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Assessment of empirical equations for predicting scour depth around gravity base foundations

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ABSTRACT: Scour development around offshore foundations, particularly the depth of scour hole, is a critical concern for structural stability. Despite extensive research on scour around offshore monopile foundations, there is a paucity of empirical equations tailored for Gravity Base Foundations (GBFs). This study addresses this gap by compiling and evaluating empirical solutions for predicting scour depth around GBFs. Some equations are specifically designed for GBFs, while others are adapted from methods used for compound and complex bridge piers (CBPs) due to their shape similarities with GBFs. Additionally, the study reviews existing equations for the temporal evolution of scour depth. The performance of these equations is assessed using results from a tank test campaign conducted by IH Cantabria for the ELISA GBF. Although this experimental work examined scour hole development around GBF under various environmental conditions, the current-only unprotected scour tests are considered as the reference experimental data. The findings provide scattered results by assessment of empirical equations, contributing to improved predictive capabilities for scour depth around GBFs.

Keywords: Offshore foundations; gravity base foundation; scour; empirical equations

1 INTRODUCTION

Gravity Base Foundations (GBFs) are support structures with flat bottoms that rely on their own weight to resist overturning moments and sliding shear forces. Typically constructed with reinforced concrete, they come in various shapes, sizes, and weights based upon specific design requirements (Russell, 2020).

A critical concern with offshore structures is the development of scour around the foundation, often necessitating the deployment of protection measures. Increased flow acceleration and turbulence generated around the structure result in the localized transport of sediment, creating gradients in sediment transport rates that in turn, cause scour (Hoffmans and Verheij, 1997, Whitehouse, 1998). The most discussed aspect of scouring has been determining the depth of the scour hole. As there is no fully theoretical equation available to calculate it, one approach is to develop (semi-) empirical solutions. While there has been extensive research conducted to calculate scour depth for monopile foundations, there are comparatively limited research available related to GBFs.

This study aims to compile and evaluate existing formulations for calculating equilibrium scour depth and the temporal evolution of scour around gravity base foundations (GBFs) and compound and complex bridge piers (CBPs), comparing them with results from a tank test campaign by IH Cantabria for ELISA GBF (Sarmiento et al., 2024). Before analysing these equations, the experimental conditions of the tank tests will be discussed in detail. Following this, a brief review of empirical equations for predicting scour depth and its temporal evolution for GBFs and CBPs will be presented. Finally, the performance of the equations will be assessed through comparison with the experimental results.

2 EXPERIMENTAL CONDITIONS

The Environmental Hydraulics Institute of Cantabria conducted an extensive test campaign (Sarmiento et al., 2024) to study scour development around the ELISA GBF, designed by Esteyco for the Empire Wind offshore wind farm project, and to evaluate the effectiveness of proposed scour protection systems. As part of the physical experiments, "unprotected scour tests" were performed to observe scour formation around the GBF without any protective measures.

The prototype of ELISA GBF consists of a cylindrical base with diameter of 40 m and height of 8.8 m connected to a hexagonal pile (tower) with maximum width of 11.2 m. Figure 1 illustrates the geometry and dimensions of the scaled model. Considering the geometry of the structure, the target water depth, the environmental conditions, and the dimensions of facilities, a 1:35 geometrical scale was chosen resulting in a model base diameter of 1.143 m and model water depth of 1.029 m.

Based on its dimensions, the basin was divided into two separate platform to run two different configurations simultaneously (Figure 2). The sand pits in both platforms are 11.5 m long, 8 m wide, and 0.25 m deep.

For a sandy seabed at prototype scale (median grain size of d_{50} = 0.45 mm), Froude scaling results in sediment particles with cohesive behaviour. Since cohesive and non-cohesive materials behave differently in scour development, the grain size in the experiments must be larger than the threshold of sandy soils to replicate sandy soil behaviour. Considering available resources and constraints, fine sand with d_{50}= 0.15 mm and density of 2616 kg/m^3 was used in the sand pit to model scour.

