Can fixed-foundation offshore wind farms generate dangerous waves?

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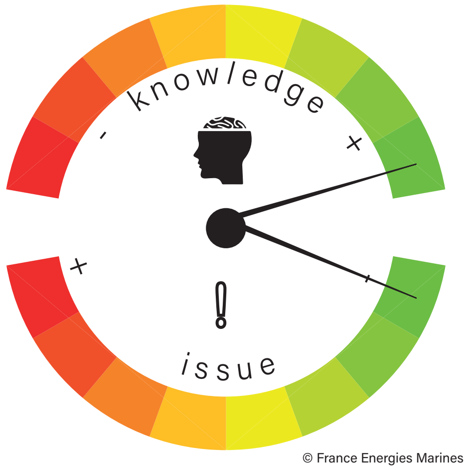

Question deemed

"a non-issue, with no knowledge gap"

by the experts

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Dangerous waves

A wave can be dangerous due to its characteristics (height, steepness), its unpredictable appearance and/or its location, at a varying distance from the coast. It can have harmful impacts on boats, coastal areas and offshore infrastructures.

Several types of dangerous waves exist:

- **tsunamis** generated by geological or meteorological phenomena,
- **rogue waves** generated by specific sea state conditions,
- **impact waves** generated by an object falling into the water.

In this bulletin, a worst case scenario approach was applied at all stages in order to obtain the results corresponding to a combination of the worst possible circumstances.

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1. Can fixed-foundation wind farms trigger geological changes capable of generating tsunamis?

What is a tsunami?

A tsunami is a long wave which propagates with a depth far lower than its wavelength (non-dispersive conditions). The movement associated with this wave concerns the entire water column.
Tsunamis are most frequently of geological origin (submarine earthquake, volcanic eruption, coastal or submarine landslide), meteorological origin, or triggered by asteroid impact.
A tsunami causes the rapid, exceptional inundation of coastal areas by the sea, due to a temporary and abnormal rise in sea level.

Tsunamis in numbers

Offshore:

- Propagation speed: hundreds of km/h
- Wavelength: several hundred km
- Height: 1 cm to 1 m

On the coast:

- Depends on local conditions
- Propagation speed: tens of km/h
- Wavelength: several hundred m
- Height: up to several tens of m
- Run-up height: tens of m

