Ensuring an Adequate Separation Distance between Wind Turbines and Buried Energy Infrastructure

There has been significant investment in the UK in wind power over recent years with wind power currently making up to 2.2 percent of the UK's energy supply. The UK has a target of generating 15 percent of all electricity from renewable sources by 2020 (source: Renewable UK). A significant proportion of this wind power is being provided by onshore wind turbines. These wind turbines range from small domestic wind turbines up to large utility scale wind farms.

Although relatively rare, a number of wind turbine failures have occurred over the past 30 years. The extent of these failures can vary from gearbox fires through to blade failures and catastrophic failures of the wind turbine mast. These larger scale wind turbine failures could have a significant impact on buried pipelines in the vicinity of the wind turbine. These buried pipelines include high pressure gas, gasoline and oil pipelines. The failure of these pipelines would lead to the release of flammable material with potential hazards to individuals and/or property in the vicinity of the pipeline. These failures can also lead to significant energy supply failures as a result of the consequential pipeline damage.

This paper summarises the work that has been undertaken by the UK Onshore Pipeline Operators' Association (UKOPA) to specify an appropriate separation distance between wind turbines and buried energy infrastructure. This separation distance has been developed using a risk-based approach to ensure that the risk of pipeline failure is acceptably low. The study was based on data collected for wind turbines in the UK and used a methodology that has been developed in the Netherlands. The study has assessed all of the wind turbine failure modes that could be a potential threat to the integrity of a pipeline including: blade failure; fall of the nacelle or rotor and toppling of the mast.

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1 INTRODUCTION

Failures of wind turbines have been identified as having the potential to threaten the integrity of buried pipelines located in the vicinity of these turbines. Any resulting failures of these pipelines could lead to the release of flammable material with potential hazards to individuals and/or property in the vicinity of the pipeline. These failures can also lead to significant energy supply failures as a result of the consequential pipeline damage. This paper summarises the work sponsored by the UK Onshore Pipelines Operators' Association (UKOPA) to determine an appropriate separation distance between wind turbines and buried pipelines, based on risk.

In order to assess the potential risk to pipelines from wind turbines a risk model was developed that is based on a methodology previously developed in the Netherlands. A survey was also performed of wind farms currently operating in the UK, in order to assess typical sizes of wind turbines and their locations. This information was used in the risk model.

The risk model was used to assess how the risks reduce as the separation distance between the wind turbine and the pipeline is increased. Based on this assessment a separation criterion is recommended to ensure that the risks of pipeline failure remain acceptably low.

2 POTENTIAL IMPACT ON BURIED PIPELINES

Although there are a large number of possible failure modes for a wind turbine, it is considered that there are only three basic modes that can affect a buried pipeline:

- A blade detaching from the hub or root, leading to loss of the blade which then impacts the pipeline. If one blade fails the resulting imbalance may cause loss of the other two blades and possibly a mast or nacelle failure.
- Nacelle directly impacting on the pipeline, with either the nacelle separating from the mast at the slewing ring or the nacelle falling with the mast. In this case the impact from the nacelle is concentrated over a small area.
- Collapse of the mast, essentially rotating about the base or a point near the base and falling linearly to the ground. In this case, the mast falls across the pipeline and the impact is distributed along the length of the mast. This would be expected to be less damaging than a nacelle impact.

To assess the effects on the pipeline, two approaches were taken. The first was a simple energy balance, which compares the energy required to plastically deform (dent) the pipeline with the available energy from the component impacting the pipeline. This is a simple analysis and gives an indication of the likelihood of failure for generic cases. It cannot, however, take account of specific features of an actual pipeline or the possible beneficial effects of protective measures such as reinforced concrete protective slabs. The second approach, non-linear finite element modelling, can include these effects, but requires substantially more data and effort.

2.1 *Energy Balance Analysis*

For the nacelle, the energy available to damage the pipeline is the gravitational potential energy of a mass m falling through a height h under the acceleration due to gravity g:

$$PE = mgh$$

Manufacturers' data suggest that for typical industrial wind turbines m is in the range 30 – 60 tonnes and h can be in the range 50 – 100 metres. This gives an available energy in the approximate range 15 MJ to 60 MJ.