The prototype-scale current velocity is 0.82 m/s. If Froude scaling is applied to this parameter, considering the scaling of the sand particles, the resulting current velocity at the laboratory scale would lead to a lower seabed mobility parameter ($MOB = \theta/\theta_{cr}$) than expected at the prototype scale. Consequently, seabed fluctuations and scour around the foundation would be underestimated. It should be noted that the mobility parameter indicates the capability of flow to move the seabed particles. Hence, to replicate the prototype condition in the experiments, the same mobility parameter at both scales must be achieved. For this purpose, the current velocity in the experiments should be distorted. At the end, the current velocity of 0.42 m/s was achieved.

The unprotected scour tests were conducted in seven steps: the first three lasted 20 minutes each, and the remaining four ran for 60 minutes each, resulting in a total duration of 300 minutes (5 hours). It should be noted that all the experiments have been conducted under live-bed scour conditions, i.e., $u_*/u_{*,cr}$ or $U/U_{cr} \geq 1$ when the foundation is absent; U is depth-averaged flow velocity (m/s), U_{cr} is its critical value (m/s), u_* is bed shear velocity, and $u_{*,cr}$ represents its crtitical value.

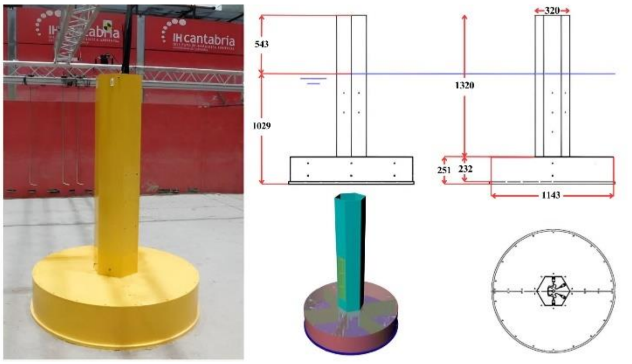

Figure 1. Geometry and dimensions of the scaled model of ELISA GBF (Sarmiento et al., 2024).

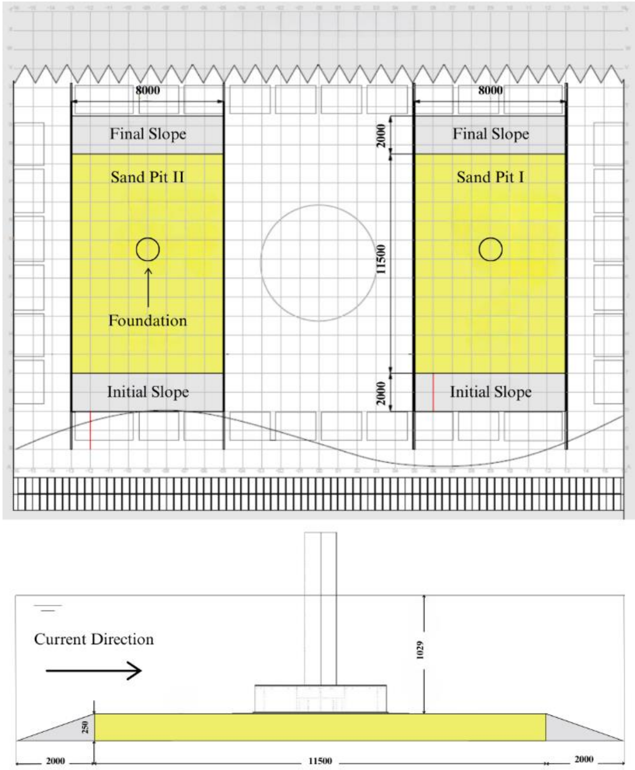

Figure 2. Tests layout (Sarmiento et al., 2024).

