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Flood Safety on Dikes with Wind Turbines

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Abstract. Many governments want to realize wind power, because it is a technology that promotes sustainable energy. That is why there is need for locations for wind farms (groups of wind turbines). Dikes are good locations for wind farms, because of favourable wind conditions, the absence of cultivation and the presence of road infrastructure. However, wind turbines near dikes might have negative effects on their primary function: flood safety. A recent trend is that wind turbines become larger. This increases the possibility of damage if the superstructure fails. Current directives, handbooks and guidelines treat the topics of flood safety and failure of wind turbines separately. A custom-made overview of the risks is needed for each project to ensure an adequate risk reduction strategy. An integrated approach is required to assess flood risk resulting from failure of these superstructures. This paper presents an integrated risk approach for wind turbines on dikes based on new research. This approach consists of systematic steps and includes the life cycle of both structures (wind turbines and dikes), which are assuredly interlinked. One important risk during the exploitation phase is highlighted: the incident of a falling blade or nacelle. The probability of such an incident is very low. However, if it falls on an important dike even this small probability might become relevant. This is because the required minimum probability of dike failure is relatively low. A Quantitative Risk Assessment (QRA) provides insight into the probability of a falling object on an earth dike.

Keywords. Flood safety, wind turbines, dikes, projectile penetration, Quantitative Risk Assessment

1. Introduction

Dikes have always been suitable locations to realize wind power. Historic wind mills were used on dikes to drain water for land reclamation. Dikes are still good locations for modern wind farms (groups of wind turbines), because of favourable wind conditions, the absence of cultivation and the presence of road infrastructure. There is a need for locations for wind farms, because wind is a technology that promotes sustainable energy. However, modern wind turbines near dikes might have negative effects on their primary function: flood safety.

A recent trend is that wind turbines become larger. An hub height of 50 m was usual 20 years ago, hub heights of more than 100 m are normal nowadays. This is because these big wind turbines are 10 to 20% more energy efficient than small wind turbines. A few big wind turbines produces the same amount of energy as many small wind turbines, but can be better integrated in the landscape (POF, 2009). A disadvantage of large wind turbines is that the possibility of damage increases if the superstructure fails. A custom-made overview of the risks is needed for each project to ensure an adequate risk reduction strategy. To assess flood risk as a consequence of failure of these tall superstructures, an integrated approach is required. There are many directives, handbooks and guidelines that treat the topics of flood safety (TAW, 1998; TAW, 2003; MIM 2007; CIRIA, 2013; MIM 2014). Others reports treat the failure of wind turbines in general (Fugro 1983, RON 2014), but these reports do not treat flood safety on dikes with wind turbines in detail.

The aim of this paper is to present an integrated risk approach for wind turbines on dikes based on new research. This approach consists of systematic steps and includes the life cycle of both structures (wind turbines and dikes), which are assuredly interlinked.

2. Effects of Wind Turbines on Dike Safety

A wind turbine is defined as a non-water retaining object (NWO) from the viewpoint of dike safety. A NWO is an object in or near a dike without a water retaining function and that even may lead to weakened dike. Other examples of NWO's are buildings, pipelines and trees. In general NWO's may not cross the assessment profile. This is a theoretical minimum dike profile of defined dimensions that must fit inside the actual dike profile. This must guarantee that damage to the flood defence as a result of the presence of the NWO will not lead to immediate failure of the dike. Furthermore, the interface between the dike revetment and the NWO must be firm to prevent erosion during wave overtopping (TAW, 1998).

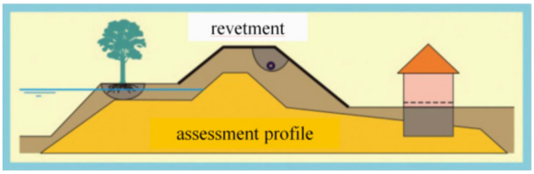

Figure 1. Non-water retaining objects in a dike (MIM, 2007)

Wind turbines are a special type of NWO's, because of their large size and because of the rotating parts, that cause vibrations. They are also special because their estimated lifetime is 20 years, much shorter than most other NWO's. Wind turbines may have effects on dikes safety during three phases in their life cycle: construction phase, exploitation phase and dismantling phase. In each phase the wind turbine might have negative effects on dike safety. Some of these effects are the same as for buildings, some are wind turbine specific. Some of these effects will be worse for larger wind turbines, some are not scale specific (see table 1).