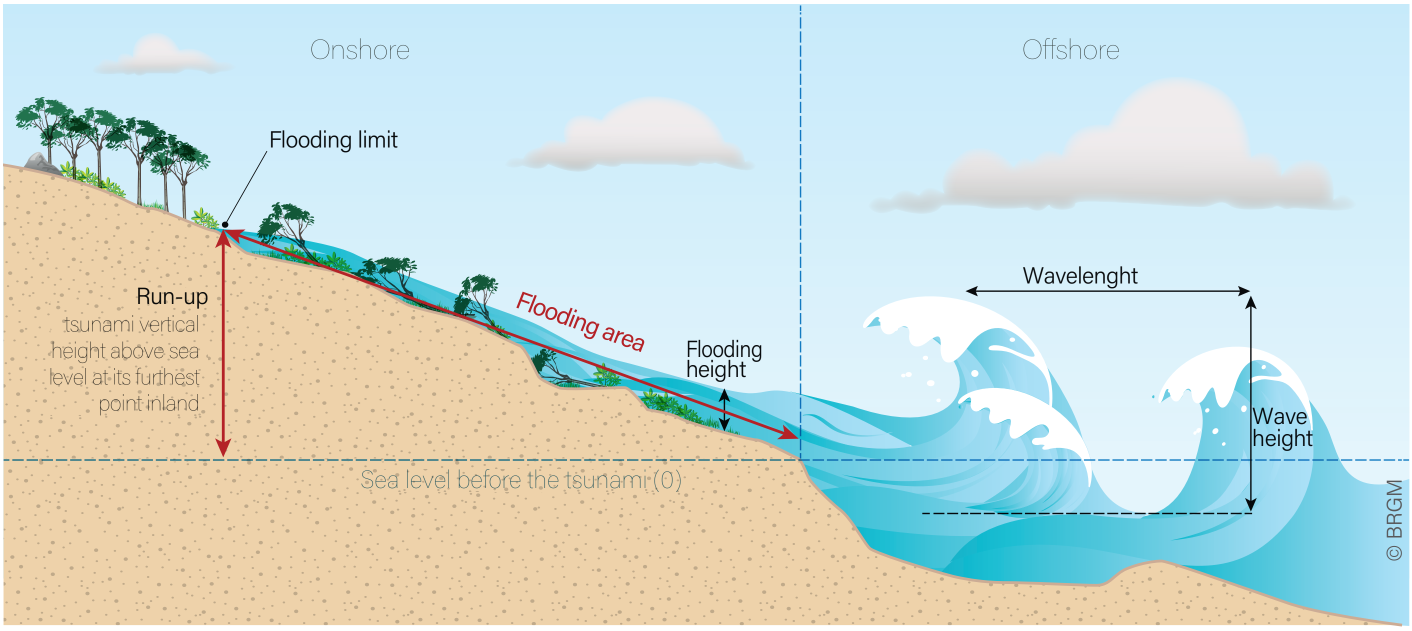

Fig. 1 *Tsunami on the coast*

Coastal landslides or collapses triggered by a fixed-foundation wind farm?

In the case of a fixed-foundation offshore wind farm, only submarine and coastal landslides can trigger tsunamis. Wind farms cannot cause volcanic eruptions, earthquakes or asteroid impact.

Coastal landslides or collapses result from the combined effects of geological (coastal sediment deficit, bedrock alteration), oceanographic (swell, tides, current) and meteorological (precipitation, frost) phenomena. Fixed-foundation wind farms can have a very minor influence on swell, currents and sediment transport which could destabilise coastal cliffs.

In order to estimate the probable influence of wind farms on sediment transport, experts have calculated scour, i.e. erosion at the base of the turbine. The scour depth can reach up to 1.7 times the diameter of the monopile and the scour distance 10 times the diameter. In the case of a gravity foundation with a 36 m diameter base, there is no major influence on the sediment dynamics beyond 360 m. For other types of foundation (jacket, monopile) which have a smaller diameter, this distance is shorter. As wind farms are located around ten kilometres from the coast, they cannot increase the risk of tsunamis caused by coastal landslides.

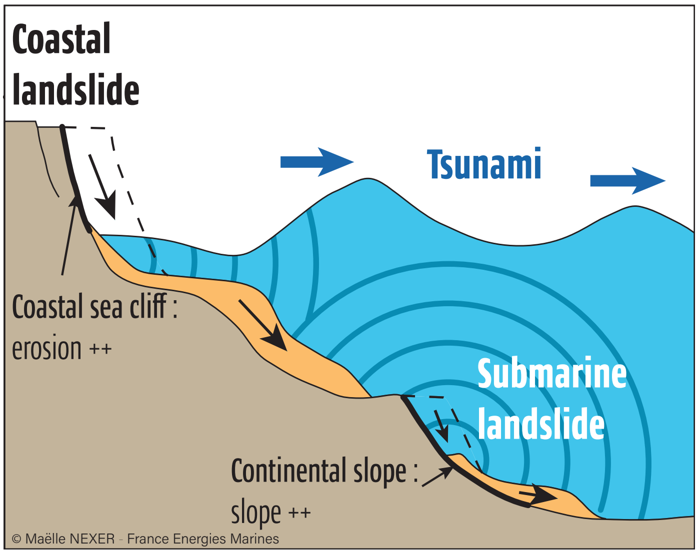

Fig. 2 *Tsunami generation mechanism due to a coastal or submarine landslide.*

Can fixed-foundation wind farms trigger submarine landslides?

Submarine landslides occur when the continental slope is steep (Fig. 2). Fixed-foundation wind farms are located on a part of the continental shelf with a very low slope (Fig. 3). A fixed-foundation offshore wind farm therefore cannot generate submarine landslides.