3 EMPIRICAL EQUATIONS

In the following, the existing equations for determining scour hole depth are classified into two distinct categories: those designed specifically for offshore GBFs and those for CBPs.

3.1 Equations for gravity base foundations

An equilibrium scour depth equation was introduced by (Khalfin, 1983) for GBFs based on physical model tests under clear-water and live-bed scour conditions and unidirectional currents. In the Scour Manual (Hoffmans and Verheij, 1997), Khalfin's equation was modified to adapt it for a rectangular and submerged caisson by incorporating the parameters α_c and h_b, respectively:

$$\frac{S_{eq}}{D} = 8.96\left(2\frac{0.5\alpha_c U}{U_c} - 1\right)\left(\frac{h_b}{D}\right)^{1.43}\left[\frac{(0.5\alpha_c U)^2}{g h_b}\right]^N \quad (1)$$

$$N = 0.83\left(\frac{h}{D}\right)^{0.34} \quad (2)$$

where s_{eq} is equilibrium scour depth (m), D is the caisson diameter (m), U is depth-averaged flow velocity (m/s), U_{cr} is critical depth-averaged flow velocity (m/s), h_b is the height of the caisson, U^2/gh_b represents Froude number, h is water depth, and g is gravitational acceleration (m/s^2). For live-bed scour condition: $U_c/U_{cr} = 1$. Additionally, a flow intensity modification factor (α_c) was introduced to consider turbulence near the corners of rectangular structures; α_c is set to 2 for cylindrical foundations and 2.3 for rectangular ones.

A new approach to forecast clear-water scour around cylindrical structures was proposed by (Tavouktsoglou et al., 2017) relying on the impact of the streamwise depth-averaged Euler number which represents the dimensionless adverse pressure gradient ($Eu = \frac{dp/d\phi}{U^2\rho}$) that causes the creation of the horseshoe vortex, which is one of the main drivers of scouring around the foundation; noting that $dp/d\phi$ is the local pressure gradient relative to the angular direction (kg/m·s^2) and ρ is fluid density (kg/m^3). They proposed an equation for calculating the equilibrium scour depth in clear-water condition:

$$\frac{S_{eq}}{D} = \prod_1^n f_i = \frac{a\zeta + b}{\zeta + c} \quad (3)$$

$$\zeta = \left[\frac{1}{log(Re_D)}\right]\left(\frac{h}{D}\right)(Fr)(Eu)^{0.5}\left(\frac{U}{U_c}\right)^{0.5} \quad (4)$$

where $\prod_1^n f_i$ is the product of influencing parameters, a, b, and c are the coefficients obtained through the optimization of parameters and based on the available data, Re_D is foundation Reynolds number ($Re_D = UD/\nu$), and Fr is Froude number.

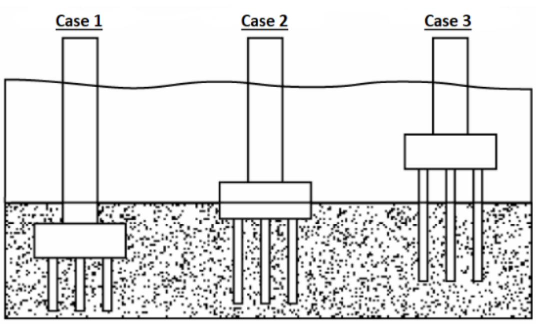

Figure 3. Complex bridge pier schematic configurations (Sheppard and Glasser, 2004).

There are other methods for calculating scour depth around GBFs under the combined effect of waves and currents. However, since this paper focuses exclusively on equations for current-induced scour around GBFs, the details and performance of these equations are not described here.

3.2 Equations for complex bridge piers

This section outlines the equations widely used for determining the scour depth around compound and complex bridge piers. Typically, bridge piers comprise a column, a caisson/pile cap, sometimes connected to a pile group (Figure 3).

