

SCOUR PROTECTION SOLUTIONS FOR OFFSHORE WIND MONOPILES

IVA MEJAŠIĆ¹, LEON KUČINIĆ¹, KENNETH GAVIN², IRINA STIPANOVIĆ^{1,3}

¹ *Infra Plan Consulting, Zagreb, Croatia*

² *InGEO2 B.V., Delft, the Netherlands*

³ *University of Twente, Enschede, the Netherlands*

Abstract

Armourstone is an essential scour mitigation solution for monopile foundations of offshore wind turbines. Multiple design approaches exist with unclear performance comparisons. This paper implements and compares three approaches, De Vos et al. (2011) Static, De Vos et al. (2012) Dynamic and DNV RP-0618 (2022) under identical conditions which represent 50-year return period wave in combination with 5-year return period water depth and current velocity. Three methods produce required median stone size in range from 9.1 to 32.7 cm which can be attributed to different stability philosophy and orbital velocity formulations. Parametric sensitivity showcases that wave height and water depth dominate change in required median stone size for all approaches while current velocity contributes the least. DNV approach produces the smallest required stone while Dynamic approach reduces sensitivity to all parameters in comparison to zero-movement Static Approach. Field validation of competing orbital velocity formulations is needed to resolve the difference in spread of calculation results.

Key words

Scour protection, monopile foundation, armourstone, sensitivity analysis, offshore wind

1. Introduction

In the last two decades, offshore wind industry has experienced rapid growth. Monopile foundations are the most common foundation type in European waters, especially in shallow to medium water depths. These foundations are particularly vulnerable to scour, which is local erosion of seabed sediment caused by flow changes around a structure. The monopile alters the surrounding flow, creating horseshoe vortices upstream and lee-wake vortices downstream, while also causing flow contraction and increasing turbulence. These changes increase local bed shear stress and turbulence intensity, both factors increase sediment transport near the structure, leading to sediment removal and formation of scour hole (Sumer & Fredsøe, 2002).

Development of scour hole removes the soil supporting the monopile foundation and reduces its lateral capacity and threatening its structural stability (Bhattacharya, 2019). Due to this risk, scour is a vital consideration in the design process, as failure to account for it can lead to foundation failure. Scour protection is installed to maintain lateral soil capacity, reduce pile deflection, and protect secondary structures.

Most common solution of mitigating the effects of scour is the placement of rock armour around the foundation. It owes its frequency of use to its structural simplicity, proven performance and established design procedures. Alternative approaches such as frond mattresses, flow-altering devices, and ground improvement methods exist for specific site conditions, though rock armour continues to dominate due to its reliability and

cost-effectiveness in typical offshore wind environments. This paper implements three approaches for identical monopile site conditions and performs parametric sensitivity analysis to identify the primary drivers of disagreement between methods.

2. Methodology

Multiple design methods are available for sizing the required median rock diameter. The static approach as presented in De Vos *et al.*, 2011 showcases the traditional framework which focused on stopping all stone movement under extreme wave conditions. Later, this was extended by De Vos *et al.*, 2012 into a dynamic approach which permits controlled reshaping and accounts for cumulative storm damage through an empirical damage parameter and showcases the scientific evolution towards performance-based design. DNV RP-0618, 2022, introduced a mobility-based criterion using the Shields parameter, defining stability classes based on allowable stone movement and established itself as a recognized industry guideline through its integration with the DNV certification framework. The methods and a case study site are described in the following section.

2.1. De Vos Static Approach (2011)

The static approach represents the zero-movement philosophy, meaning that no stone movement is allowed under the extreme wave conditions that monopile experiences in its design lifetime. The design process follows an iterative process in which the hydrodynamic load is compared to the resistance of the armourstone. Representative wave height is defined as $H_{1/10}$ which corresponds to the average of 10 % highest waves in storm sequence. It is related to the significant wave height H_{m0} as:

$$H_{1/10} = 1.27H_{m0} \quad (1)$$

Near bed orbital velocity is calculated using linear wave theory which takes into account water depth d , peak wave period T_p , and wave length L through the dispersion relation:

$$U_m = \frac{\pi H_{1/10}}{T_p \sinh\left(\frac{2\pi d}{L}\right)} \quad (2)$$

Current-induced and wave-induced bed shear stresses are calculated separately. The current shear stress is determined using logarithmic velocity profile where bed roughness length is defined by the stone size. Wave shear stress is determined using the wave friction factor f , applicable for A/k_s in the range between 0.2 and 10, where A is amplitude of the wave orbital motion at the bed and k_s is sediment roughness:

$$\tau_c = 0.5\rho_w f_c U_c^2 \quad (3)$$

$$\tau_w = 0.5\rho_w f_w U_m^2$$

Resistance of the stone is expressed via critical bed shear stress for the $D_{67.5}$ to account for the influence of grading width (D_{85}/D_{15}):

$$\tau_{cr,stone} = \theta_{cr}\rho_w g(s-1)D_{67.5} \quad (4)$$

Where critical Shields parameter $\theta_{cr} = 0.035$ and s is the relative density of the stones. The required critical bed shear stress is given by empirically derived formula:

$$\tau_{cr,pred} = 83 + 3.569\tau_c + 0.765\tau_w \quad (5)$$

The required D_{50} is calculated iteratively, since both the load and the resistance depend on the stone size.

2.2. De Vos Dynamic Approach (2012)

The Dynamic approach moves away from zero-movement criterion and permits controlled stone displacement from the cumulative damage as long as it stays within the acceptable limits. Instead of focusing on a single wave to design for, method accumulates damage over the entire duration of a storm, typically with $N=3000$ equivalent waves. This approach allows for use of significantly smaller stone size compared to the static approach. Wave conditions are characterized as a spectre using the energy period $T_{m-1,0}$ and the spectral near-bed orbital velocity for irregular seas, rather than single representative wave height:

$$T_{m-1,0} = \frac{T_p}{1.107} \quad (6)$$

$$U_m = \frac{\sqrt{2}\pi H_{m0}}{2T_{m-1,0} \sinh\left(\frac{2\pi d}{L}\right)} \quad (7)$$

The factor $\sqrt{2}$ converts the spectral standard deviation of the orbital velocity to an amplitude, which is the key distinction from the static approach, where the near bed orbital velocity was calculated using a single monochromatic wave. This spectral representation is more physically consistent with the irregular real sea states. Damage accumulation is expressed through three-dimensional damage number S_3D , which is a physically measure of the severity of armour layer deformation. S_3D used in the calculation is 0.5. The design formula relates S_3D to governing hydraulic and structural parameters as:

$$\frac{S_{3D}}{N^{b_0}} = a_0 \frac{U_m^3 T_{m-1,0}^2}{\sqrt{gd}(s-1)^{1.5} D_{n50}^2} + a_1 \left(a_2 + a_3 \frac{\left(\frac{U_c}{w_s}\right)^2 (U_c + a_4 U_m)^2 \sqrt{d}}{g D_{n50}^{1.5}} \right) \quad (8)$$

Where empirical coefficients $b_0=0.243$, $a_0=0.00076$, $a_2=-0.022$ and $a_3=0.0079$. First part of the formula represents wave dominated contribution to damage, while the second part represents combined wave-current contribution. Wave-current interaction coefficients a_1 and a_4 , which govern the wave-current interaction, depend on relative current strength and the direction of the current relative to the waves. Output of the design is the dimensionless damage parameter S_{3D} for which the designer selects appropriate threshold (≤ 0.5 for limited reshaping or ≤ 1 for moderate deformation). Important difference from static method is that the contribution of waves and current are taken into account additively within the damage formulation.