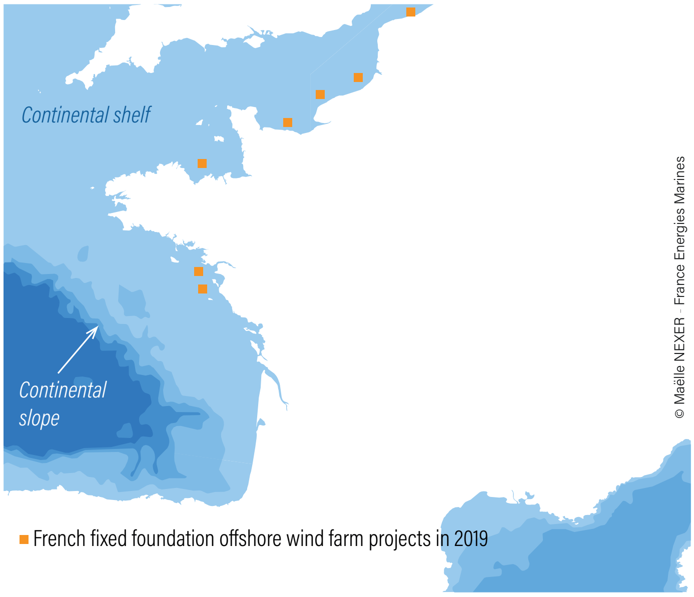

Fig. 3 *Map showing fixed-foundation wind farm projects in France in 2019*

In short:

Fixed-foundation wind farms cannot trigger tsunamis.

2. Can fixed-foundation wind farms alter the sea state to the extent of creating rogue waves?

Sea state changes within a fixed-foundation wind farm could be due to the diffraction phenomenon and the modulational instability caused by the turbine network.

What is a rogue wave?

A rogue wave is a short wave with a severe combination of height and steepness. Rogue waves are exceptionally large in relation to surrounding waves (rogue wave height > 2 times height of surrounding waves) (Touboul and Kharif, 2015) (Fig. 4).

Waves are generated by wind; a rogue wave can be caused by:

- the effect of a strong current running counter to the wave direction,
- the meeting of two wave systems (two converging low pressure systems),
- Focusing is the concentration of wave energy at a given place and time. It may or may not be accentuated by non-linear effects.

A rogue wave can appear in a given sea state that has been underestimated: all phenomena triggering it may not have been taken into account in short and long term forecast models.

Rogue waves in numbers

Offshore:

- Propagation speed: a few tens of km/h
- Wavelength: tens to hundreds of m
- Height: < 20 m
- Possibility of breaking

On the coast:

- A few rare cases of coastal flooding

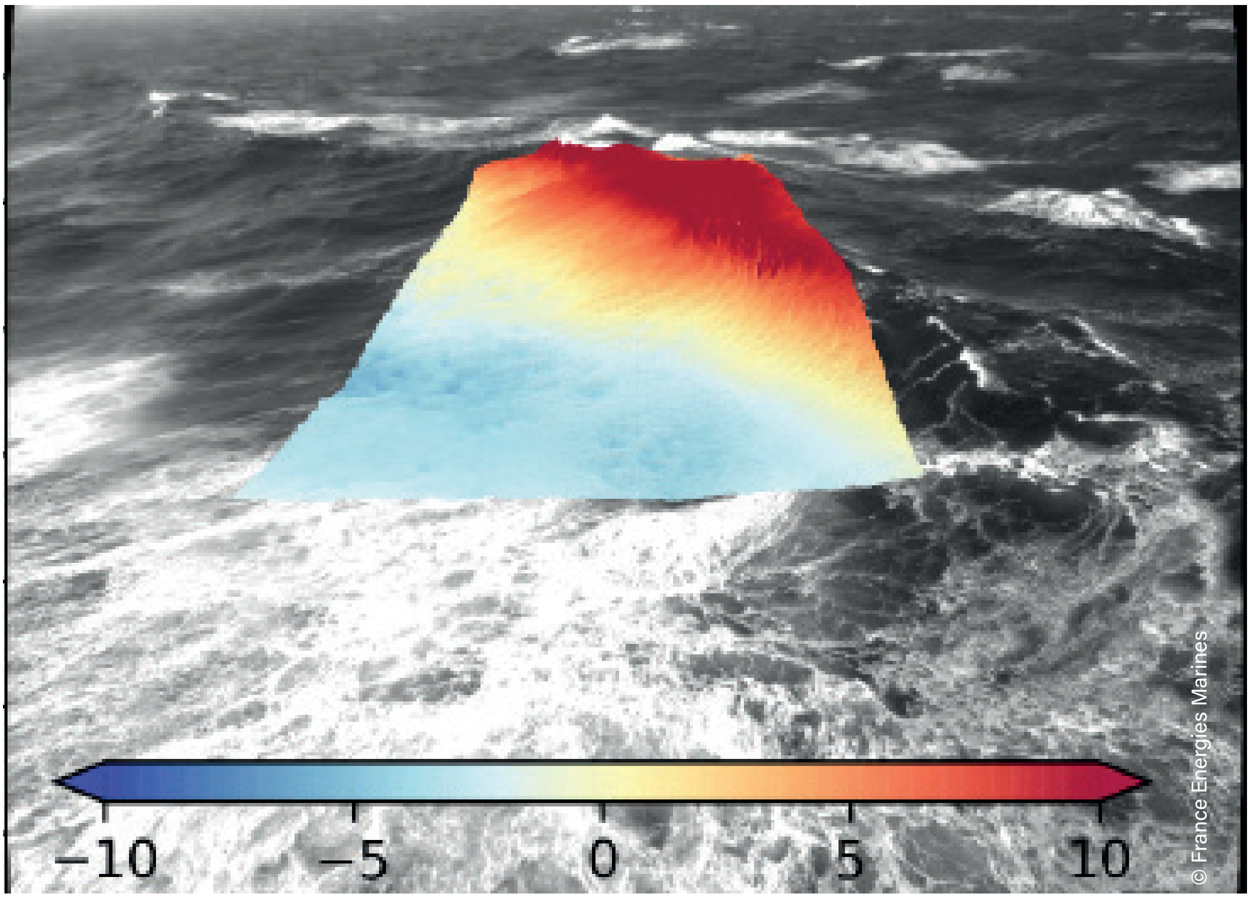

Fig. 4 *17 m high rogue wave off Ushant Island - DIME project (scale in m)*

Diffraction

The greater the diameter of the foundations, the more diffracted the waves will be. Thus in the case of jacket foundations (steel lattice), waves are not modified as the dimensions of the obstacle are far lower than the wavelength.
In the case of monopile and gravity foundations, the waves that can be diffracted have a lower amplitude and shorter period. These waves propagate radially. 500 m from the turbine, only 5% of the height of the induced wave remains. In the worst case scenario, i.e. gravity foundations with a diameter of approximately 30 m, the sea state at a distance of 2 km from the farm is identical to what it would be without the farm. There is therefore no increase in the risk of dangerous rogue waves being generated due to diffraction inherent to the geometry of the wind farm.

Modulational instability

The modulational instability mechanism (Benjamin-Feir instability) can also lead to the formation of rogue waves. This mechanism corresponds to non-linear resonance of the different waves present in a wave train (Kharif and Pelinovsky, 2003).

If there is low disturbance, the balance between a wave and neighbouring waves could be upset. One of the waves in the group will thus absorb the energy of its neighbours by resonance and thus become far larger. This growth could cause the wave to triple its initial height. However, this very large wave will have a limited lifetime, as it will ultimately return the energy to its neighbours.

In practice, this mechanism applies to waves with very low spectral spread, occurring at great depth in relation to their wavelength.

The experts examined the disturbances that could be induced by the spacing between turbines. Can they trigger this instability mechanism? The sea state climatology in wind farms off the French coastline indicates that such conditions cannot occur, given the respective characteristic dimensions of the wind farms and sea states.

In short:

The diffraction phenomenon within a fixed-foundation wind farm network does not generate dangerous waves for humans.
Similarly, the sea state climatology in wind farms off the French coastline indicates that dangerous waves cannot be created by the Benjamin-Feir instability mechanism.

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3. Can impact waves generated by a falling object at an offshore wind farm be dangerous?

In very rare cases, if turbine failure occurs, the fall of an object into water can create an impact wave which can propagate. If this phenomenon occurs, is the wave dangerous?

What is an impact wave?

Impact waves are generated by a non-natural falling object.
The impact of an object on water generates a splash and concentric radiation waves which create an impact wave (Fig. 5). Concentric waves are restricted to the surface and dissipate rapidly. The splash is a mixture of air and water which dissipates part of the impact energy. It does not contribute to the generation of an impact wave and is not dangerous.
The smoother the surface, the greater the contact surface area between the object and the water will be, promoting energy transfer. The impact will therefore be highest in calm seas and lowest in rough seas.

