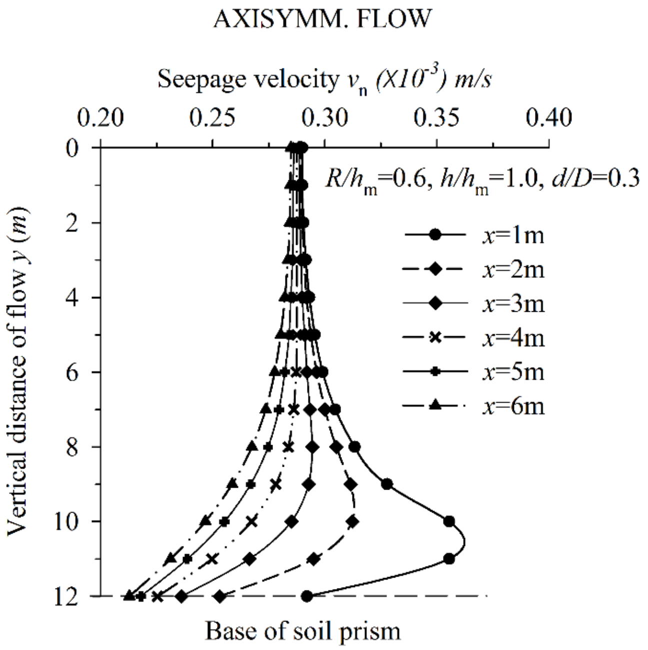

Figure 7. Seepage velocities in a cylindrical wall

Figure 8 further shows the estimated safe penetration depth according to cut-off wall diameter.

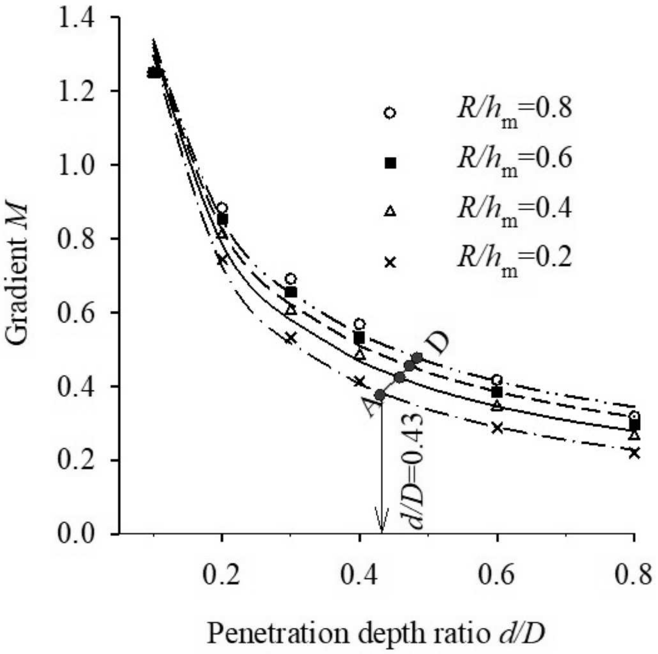

Figure 8. Estimation of safe penetration depth

The optimum penetration depth is indicated on the line A-D for d/D = 0.43, 0.46, 0.47, 0.49 at R/h_m = 0.2, 0.4, 0.6, and 0.8. The values for optimum penetration depth were obtained by applying the tangent intersection method (Graham et al., 1982). The values for the seepage gradient M were obtained from discharge at various stages of penetration.

The average safe penetration depth is d/D = 0.463. This value is comparable to the limiting penetration depth ratio of 0.46 experimentally estimated by Yousefi et al. (2016).

3.2 *Evaluation of the exit gradients*

The analysis of equipotential lines can guide the estimation of exit gradients inside the cut-off wall. Figure 9 is an example to show the estimation of the exit gradient using equipotential lines inside the cut-off wall. The exit gradient ie = Δh/Δs, where Δs is the separation between the equipotential lines inside the cut-off wall at the downstream face, u1 and u2 are pore pressure contour lines, and Δh is the difference in head between the contours (h1-h2). From u = γ'h, it follows that h1=u1/γw' and h2 = u2/γw'.