For a blade there may be a contribution from the rotary inertia, but for simplicity this has been ignored; this will underestimate the available kinetic energy. If v is the velocity of the centre of mass of the blade the kinetic energy is then:

$$KE = \tfrac{1}{2} m v^2$$

Taking a typical blade fragment mass of 3 tonnes and a velocity of 30 m/s (about half the typical blade tip velocity) the available energy is 1.4 MJ. There will also be a contribution from the potential energy depending on the blade position at the time of failure. Taking a height for the blade centre of mass of 50 m gives an additional contribution to the energy of 1.5 MJ, so that the total energy is around 3 MJ.

It is assumed that all of the energy is available to damage the pipeline. In reality, wind turbine blades are made from light weight fibre reinforced composites which may well shatter on contact with the ground rather than transmit all their energy to the pipeline, but this has been ignored for this simple analysis. Similarly, no account has been taken of energy dissipated in deforming or moving the soil cover over the pipeline.

There are models available to predict the dent depth-force relationship for an indenter plastically deforming a steel pipeline. If the relationship between the dent depth and the force is known, the work required to create a dent of a given depth can be found by integrating this relationship over the indentation depth. For this scoping study the analytic model due to Liu and Francis [1] was chosen, as it gives a closed form relationship between the force and dent dimensions as a function of the internal pressure, pipe diameter, wall thickness and yield strength. It was assumed that the pipe was dented to a depth equal to half the diameter; even if this depth of dent did not cause a loss of containment it would produce a very severe restriction to the flow and would require remedial action by the pipeline operator.

Results for four typical transmission pipeline geometries are shown in Table 1:

Pipe nominal diameter, mm	Operating pressure, bar g	Wall thickness, mm	Material grade	Denting Energy, MJ
324	58	7.14	L320	0.1
457	38	9.52	L360	0.2
	70	9.52	L360	0.3
914	70	12.7	L415	2.3
1220	85	15.9	L555	6.6

Table 1: Energy required to damage typical transmission pipelines

For the two smaller pipe diameters the energy required to severely damage the pipe is much less than that estimated to be available from either a blade or the nacelle. For the 457 mm diameter case, increasing the operating pressure increases the resistance to denting, but not to an extent that failure would be avoided. For the two largest diameters, the required energy is comparable with that available from the blade, suggesting that failure due to a blade impact in these cases is not inevitable. However, the energy available from the nacelle exceeds the resistance in all cases, suggesting that direct impact from the nacelle of an industrial scale turbine will cause a pipeline failure.

2.2 Finite Element Analysis

For a specific case, the finite element method can potentially be used to give more accurate predictions. The model can include effects such as energy dissipation in the soil and brittle failure of a fibre reinforced composite blade, although obtaining the required material properties may be difficult, and the turbine manufacturers regard much design information as commercially sensitive.

Two cases were considered to investigate the issues and the possible benefits of a more detailed modelling approach. One case modelled a single blade impacting the pipeline (consistent with a blade-off failure) and the second case modelled the effects of the nacelle and rotor assembly impacting the pipeline. The intermediate case of the mast falling across the pipeline was not considered as it was assumed that the nacelle impact would be the worst case.

2.2.1 Overview

The model was generated using the Abaqus/Explicit version 6.9.1 finite element analysis program from Dassault Systemes. The explicit code was selected as it is better able to model large displacements and impacts than an implicit code. A coupled Eulerian-Lagrangian formulation was used in the generation and analysis of the model. The soil surrounding the pipe was modelled with an Eulerian mesh, where the elements are fixed and the material ‘flows’ through the elements. This allows for the calculation of large soil displacements as the blade or nacelle penetrates the soil. The blade or nacelle, pipe and reinforced concrete protective slab were modelled as Lagrangian entities, where the material is fixed and moves with the mesh. The meshes were then coupled using a general contact condition.

The blade or nacelle was added above the soil region and gravity loading was applied to the whole model domain. An initial velocity was prescribed for the component falling towards the pipeline.