Impact waves in numbers

Close to the impact point

- Propagation speed: < 10 km/h
- Wavelength: several tens of m
- Height: several m
- Possibility of breaking
- Lifetime: a few hundred m

On the coast:

- No breaking: amplitude ~10 cm

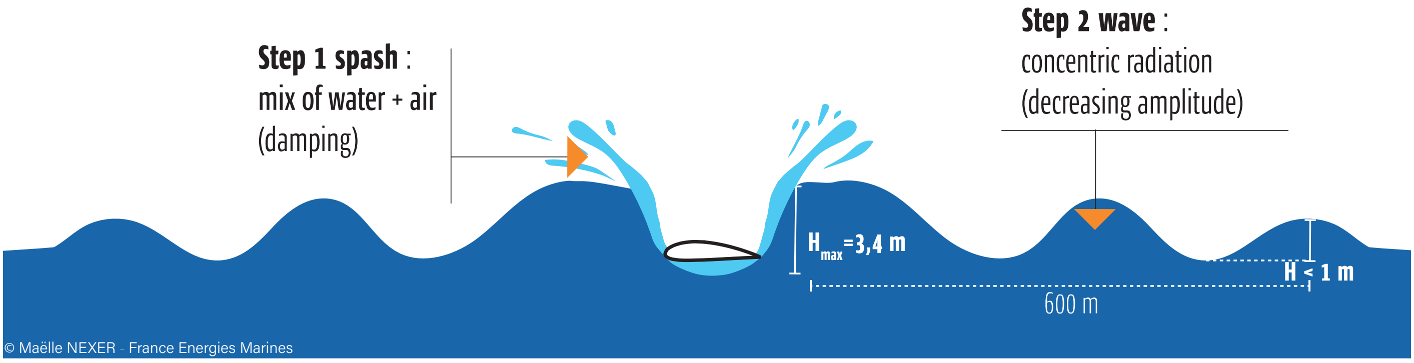


Fig. 5 *Impact wave generated by a turbine blade falling into the sea*

A spot of physics

The physics at play when objects hit the water are very complex as they involve the air compressibility and water viscosity. They also feature the fluid/structure interaction governing the dissipation of energy through the deformation of impacting and impacted media related to their difference in density and shock resistance. Thus, only a very complex chain of calculations involving highly non-linear physics is able to accurately resolve this problem, which is not the aim here. The philosophy behind our method is therefore to put forward a simplified approach while ensuring that the hypotheses at each stage remain conservative, in order to conclude with a maximum theoretical value which will never be exceeded.

Wave height estimation

We note that the probability of a wind turbine suffering a major failure to the extent of causing a falling object is very low.
To determine whether the wave generated in this case is dangerous, the experts first calculated the height of the wave generated by an falling object detached from a turbine. In order to remain conservative in subsequent calculations, the worst case scenario was taken, i.e. a flat surface hit by an object. It should be noted that this sea state does not exist in the natural environment.

Fall of a wind turbine

In the event of rupture, the tower would hit the water progressively from the base to the nacelle. The impact would therefore be minimal.

Furthermore, the curved shape of the tower means that the surface area instantaneously in contact with the water is reduced. Given that the impact force of an object on water is proportional to the instantaneous contact surface area and its speed squared, the fall of a tower into the water will not generate a dangerous wave.

Fall of a blade

As it is almost impossible for three blades to break at the same time, the scenario of the rotor falling was not studied. The scenario considered here consists in a 86 m-long blade from a 10 MW turbine falling off at maximum rotation speed (10 rpm) from a horizontal position, assuming that the blade stops rotating and falls flat onto the sea surface.

This study shows that the wave generated by such an impact theoretically would not exceed 3.4 m, and 600 m from the impact point would be less than 1 m high. This wave is not considered as dangerous given that offshore wind farms are located over 10 km from the coast and the turbines are spaced 1 km apart.