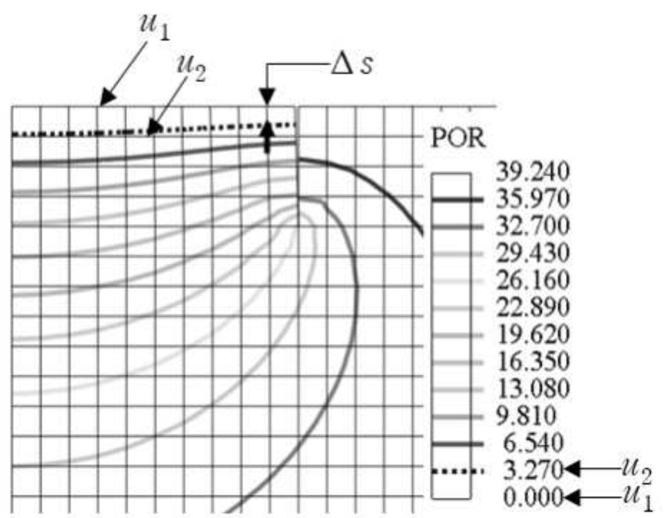

Figure 9. Calculation of the exit gradient inside a cut-off wall

The exit gradient was estimated at each stage of cut-off wall penetration depth considering varying cut-off diameters (R/h_m = 0.2 — 0.8) and upstream water head (h/h_m = 0.25 — 1.0).

Figure 10 shows an example for h/h_m = 1.0). Similar trends were observed for all cases. The exit gradient decreased with the increase in penetration depth and cut-off wall diameter. The exit gradient is significantly decreased by the increase in penetration depth.

All other cases of h/h_m = (0.25, 0.5, 0.75) showed similar trends as in Figure 10, and thus not shown here. Following the analysis of all cases, equation (1) is proposed to simplify the estimation of the exit gradient inside the cut-off wall. Equation (1) is derived from the relationship between the normalised exit gradients and cut-off wall penetration depth as shown by Figure 11.

$$i_e/i_0 = 0.8655 \times (d/D)^{-0.8} \quad (1)$$

where $i_0 = i_e$ at $d/D = 0.8$, and can be estimated by applying equation (2)

$$i_0 = i_t\{1.423 - 0.532 \times (R/h_m)\} \quad (2)$$

$i_t = i_e$ at $d/D = 0.8$ and $R/h_m = 0.8$ (Fig. 12)

$$i_t = 0.44 \times [h/h_m] \quad (3)$$

Preliminary analyses were carried out to compare the factors of safety calculated by Terzaghi's expression (Terzaghi, 1943) and McNamee's expression (McNamee, 1949). The piping safety factor calculated by the two formulas showed almost the same result. However, according to Terzaghi (1943), the factor of safety (F_s) is the ratio of the submerged weight of the soil (W') to the total upward force (F) acting at the base of the soil prism. Using Terzaghi's expression requires prior estimations for the volume of the soil prism, the average water head acting at the base of the soil prism, and the cross-sectional area of the soil prism, which cannot be easily accurately predicted.

Therefore, in this study, the piping safety factor was calculated by using Equation (2) that uses the runoff hydraulic gradient.

The calculated value of the exit gradient is then applied to equation (4) of McNamee (1949) to estimate the factor of safety (F_s) of the cut-off wall.

$$F_s = i_c/i_e \quad (4)$$

where i_c = critical hydraulic gradient calculated from:

$$i_c = \frac{\gamma'}{\gamma_w} = \frac{G_s - 1}{1+e} \quad (5)$$

where e = void ratio of the soil; G_s = specific gravity of the soil.

The proposed equation was found to give reasonable predictions for the exit gradients. The relative error between the FE and calculated values averaged 4%, which is reasonable.

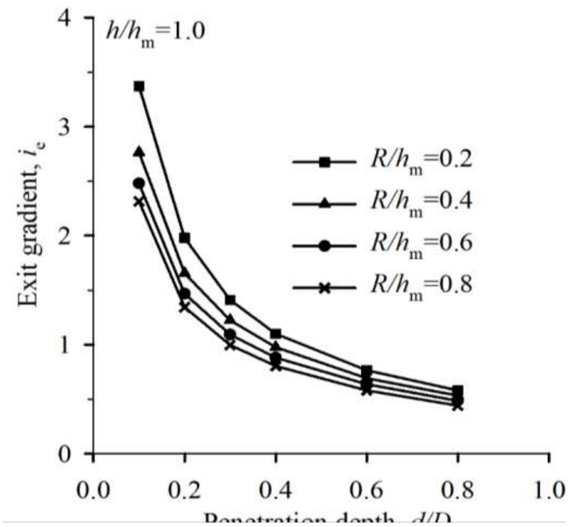

Figure 10. Trend of the exit gradient at different stages of penetration and cut-off wall radius at h/h_m = 1.0