2.3. DNV RP-0618 Approach (2022)

DNV applies a mobility-based approach, which requires that loads do not induce motion onto the armourstone under the governing design sea state. Near bed orbital velocity is calculated using empirical formulation by Soulsby (1997) for JONSWAP spectra which accounts for the exponential decay with water depth:

$$U_m = \frac{H_{m0}}{2\sqrt{2}} \cdot \sqrt{\frac{g}{d}} \cdot \exp\left[-\left(\frac{3.65}{T_z} \cdot \sqrt{\frac{d}{g}}\right)^{2.1}\right] \quad (9)$$

Wave-induced and current-induced bed shear stresses are calculated separately and combined using vector addition to calculate the maximum combined shear stress acting on the armourstone. This way the effect of direction angle between wave and current is taken into account.

$$\tau_m = \tau_c \left[1 + 1.2 \left(\frac{\tau_w}{\tau_c + \tau_w} \right)^{3.2} \right] \quad (10)$$

$$\tau_{max} = \sqrt{\tau_m^2 + \tau_w^2 + 2\tau_w\tau_m \left[\cos\left(\frac{\alpha\pi}{180}\right) \right]}$$

For each calculated stone size D_{50} , maximum Shields parameter is calculated and normalized by the critical Shields parameter, using Soulsby-Whitehouse (1997) formulation to obtain the mobility number. As with the dynamic method, designer chooses a suitable mobility class, and in this case, the “limited movement” class is determined by $Mob \leq 0.415$ which corresponds to a safety margin of about 2.4 relative to the initial motion. Additional conservatism is introduced through the load combination, one of the main factors is taken with a 50-year return period and others with 5-year return period. In this case, governing load combination takes 50-year return period for wave height, and 5-year return period for water depth and current velocity.

2.4. Case Study Site Parameters

All three methods were applied with the same set of environmental input parameters. Baseline parameters are summarised in Table 1. Metocean conditions are chosen for the governing load condition according to the DNV RP-0618 and are representative of the offshore conditions in a semi-enclosed, shallow water basin characterised by moderate wave climates and low currents. Presented conditions reflect the hydrodynamic environment that drives sediment mobility and scour development around monopile foundations.

Table 1 Baseline design parameters

Parameter	Symbol	Value	Unit
Water depth	d	18.709	m
Significant wave height	H_{m0}	5.11	m
Peak wave period	T_p	8.92	s
Depth-averaged current	U_c	0.5	m/s
Rock density	ρ_s	2650	kg/m ³
Water density	ρ_w	1025	kg/m ³
Grading width	D_{85}/D_{15}	2.5	-

3. Results & Discussion

3.1. Baseline Comparison

Three different methods, De Vos Static (2011), De Vos Dynamic (2012) and DNV, give a range of required median stone size from 32.7 cm to 9.1 cm for the baseline parameters stated in Table 1, which is 3.6-fold increase from smallest to largest, as presented in Figure .

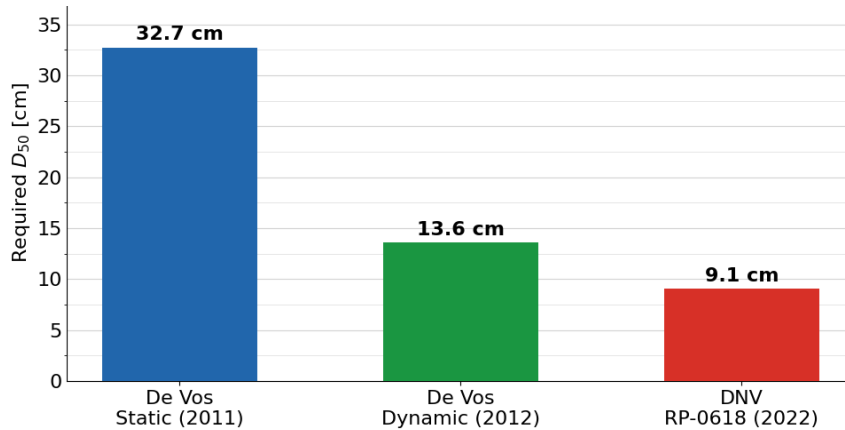


Figure 1 Required Armourstone size [cm]

3.2. Parametric Sensitivity

Four environmental parameters were varied independently in sensitivity analysis, described in the following figures. In Figure , sensitivity to water depth is shown in form of a graph where y-axis is water depth and x-axis is required median stone size. Blue colour represents De Vos Static (2011) approach, green represents De Vos Dynamic Approach (2012) and red is DNV-RP-0618, the same applies for figures 3-5. Water depth and wave height dominate the influence of the design outcome for all methods as shown in Figure and Figure .