Table 1. Wind turbine events with effects on dike safety (Fugro, 1989)

Event	Wind turbine specific	Scale specific
Construction phase		
Pile driving vibrations	–	+
Heavy crane load	+	+
Seepage along foundation piles	–	–
Excavation for foundation block	–	–
Installation of power cables	+	–
Exploitation phase		
Wind turbine vibrations	+	+
Blade or nacelle fall	+	+
Mast fracture	+	+
Seepage along power lines	+	–
Ice shedding from blades	+	–
Damage of dike grass cover	–	–
Blocking of groundwater flow	–	–
Dismantling phase		
Dismantling vibrations	–	–
Remaining obstacles	–	–

Most wind turbine related risks can be reduced sufficiently by certain measures. For example, pile driving vibrations and seepage will be reduced, if an appropriate pile foundation is chosen. Wind turbine induced vibrations in a dike corps will be low enough, if there is a safe distance between dike and wind turbine. The risks of heavy crane load and excavation will be managed, if the bearing capacity and slope stability are checked in the construction plan. The risks of blade or nacelle fall or mast fracture require special attention. That is why they are taken in account in the rest of this paper.

3. Risk of an Incident With a Falling Object

One of the important risks during the exploitation of a wind turbine is an incident with a falling blade or nacelle. The probability of such an incident is very low. However, if the object falls on an important dike even this small probability might become relevant. This is because the accepted maximum probability of dike failure is relatively low. A Quantitative Risk Assessment (QRA) provides insight into the probability of a falling object on an earth dike.

The probability of flooding because of an incident with a falling wind turbine object P_f depends on a chain of events (Eq. 1).

$$P_f = P_b + P_m + P_n$$

$$P_b = P_{b1} \times P_{b2} \times P_{b3} \times P_{b4}$$
$$P_m = P_{m1} \times P_{m2} \times P_{m3} \times P_{m4}$$
$$P_n = P_{n1} \times P_{n2} \times P_{n3} \times P_{n4} \quad (1)$$

Hereby:

P_b Probability of flooding because of a dike damage caused by a falling blade.

P_m Probability of flooding because of a dike damage caused by a falling mast.

P_n Probability of flooding because of a dike damage caused by a falling nacelle.

P_{x1} Probability of failure of a wind turbine component.

P_{x2} Probability of an impact of a falling blade, mast or nacelle in a dike

P_{x3} Probability of dike failure because of an impact.

P_{x4} Probability of flooding in case of a dike failure.

Starting point is that only a falling blade, mast or nacelle might have serious effects on dike safety. Small falling objects, ice shedding and oil leakage have minor effects (RON, 2014). Another simplified assumption is that the probabilities of falling of a blade, mast and nacelle are independent stochastic variables.

The probability of failure P_{x1} for specific wind turbine types might be requested at certifying institutes. Failure frequencies for generic wind turbines are based on casuistry for wind turbines with a steel shaft in Denmark, Germany and the United Kingdom (table 2).

Table 2. Failure frequencies for generic wind turbines, 95% reliability percentile (RON, 2014)

Scenario	Failure frequency per turbine per year
Blade fracture	8.4×10^{-4}
Mast fracture	1.3×10^{-4}
Nacelle fracture	4.0×10^{-5}

The probability of an impact of a falling blade, mast or nacelle in a dike P_{x2} can be calculated by external ballistic models, which deal with the behaviour of a non-powered projectiles in flight (see figure 2). The simplest model is the trajectory model, that does only take gravity in account. More advanced models use more parameters like air resistance, wind and spin drift (RON, 2014). If a dike is situated outside the maximum throw away distance the probability of impact is zero (see table 3).