The process of calculating the scour depth can be categorized in three general cases (refer to Figure 3), but in the context of this study, only the equations proposed for case 2 or compound bridge piers (column and pile cap) will be discussed, since it is the case that the pier shape resembles a GBF before scouring.

One of the first equations to predict scour depth around CBPs was developed by (Parola et al., 1996) by introducing an equivalent column height, which accounts for the pier column's contribution and is added to the pile cap height. Other tests on CBPs under threshold sediment motion conditions ($u_*/u_{*,cr} = 1$) were conducted by (Melville and Raudkivi, 1996), who proposed three methods for estimating equivalent scour depth. However, since these methods significantly overestimate the experimental scour depth results for the ELISA GBF, the details of formulation and the results are not described here.

In the HEC-18 report (Richardson and Davis, 1995), a method was developed for scour around uniform bridge piers both in clear-water and live-bed conditions. The authors proposed the concept of superposition for bridge pier components, which involves separately summing the scour depth induced by the column, pile cap, and pile group without considering the influence of other components and described it in detail in later editions. However, the last edition of HEC-18 (Arneson et al., 2012) recommends considering FDOT method (Sheppard and Renna, 2005) for complex bridge piers.

FDOT's method for calculating scour depth around CBPs assumes that a complex pier can be represented by a single circular pile characterized by an equivalent diameter, D_{eq}. The method for determining the equivalent diameter has been detailed in the literature (Sheppard and Renna, 2005, Sheppard and Glasser, 2004) and is therefore omitted here for brevity.

After determining the equivalent diameter, the authors recommended to use their single pile (uniform pier) equation by deploying D_{eq} as the pier diameter. Hence for live-bed condition:

$$\frac{S_{max}}{D_{eq}} = F_1\left[2.2\left(\frac{V/_{V_c}-1}{V_{lp}/_{V_c}-1}\right)+2.5F_2\left(\frac{V_{lp}/_{V_c}-V/_{V_c}}{V_{lp}/_{V_c}-1}\right)\right] \quad (5)$$

where V_{lp} is live-bed peak velocity (m/s) and F_1 and F_2 are correction factors for relative flow depth (water depth to equivalent diameter ratio) and ratio of equivalent diameter to median grain size, respectively.

Based on the equivalent pier diameter approach, (Coleman, 2005) proposed a method for clear-water condition. For case 2, the equivalent diameter reads as:

$$D_{eq} = D_c\left(\frac{D_c}{D_{pc}}\right)^{\left(\frac{D_c}{D_{pc}}\right)^3+0.1-0.47\left(0.75-\frac{Y}{D_c}\right)^{0.5}} \quad (6)$$

where D_c is column diameter (m), D_{pc} is the pile cap diameter (m), and Y is the cap's top elevation (m) which is measured from the initial bed level and is considered negative if it is above the bed level (case 2 and 3). After determining the equivalent diameter, it can be replaced in the existing uniform pier equations.

There are further studies about scour depth around CBPs. Nonetheless, since they are primarily based on the previously mentioned methods and are less commonly used, their descriptions are omitted here.

3.3 Temporal evolution of scour depth

The first proposed equation in the case of temporal development of scour around offshore gravity base structures can be found in the study of (Teramoto et al., 1973). This empirical equation which is based on the study on sit-on-bottom gravity structures in clear-water condition ($u_*/u_{*,cr} < 1$) and relatively small velocities is as follows:

$$S_{max} = 0.072h\left(\frac{u_*}{u_{*,cr}}\right)^{2.75}\left(\frac{Fr^2U}{h}t\right)^{0.364} \quad (7)$$

where t is time (s).