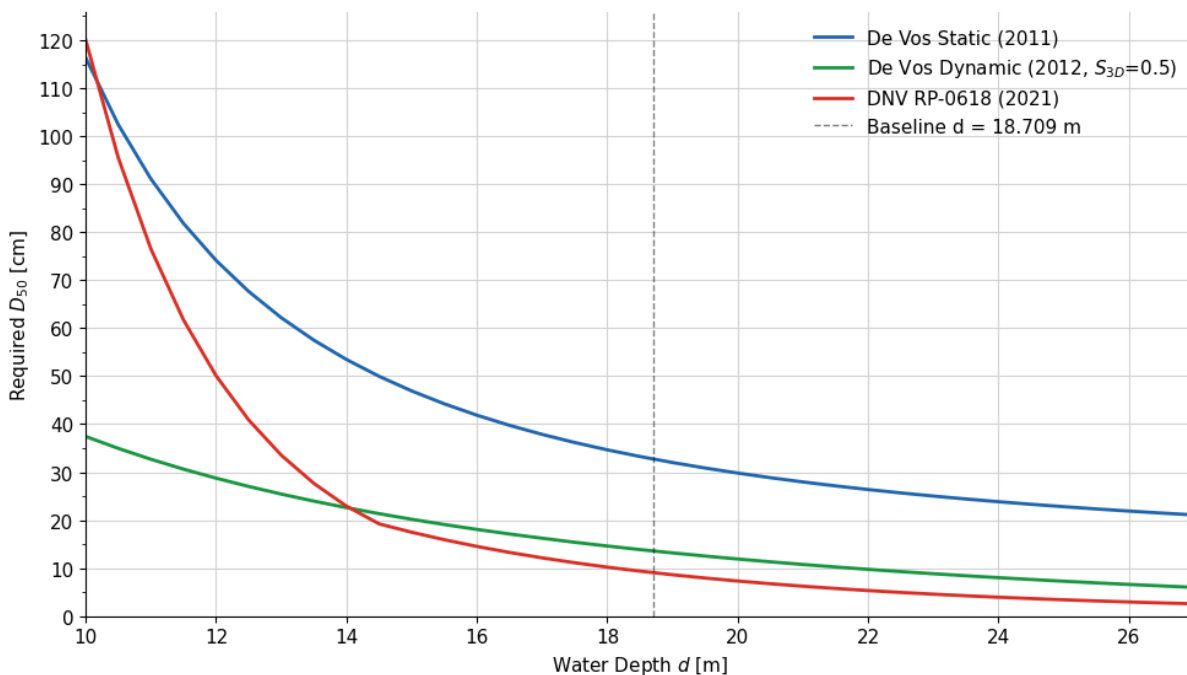


Figure 2 Sensitivity to water depth [m]

DNV and Static Approach show the highest sensitivity to water depth as the required D_{50} decreases from ~120 cm at 10 m water depth to below 20 cm at 30 m water depth, as shown in Figure . DNV shows an inflection point where wave friction formulation transitions from Dixen regime to intermediate regime. Dynamic approach is significantly more robust as it varies from 38 cm at 10 m of water depth to 6 cm for 27.5 m where it stops due to A/k_s falling outside of calibrated range.