Calculation method

The blade fall movement is broken down into three phases:

Phase 1: Detachment of the blade and fall through the air

Phase 2: Impact on the free surface

Phase 3: Transformation of kinetic energy into potential energy and attenuation of this energy by propagation

For subsequent calculations, the experts therefore applied the following hypothesis: the kinetic energy of the impact is converted into displacement energy of a volume of water.

For phases 2 and 3, two scenarios were compared and gave almost identical results, with just a 0.01 m difference:

Scenario 1

Single wave approach: we assume that all the energy is transferred to a single wave and that its attenuation through radial propagation is exclusively due to concentric energy dispersion.

Scenario 2

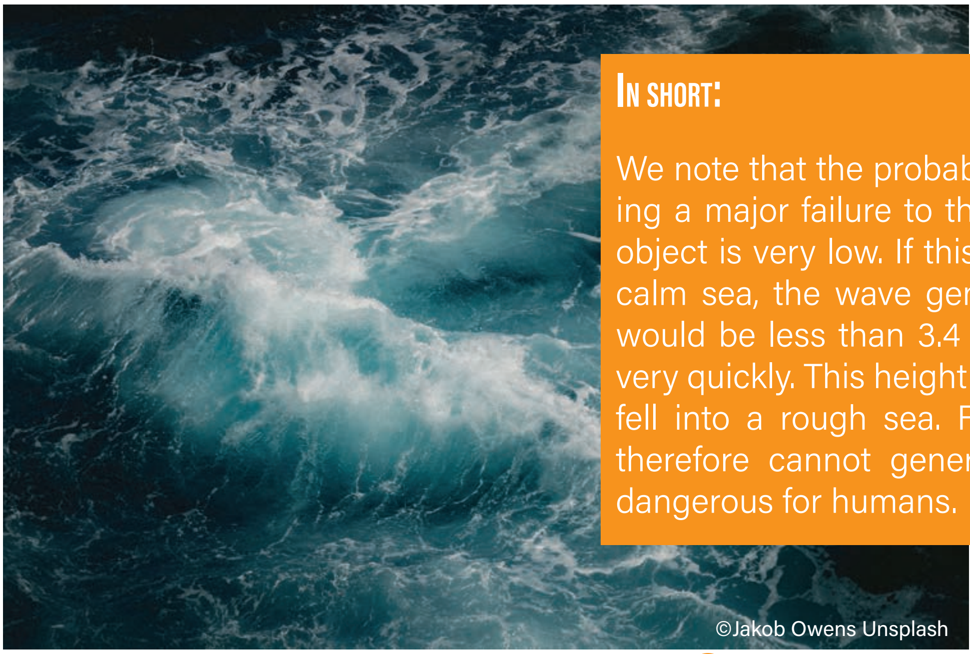
Tsunami approach: we used a model developed to estimate tsunamis following asteroid impact in the ocean put forward by Ward et *al.* (2000).

Furthermore, we note that the wave generated will be far lower, mainly for the following reasons:

- All the impact energy is assumed to be transferred to the generated wave, while models specifically developed for asteroid impact show that only 15% of this energy is actually involved in tsunami generation. However, these models are not applicable without adaptation, as they are designed for compact, dense, spherical materials, while our scenario deals with a long, light object (with a density 44 times lower than that of an asteroid). The energy transferred to the wave will necessarily be lower.

- This energy is concentrated in a single wave, while in reality a wave train is generated, thus dividing the energy between several waves.

- The density difference between the two media as well as the impact speed suggest that it is highly probable that the blade would disintegrate upon impact, thus dissipating the majority of the energy at play without creating a wave, like in the case of a blade falling onto land.



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In short:

We note that the probability of a wind turbine suffering a major failure to the extent of causing a falling object is very low. If this phenomenon occurred in a calm sea, the wave generated by the falling object would be less than 3.4 m high and would dissipate very quickly. This height would be far less if the blade fell into a rough sea. Fixed-foundation wind farms therefore cannot generate impact waves that are dangerous for humans.

Conclusions

Tsunamis

Non-issue

Tsunamis are most frequently of geological or meteorological origin, or are triggered by asteroid impact. In the case of a fixed-foundation offshore wind farm, only submarine and coastal landslides could generate tsunamis. Given that wind farms are located around ten kilometres from the coast, they cannot increase the risk of tsunamis caused by coastal landslides. Fixed-foundation wind farms are located on a part of the continental shelf with a very low slope, hence they cannot generate submarine landslides. The experts concluded that a wind farm cannot trigger a tsunami.