The most referenced set of equations for predicting temporal development of scour around circular foundations was proposed and developed by (Sumer et al., 1992) for monopiles:

$$S(t) = S_{eq}\left[1-exp\left(-\frac{t}{T_s}\right)^n\right] \quad (8)$$

$$T_s = \frac{D^2}{\left[g(s-1)d_{50}^3\right]^{0.5}}T_* \quad (9)$$

$$T_* = \frac{\delta\theta^{-2.2}}{2000D} \quad (10)$$

where $s(t)$ is the scour depth at time t, T_s is the time scale of the scour development (s), n is a power which is normally equal to unity, s is the specific gravity, T_* is the dimensionless time scale, δ is boundary layer thickness (m) and θ is the Shields number. The time scale (T_s) represents the duration needed for the scour depth to develop to 63% of its equilibrium value (Whitehouse, 1998).

In their study for F3 offshore platform, (Bos et al., 2002) proposed a simpler formula for T_s based on their limited available data, which is only dependent on median grain size (m):

$$T_s = 0.2 + 60d_{50} \quad (11)$$

For the time-dependent development of scour around compound and complex bridge piers, there are limited equations available; however, most of them are not applicable within the context of this study. The performance of the formulae proposed by FDOT (Sheppard and Renna, 2005), although it is not recommended by the authors to be deployed for design purposes, can be examined by using appropriate safety factors. The formulae are as follows:

$$\frac{S(t)}{S_{eq}} = exp\left\{C_1\left|\frac{U_c}{U}ln(\frac{t}{T_s})\right|^{1.6}\right\} \quad (12)$$

$$T_s\ (days) = SF\cdot C_2\frac{D_{eq}}{U}\left(\frac{U}{U_c}-0.4\right)\left(\frac{h}{D_{eq}}\right)^{0.25} \quad (13)$$

Noting that the time scale formula is valid for $\frac{h}{D_{eq}}$ <6. In these equations, $C_1 = -0.04$ and $C_2 = 127.8\ days/s$ and SF is the safety factor which is 0.5 for live-bed scour condition.

4 RESULTS

4.1 Experimental results

Figure 4 presents the laser scanner measurements recorded at the end of the second and final time intervals to show the scour evolution, with erosion indicated by negative values and deposition by positive values. Measured results indicate that the scour hole depth reaches its peak at an angle between 60 and 90 degrees relative to the flow direction. These regions align with the highest flow contraction, and in turn, the maximum shear stress amplification. The unprotected scour test concluded after step 7 to prevent structural collapse; following curve fitting, the equilibrium scour depth was projected to be around 5.04 m (Table 1).

4.2 Scour hole depth estimation

In this section, the estimated scour depth values calculated from the equations described in section 3 are compared with the experimentally measured depths. Since each equation uses a specific parameter to non-dimensionalize the scour depth, the dimensional scour depths (in meters) are compared.

As shown in Table 1, the equation proposed by (Hoffmans and Verheij, 1997) provides the most accurate prediction of scour depth compared to experimental result, i.e., a calculated depth of 5.53 m compared to the measured value of 5.04 m, with a relative difference of slightly less than 10%. It should be noted that the equation only accounts for the influence of the submerged caisson (without tower), so the calculated scour depth might be underestimated. Including the tower's effect on scour could increase the final calculated value higher than 5.53 m.

The method developed by (Tavouktsoglou et al., 2017) significantly overpredicts the scour depth which was predictable, because it has been developed for clear-water condition represented by $U/U_{cr} \leq 1$. In ELISA GBF experiments, the scour condition was in the live-bed regime, i.e., relatively high velocity values ($U/U_{cr} \cong 1.37$). Since the velocity value is included in Re, Fr, Eu, and U/U_{cr} in Equation 4, minor changes in current velocity might affect the calculated scour depth significantly.

The high overestimation of the empirical methods for scour depth prediction developed for CBPs is clearly seen in Table 1. There are several reasons for these high discrepancies.

Firstly, while the shape of CBPs is similar to GBFs before scouring, the key difference lies in their positioning. CBPs are embedded within the seabed, whereas GBFs rest on the seabed surface, making GBFs vulnerable to undermining caused by scouring. This might be one of the reasons of discrepancy.