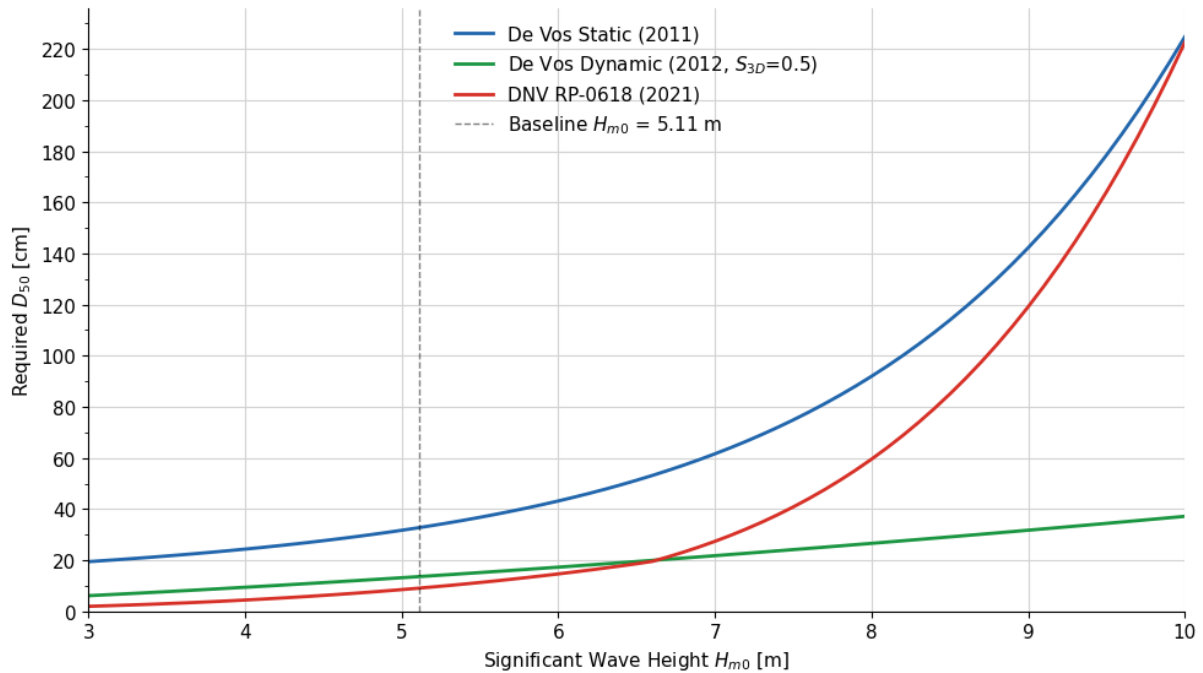


Figure 3 Sensitivity to Wave height [m]

Static Approach and DNV exhibit similar strong sensitivity to wave height with required D_{50} increasing from an initial value of ~ 20 cm at $H_{m0}=2.5$ m to ~ 225 cm at $H_{m0}=10$ m (**Figure**). DNV shows an inflection point at $H_{m0} \approx 7$ m where the wave friction factor crosses between the empirical regimes which causes the curve to rise more steeply towards the $H_{m0}=10$ m. Dynamic approach shows a robust behaviour as the whole range of wave heights keeps the required D_{50} below 50 cm. This reduced sensitivity is due to the damage accumulation mechanism.

Sensitivity to peak period varies between methods as they diverge due to the difference in methods in which they account for wave loads as shown in the **Figure**. Current velocity shows negligible influence across the typical range shown in the **Figure**.

Peak period stands out compared to other parameters as it is the main driver of increase in required D_{50} for dynamic approach which shows near linear sensitivity with D_{50} increasing from 5 cm at $T_p=5$ s to 38 cm at $T_p=15$ s, as shown in **Figure**. Longer wave periods produce proportionally higher damage per wave cycle for constant wave height. Lower bound at $T_p \approx 7$ s is outside of valid range for which the method is applicable and therefore does not produce any values. Static approach shows a non-linear behaviour as it increases sharply from 16 cm at $T_p=5$ s and peaks at 33.5 cm at $T_p \approx 9.5$ s where it starts to decrease to 29 cm at $T_p=15$ s. This is due to the longer periods increasing wavelength L faster than the orbital velocity for this water depth. DNV shows the least amount of sensitivity as it varies from 1 cm to 15 cm during the whole range of examined peak periods. Soulsby (1997) formula incorporates exponential decay with T_z which in turn produces weaker dependence on period compared to linear wave theory approaches.