Rogue waves

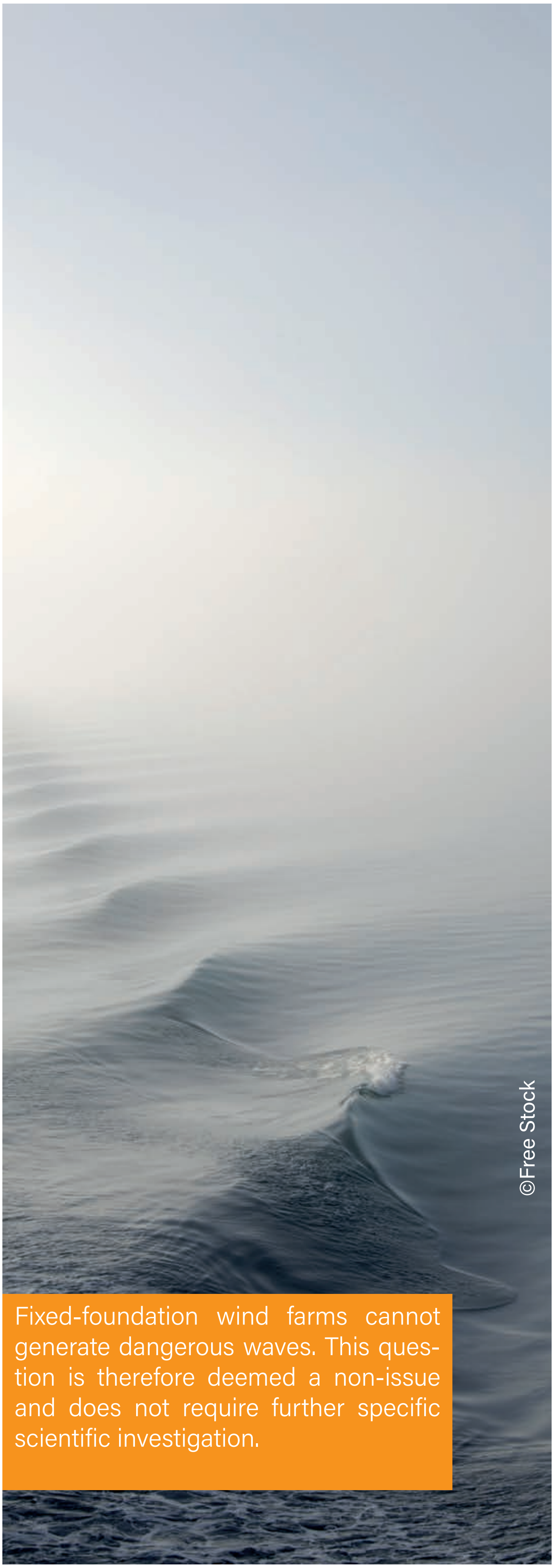
Non-issue

A rogue wave is a short wave with great height and steepness. In the case of a fixed-foundation wind farm, the experts concluded that diffraction and modulational instability could perhaps be factors in the generation of rogue waves. Taking into account the dimensions of French wind farm projects as well as the climate conditions, the experts calculated the probability of the appearance of such phenomena within these areas. For them, the diffraction phenomenon in a fixed-foundation wind farm does not affect the level of sea state-related danger for humans. Similarly, the sea state climatology in wind farms off the French coastline indicates that dangerous waves cannot be created by the Benjamin-Feir instability mechanism.

Impact waves

Non-issue

We note that the probability of a wind turbine suffering a major failure to the extent of causing a falling object is very low. To determine whether the wave generated in this case in dangerous, the experts calculated the height of the wave generated by a falling object from a turbine. If this phenomenon occurred in a calm sea, the wave generated by the falling object would be less than 3.4 m high and would dissipate very quickly. This height would be far less if the blade fell into a rough sea. Fixed-foundation wind farms therefore cannot generate impact waves that are dangerous for humans.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Fixed-foundation wind farms cannot generate dangerous waves. This question is therefore deemed a non-issue and does not require further specific scientific investigation.

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