Table 3. Maximum throw away distance for generic wind turbines (RON, 2014)

Scenario	Maximum throw away distance
Blade fracture	1.6 to 2.4 x hub height (at rated speed)
Mast fracture	Hub height + 0.5 x rotor diameter
Nacelle fracture	0.5 x rotor diameter

The probability of flooding because of dike failure due to an impact of a falling object P_{x3} depends on the size of the impact crater and the failure mechanism which may occur because of the impact crater. The estimation of the impact crater size will be discussed in the next paragraph. Dike failure mechanisms which may be effected by an impact crater are overflow, wave overtopping, macro-instability, micro-instability and revetment damage. A custom-made dike assessment is needed to quantify these effects (MIM, 2007).

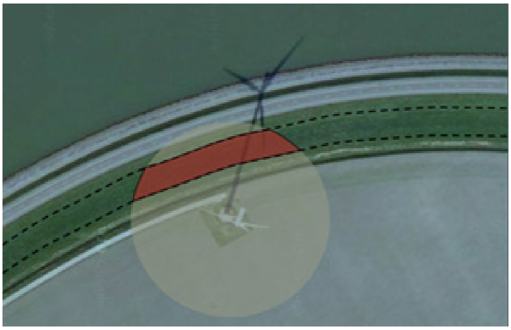

Figure 2. Estimation of the probability of an impact of a falling wind turbine object in dike)

The probability of flooding because of dike failure P_{x4} depends on the actual flood level and flood fighting measures. Dike failure will only lead to flooding if a high flood level is present in the same moment. This will often be true, because both the probability of a high flood level as the probability of wind turbine failure are higher during severe storm conditions. Custom-made hydraulic modelling is needed to quantify these effects. The probability of repairing damage to a dike in time depends on the robustness of the dike and the effectivity of the flood emergency plan.

4. Estimation of the Impact of a Falling Object

An estimation of the impact of a falling object can be made based on three different methods. All of them calculate the penetration depth of a fallen mast, blade or rotor in the subsoil.

The first method is a terminal ballistics method, based on the empirical formula of Young for projectile penetrations in soil embankments (Young, 1967; Young, 1997). The penetration depth of a fallen object D is predicted for the shape and mass of the object, the surface hardness and the terminal velocity (Eq. 2).

$$D = 0.0008\, SN\, (m/A)^{0.7} \ln (1+2.15\, V^2\, 10^{-4}) \quad \text{for } V < 61 \text{ m/s}$$

$$D = 0.000018\ SN\ (m/A)^{0.7}\ (V-30.5) \quad \text{for } V > 61 \text{ m/s} \qquad (2)$$

Hereby:

D	penetration depth [m]
S	penetration factor, varies between 5 and 15 depending on the surface hardness [-]
N	nose performance coefficient, varies between 0.5 and 1.3 depending on the nose shape of the falling object [-]
m	mass of the falling object [kg]
A	projection area of the falling object [m^2]
V	terminal velocity of the falling object, just before hitting the surface [m/s]

This formula was developed for artillery to predict the impact of shelling in an earthen wall. The use of the formula is simple, but has some limitations. It can only model vertical impact in a homogeneous subsoil, so oblique impact or a layered subsoil are outside its scope. The empiric formula is intended for bombs with a mass of no more than a few tons, the impact of nacelles of more than 100 tons might be different.

The second method is a static energy model in which the bearing capacity of soil is calculated for different impact depths (NEN, 2012). Starting point is that the kinetic energy of the falling object is absorbed by soil displacement. The energy of the fallen object is the initial height multiplied by the mass and the standard gravity. The penetration depth is a function of the soil bearing capacity and the energy absorption. This method can include more different parameters than the formula of Young. The disadvantage is that the dynamic aspects are not considered in this static model. Phenomena such as damping, bouncing and energy losses are also not modelled.