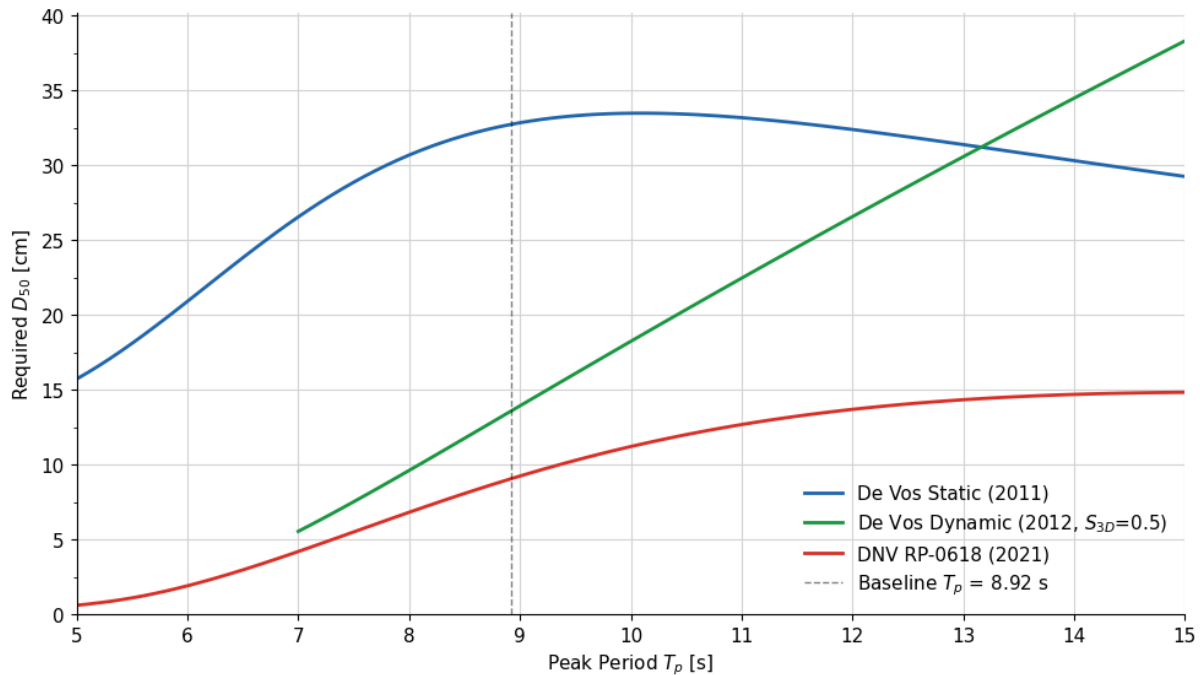


Figure 4 Sensitivity to peak period [s]