Also, according to (Lee and Sturm, 2009), empirical equations derived from small-scale experiments often overestimate scour depth when compared to field test data. The ELISA GBF experiments are considered medium- to large-scale tests, so, in terms of scale, is only comparable with the experiments carried out by (Sheppard and Glasser, 2004) which are the basis of the FDOT method. This method shows relatively better results compared to other methods propsed for complex bridge piers that can explain the observed overpredictions.

Furthermore, some of these equations are very simplified in terms of the influencing parameters on the scour depth. For example, the equations proposed by (Melville and Raudkivi, 1996, Parola et al., 1996), as the methods with the highest discrepancy, only involved the foundation geometry and the elevation of the top of caisson (Y). In the calculations of this study, for simplicity, Y was assumed to be a constant parameter equal to the caisson height that can cause considerable errors.

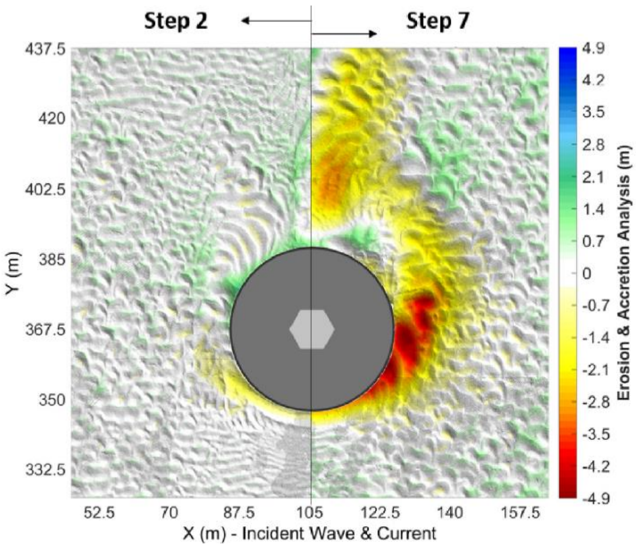

Figure 4. Laser scanner measurements of bed level change (scaled to prototype dimension); left: second step and right: last step (Sarmiento et al., 2024)

Table 1. Measured and calculated equilibrium/maximum scour depth around ELISA GBF.

Method	Foundation Type	Scour Condition	Scour Depth (m)
Experimental (Sarmiento et al., 2024)	GBF	Live-bed	5.04
(Hoffmans and Verheij, 1997)	GBF	Clear-water/Live-bed	5.53
(Tavouktsoglou et al., 2017)	GBF	Clear-water	15.44
FDOT (Sheppard and Renna, 2005)	CBP	Clear-water/Live-bed	10.02
(Coleman, 2005)	CBP	Clear-water	22.74

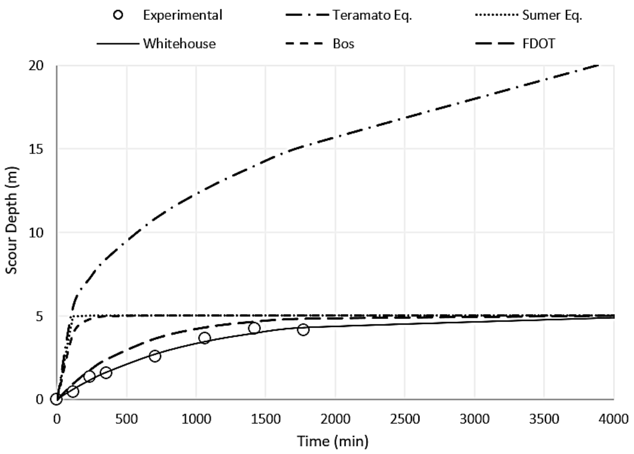

Figure 5. Temporal development of scour depth (prototype scale); measured and calculated values.