The third method is a model based on a dynamic compaction analogy with Ménard tests. The Ménard method is a soil compaction technique in which 10 to 40-ton weights are propped in free or quasi-free fall, from a height of 10 to 30 m. Field measurements are available in which the penetration depth has been related to the mass of the pounder and the drop height for several locations worldwide (Mayne et al, 1984). This relation can only be used for the estimation of the penetration depth of a blade, not for a nacelle or mast, because a blade has about the same size and weight of a Ménard weight. This method is a upper limit approach, because the dissipation of energy caused by fragmentation of fibreglass blades is not taken in account.

It must be underlined that the processes during the impact of a fallen object are very complicated, so the results of all abovementioned methods have a large range of uncertainty. None of the three methods was intended for falling wind turbine parts. Documented examples of impact craters caused by falling blades, masts or nacelles are scarce, so no validation was possible. The impact of a falling object can also lead to a pressure wave in the dike. However, it is assumed that the impact crater is more relevant for dike safety.

5. Accepted Flood Safety Reduction

The probability of flooding because of an incident with a falling wind turbine object P_f must be compared with the accepted flood safety reduction to determine if the placement of a new wind turbine next to a dike is safe. The accepted flood safety reduction depends on the importance of the dike and the local safety regulations. Specific regulations for wind turbines are often not available. A maximum probability of dike failure due to a wind turbine of 0.01 of the total probability of failure is recommended for a single wind turbine. This is comparable with the accepted safety level for water retaining structures in dikes in the Netherlands [TAW 2003]. For a group of wind turbines a recommended maximum probability is 0.001 to 0.01 of the total probability of failure for each wind turbine.

If the probability of flooding because of an incident with a falling wind turbine object is too high, then risk reduction measures are needed. Different wind turbine locations, dike reconstruction, improvement of the wind turbine structure and the set-up of an emergency plan can be applied.

6. Case Study With a Wind Turbine on a Dike

The systematic risk assessment is illustrated with a fictive example of a wind turbine near a primary dike in the Netherlands. The hub height is 110 m and the rotor diameter is 90 m. The mass of each rotor blade is 7,000 kg. The distance between the wind turbine and the dike is 50 m. The dike must be safe for water levels with a return period of 1/3,000 per year (see figure 3).

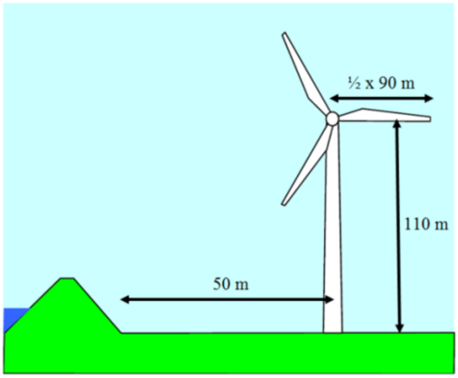

Figure 3. Case study (not on scale)

The first step is a general risk assessment. Most risks of wind turbine events (see table 1) can easily be mitigated, because of the present distance between the wind turbine and the dike. The risks of blade or nacelle fall or mast fracture is taken into account (Eq. 1). The generic failure frequencies are used (see table 2), because the wind turbine manufacturer is unknown.

The probability of an impact in the dike is calculated by external ballistic models. The probability of an impact of a falling blade P_{b2} is about 0.1. The probability of an impact of a mast fracture P_{m2} is about 0.01. This is smaller than for a blade, because the (maximum) throw away distance of a mast is smaller. The risk of a falling nacelle P_n can be neglected because the distance between the wind turbine and the dike is more than half of the rotor diameter (see table 3).