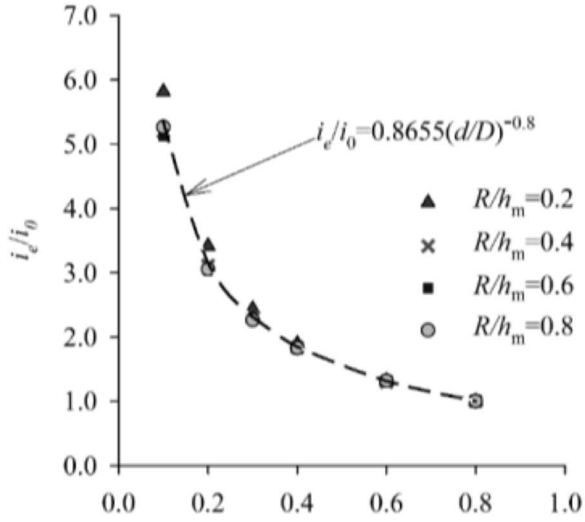

Figure 11. Exit gradient at different stages of penetration

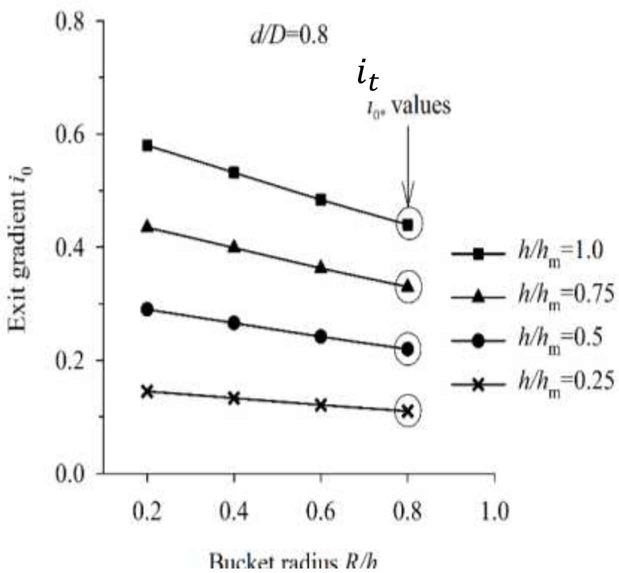

Figure 12. Values of the exit gradient (i_t)

4 CONCLUSIONS

This study investigated the application of large steel cylindrical structures as temporary cut-off walls for marine works. The following conclusions can be drawn.

The two dimensional and two-dimensionally controlled flow regimes under estimate seepage in steel cylindrical cut-off walls. The axisymmetric flow condition can reasonably estimate seepage in cylindrical steel cut-off walls.

The seepage velocities decrease with the increase of seepage length from the tip of the cut-off wall to the downstream surface inside the cut-off wall.

The seepage decreases with the increases in penetration depth and radius of the cut-off wall. The increase in penetration depth significantly reduces seepage compared to the increase in cut-off wall diameter.

The safe penetration depth of the cut-off wall is approximately 0.46*D*, where D is the thickness of the soil layer in which the cut-off is embedded.

An equation has been proposed to estimate the exit gradient inside (downstream face) the cut-off wall. The equation takes into consideration the effects of penetration depth, bucket radius, and upstream water head. The exit gradient once estimated can be applied to estimate the factor of safety of the cut-off wall.

5 RECOMMENDATIONS

The following recommendations are proposed basing on the limitations of this study.

The soil condition has been limited to medium dense sand. However, marine soil conditions and type vary from place to place. The ground can be dense or very dense sand, clay, silt or a mixed soil profile. Further studies need to be carried out to address the performance of steel cylindrical cut-off walls in various soil types and conditions.

The study assumed that no deformation will occur in the downstream soil, however, large seepage forces may induce deformation of the enclosed soil. Further studies can be carried out to address the effects of seepage forces coupled with downstream soil deformations.

The findings of this study have been derived from finite element simulation of the cylindrical cut-off wall. Experimental studies need to be carried out to supplement the findings of this study. Although 1-g experimental testing is easy and less costly to work with compared to full-scale experimentation, the findings may not represent the actual behaviour of the real field problem. Nevertheless, the findings of 1-g experimental testing can be used to validate the finite element simulation.

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