4.3 Temporal evolution of scour depth

According to the results shown in Figure 5, the equation proposed by (Teramoto et al., 1973) highly overestimates the scour development around ELISA GBF model. As mentioned earlier, the Equation 7 was developed for clear-water condition and is restricted to small shear velocities, while the experiments on ELISA GBF were in the live-bed scour condition in which the relative shear stress is higher than 1. It is also worth noting that the equation does not apply an upper time limit or account for the dependency of scour depth on the foundation geometry.

The equation developed by (Sumer et al., 1992) for monopiles is also evaluated. Since the measured equilibrium scour depth is applied in Equation 8, determining the time scale (T_s) becomes the key factor. However, when Equation 9 is used to calculate T_s, temporal evolution of scour depth cannot be accurately predicted by Equation 8. This discrepancy may be attributed to uncertainties in the input parameters. For instance, due to simplicity and insufficient data, the boundary layer thickness was simplified as being equal to the water depth. Another factor that could influence T_s is that the time scale equations, which includes the foundation diameter, were derived from experiments conducted on relatively slender monopiles.

However, using the definition provided by (Whitehouse, 1998), where the time scale represents the duration required to achieve 63% of the equilibrium scour depth, the Equation 8 accurately predicts the temporal evolution of scour depth.

Another method for calculating time scale was proposed by (Bos et al., 2002). However, this method does not effectively capture the development of scour depth over time due to the significantly larger d_{50} used in their experiments, which is approximately 100 times larger than the grain size used in the ELISA GBF tests.

Although the FDOT method (Equations 12 and 13) highly overpredits the maximum/equilibrium scour depth, the development of scour depth over time as a percentage of the maximum scour depth is only slightly above the measured trend and quite acceptable. It is important to note that the equilibrium scour depth (s_{eq}) in the Equation 12 was replaced with the measured value (5.04 m) rather than the value calculated using Equation 5 developed by FDOT. If the calculated equilibrium scour depth were used instead, the equation would significantly overestimate the temporal development of scour.

5 CONCLUSION

This study analysed the performance of existing empirical equations for calculating the equilibrium scour depth as well as temporal evolution of scour around gravity base foundations (GBFs) using ELISA GBF experimental results. The methods were categorized into those specifically developed for GBFs and those for compound/complex bridge piers (CBPs).

Among the limited equations for equilibrium scour depth around GBFs, two were examined: (Hoffmans and Verheij, 1997) and (Tavouktsoglou et al., 2017). The former provided the most accurate predictions, with an error of slightly less than 10%, while the latter significantly overestimated scour depth, as equations of (Tavouktsoglou et al., 2017) were based on clear-water scour conditions, whereas the ELISA GBF tests were conducted under live-bed conditions.

Also, given the geometric similarities to GBFs, two methods developed for CBPs—FDOT (Sheppard and Renna, 2005) and (Coleman, 2005)—were also assessed. Although both significantly overpredicted scour depth, the FDOT method showed better results, even compared to the method of (Tavouktsoglou et al., 2017).

For temporal scour development, two key approaches were evaluated: the GBF-specific method by Teramoto et al. (1973), which considerably overestimated scour depth over time, and the monopile-based method by (Sumer et al., 1992). Of the time-scale equations proposed for the latter, definition provided by (Whitehouse, 1998) accurately captured scour progression. Additionally, the results of Melville/Sheppard equations showed reasonable agreement with the ELISA GBF experimental results.

The findings of this study demonstrated that current empirical methods are inadequate for predicting both scour depth and its temporal evolution around GBFs. Hence, more reliable equations that account for various influencing factors are needed. Achieving this will necessitate the collection of additional experimental data.

AUTHORS CONTRIBUTION

Dalili Khanghah: Conceptualization, Methodology, Validation, Visualization, and Writing – original draft; **Altomare:** Supervision and Writing – review & editing; **Xironella:** Validation and Writing – review & editing; **D'Angiuro:** Conceptualization and Resources; **Garcia** and **Sarmiento:** Investigation.

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