The probability of the dike failure because of an impact depends on the impact crater size. The parameters in the empirical formula of Young (Eq. 2) are illustrated for a falling blade:

S =	25 (penetration factor for moist to wet clay)
N =	1.3 (nose performance coefficient for falling object with a sharp nose)
M =	7,000 kg (mass of the falling object)
A =	2.7 m^2 (projection area of the falling object)
V =	55 m/s ($V = \sqrt{(2gh)}$, terminal velocity of the falling object, just before hitting the surface)
h =	110 m + 45 m = 155 m (fall height)
g =	9.81 m/s^2 (standard gravity)

This leads to a penetration depth D of 1.9 m. The result of the other two methods, as mentioned in paragraph 4, are slightly different. If this is taken in account and a range of uncertainty is applied, the estimated impact crater of a falling blade is about 1 to 3 m. An impact crater in the dike crown might cause overflow or wave overtopping. An impact crater in the dike slope might cause slope instability. Mast fracture may have bigger impact than a single falling blade, because of its larger mass. For this case the probability of the dike failure due to an impact of a falling blade P_{b3} is estimated as 0.03. For a mast fracture (P_{m3}) this is 0.20.

The probability of flooding because of dike failure depends on the actual flood level and flood fighting measures. The probability of a high water is assumed to be 0.50 in this case, because there is almost continuously water against this dike. The probability that flood fighting measures fail is assumed to be 0.10. The probability of flooding because of dike failure is the multiplication of these values, so 0.05 for both the blade P_{b4} and the mast P_{m4}.

The probability of flooding because of an incident with a falling wind turbine object is estimated as:

$$P_f = P_b + P_m + P_n = 1.4 \times 10^{-7} \text{ per year}$$

With:

$$P_b = 8.4 \times 10^{-4} \times 0.1 \times 0.03 \times 0.05$$
$$1.3 \times 10^{-7} \text{ per year}$$
$$P_m = 1.3 \times 10^{-4} \times 0.01 \times 0.20 \times 0.05$$
$$1.3 \times 10^{-8} \text{ per year}$$
$$P_n = 0$$

The accepted probability of failure of this dike is 1/3,000 per year. The accepted probability of each separate failure mechanism according to the new Dutch dike safety regulations is defined by the failure probability factor (see table 4).

Table 4. Failure probability factors for dikes (MIM, 2014)

Failure mechanism	Failure probability factor
Overflow and overtopping	0.24
Underseepage	0.24
Slope instability	0.04
Revetment damage / erosion	0.10
Failure of water retaining structures	0.08
Other	0.30

The probability of failure because of the effect of a non-water retaining object belongs to the "other" category and has a failure probability factor of maximum 0.30. The failure probability factor of a single wind turbine must be a small fraction of this, for example 0.04. In that case the accepted probability of dike failure is 1/3,000 x 0.30 x 0.04 = 4.0 $x10^{-6}$ per year. This is higher than 1.4 x 10^{-7} per year, so for this case the distance of 50 m between the wind turbine and the dike seems to be safe.

This case study shows that a custom-made probabilistic approach is complicated, but will help to make substantiated decisions about the needed measures to mitigate negative effects of wind turbines.

7. Conclusions and Discussion

The main benefit of the integrated approach, as presented in this paper, is that specific risks of wind turbines are assessed in a systematic way. The probability of flooding because of an incident with a falling wind turbine object can be calculated step by step. Important remarks are that the approach is time consuming and complicated. The results of the probabilistic calculations may only be used as rough values with a large range of uncertainty.

It is recommended to do further research:

- To improve the probabilistic approach of dike safety with wind farms the total dike-ring should be taken into account. A dike-ring is an area of land that is protected from flooding by an individual dike. If a dike-ring covers many non-water retaining objects (existing wind farms, gas pipelines, buildings, etc.), it is recommended to exercise restraints in planning (more) wind farms.
- The current failure frequencies for generic wind turbines (table 2) are independent on the wind turbine type, the local wind climate and the local design code. It is recommended to differentiate these generic failure frequencies and to adjust them to local conditions.
- The external ballistic models to predict the throw away distance of falling wind turbine objects must be improved to take in account among others wind direction, wind speed and blade shape. These models should be automated by custom-made software.
- The methods to estimate the impact of falling wind turbine objects in the subsoil must be improved by physical modelling and validated by full scale tests.
- Policymakers must decide more precisely which dike safety reduction is accepted for the effects of a wind farm near a dike, based on integrated safety evaluation.

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