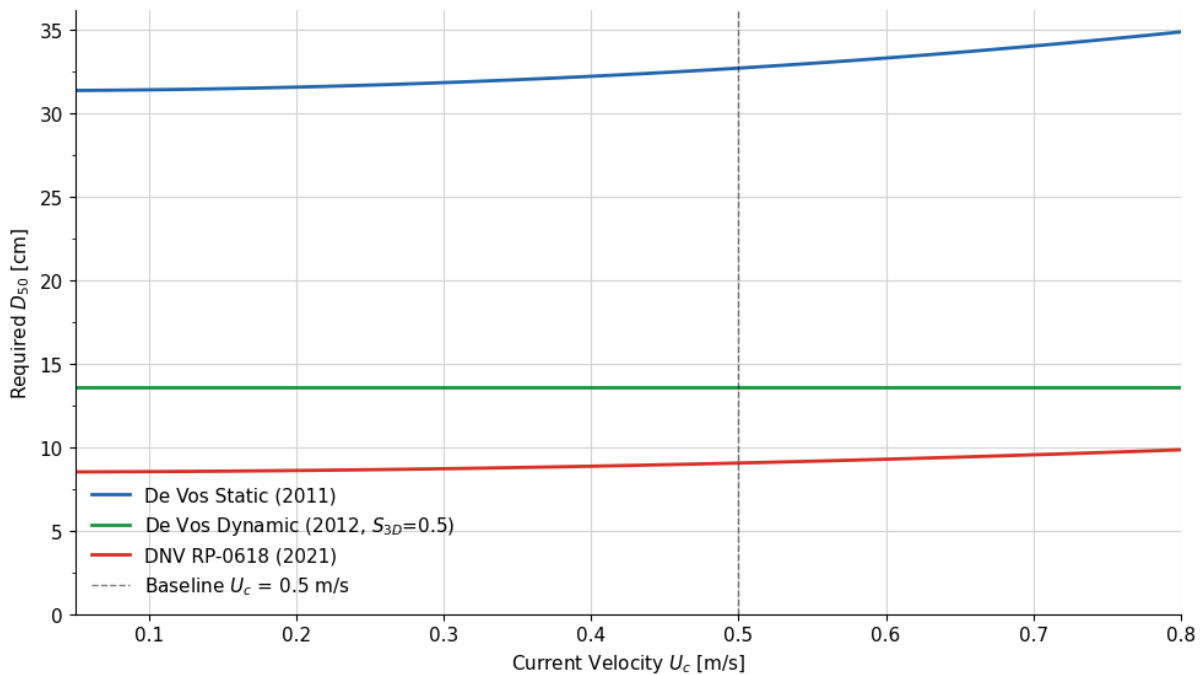


Figure 5 Sensitivity to current velocity [m/s]

Current velocity shows stark contrast as it is the least influential parameter in this sensitivity analysis as shown in **Figure**. It does not impact the Dynamic approach within the observed range, while Static and DNV approaches show sensitivity ranges of less than 3.5 cm and 1.5 m, respectively.

The range of the influence of water depth on required D_{50} are shown in tornado charts in **Figure**, **Figure** & **Figure**, from where it is evident that water depth is a dominant parameter for all methods under $\pm 20\%$ baseline variations. Wave height is also a dominant parameter for all three methods. From the tornado charts it is also

visible that the peak period is a secondary parameter when it comes to sensitivity in comparison to wave height and water depth for all methods. And finally, current velocity contributes minimally to required D_{50} variance in $\pm 20\%$ baseline variations.

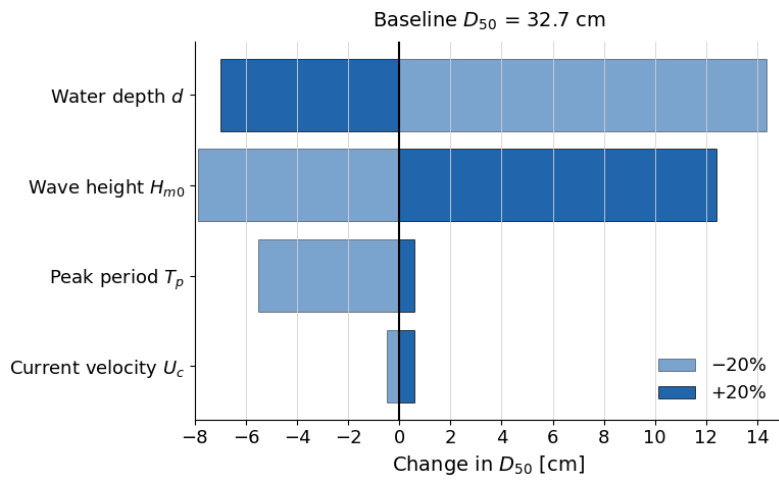


Figure 6 De Vos Static Approach (2011) – Tornado Chart

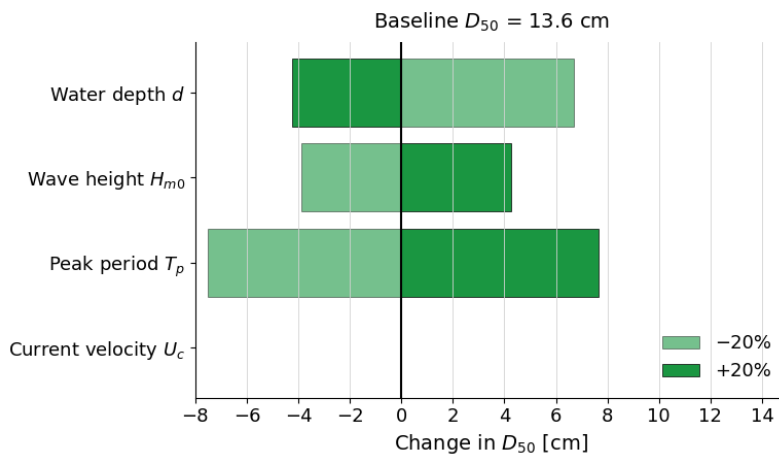


Figure 7 De Vos Dynamic Approach (2012) – Tornado Chart

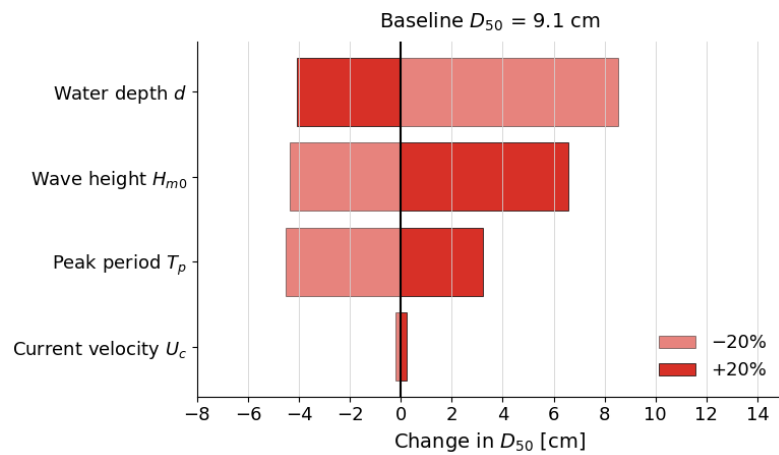


Figure 8 DNV Approach – Tornado Chart

4. Conclusion

The three methods showcased and evaluated in this paper produced a considerable spread in required armourstone size under identical environmental conditions. That highlights the significant influence of method selection on design outcomes. The variation in results can be attributed to difference in orbital velocity calculation and stability philosophy which vary from method to method.

In the sensitivity analysis it is revealed that wave height and water depth are dominant parameters in De Vos Static approach and DNV, while peak period is dominant in De Vos Dynamic approach. Current velocity was found to have a negligible influence on the stone size.

The methods also differ in how sensitive they are to changes in mentioned environmental parameters. difference in sensitivity suggests that the choice of design method can introduce greater variability in the final design than uncertainty in the metocean input parameters.

Overall, the results suggest that no single method consistently produces conservative or economical design across all possible conditions. Therefore, the selection of appropriate design approach should be made considering site specific conditions and the assumptions of each method. Field validation of the orbital velocity formulations used by these three methods is recommended to reduce uncertainty.

References

- Bhattacharya, S. (2019) *Design of foundations for offshore wind turbines*. Hoboken, NJ: John Wiley & Sons, Inc. Available at: <https://doi.org/10.1002/9781119128137>.
- De Vos, L. *et al.* (2011) "Empirical design of scour protections around monopile foundations," *Coastal Engineering*, 58(6), pp. 540–553. Available at: <https://doi.org/10.1016/j.coastaleng.2011.02.001>.
- De Vos, L. *et al.* (2012) "Empirical design of scour protections around monopile foundations. Part 2: Dynamic approach," *Coastal Engineering*, 60, pp. 286–298. Available at: <https://doi.org/10.1016/j.coastaleng.2011.11.001>.
- DNV (2021). *DNV-RP-0618: Rock Scour Protection for Monopiles*. Høvik, Norway: Det Norske Veritas.
- Soulsby, R.L. (1997) *Dynamics of Marine Sands: A Manual for Practical Applications*. London: Thomas Telford.
- Soulsby, R.L., Whitehouse, R.J.S. (1997) 'Threshold of sediment motion in coastal environments', in *Pacific Coasts and Ports '97: Proceedings of the 13th Australasian Coastal and Ocean Engineering Conference and the 6th Australasian Port and Harbour Conference*, Vol. 1, pp. 145–148. Christchurch: Centre for Advanced Engineering, University of Canterbury.
- Sumer, B.M. and Fredsøe, J. (2002) *The Mechanics of Scour in the Marine Environment*. Singapore: World Scientific.