2.2.2 Pipeline

A nominal 324 mm diameter 7.14 mm wall thickness grade X46 steel pipeline was modelled using quadrilateral shell elements. A von Mises yield criterion was used with an isotropic hardening rule and a power-law hardening relationship. The uniform elongation has been used as a simple estimation of the failure strain, as it represents the maximum load-carrying capacity of the material. Based on the power law model, a failure strain of 8% equivalent plastic strain was used in the analyses. The pipe was assumed to be buried with a depth of cover of 1.2 m. The soil properties were derived from borehole data.

2.2.3 Turbine Blade

The blade was modelled using solid elements. An approximate representation of the blade was generated, approximately 40 m long with a mass of approximately 6 tonnes. The blade was assumed to be constructed completely from Glass Reinforced Plastic (GRP); in reality it is likely to be skinned with GRP over a foam core, therefore the actual thickness and tip dimensions may vary considerably from those modelled. The material was assumed to behave in an elastic-plastic manner; this was an approximation to the more likely brittle failure behaviour. This is likely to be a conservative assumption as the blade material in the model will retain strength at high strains compared with the expected shattering of a fibre reinforced plastic.

Various initial blade velocities were modelled up to 71 m/s, which is equal to the rotational tip speed at 17.1 rpm, the maximum stated in the manufacturer's data for a typical multi-megawatt turbine.

2.2.4 Turbine Nacelle

The mast and nacelle were modelled using typical dimensions. The material properties assigned were those typical of a Grade 355 structural steel; however, the density was adjusted such that the assembly had the correct mass, as specified on the construction drawings. The mass of the rotor assembly and blades was represented by a point mass applied to the front face of the nacelle model. An initial velocity of 36 m/s was applied, representing the velocity of the assembly falling through 60 m. The model is shown in Figure 1 with the soil omitted for clarity. The relative dimensions of the turbine and pipeline should be noted!

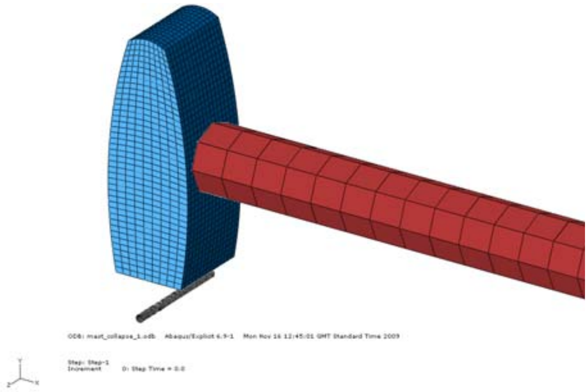


Figure 1: Model of nacelle and mast above pipeline; soil omitted.

2.2.5 Protective Measures

Only reinforced concrete slabbing was considered, as the blade and nacelle impact results suggested that thick-walled pipe was unlikely to provide sufficient protection. A slab was assumed to be placed above the pipeline, with a separation distance of 500 mm, as specified in IGEM/TD/1 [1]. A typical pipeline protection slab of the design usually used for protection from mechanical excavators was used. The worst case blade impact and nacelle impact models were then re-analysed with the slab in place and the results compared with those from the original model.

2.2.6 Blade Impact Results

The results for vertical blade impacts at two velocities are shown in Figure 2, where the grey areas have predicted strains exceeding the assumed failure strain of 8%. As expected, the area of high strain increases with increased blade velocity. In all vertical impact cases the pipeline would be predicted to lose containment.

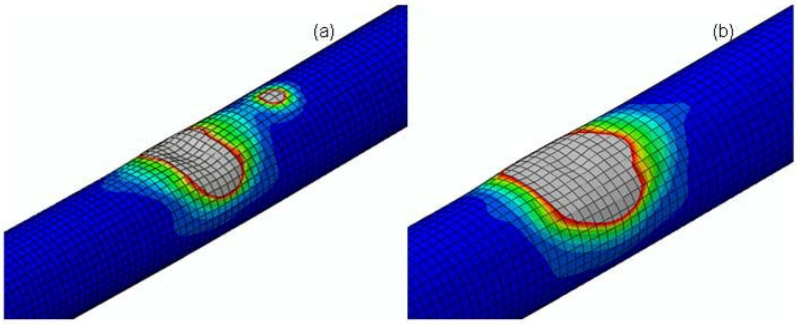


Figure 2: Vertical blade impact plastic strains at a) 36 m/s and b) 54 m/s

Oblique approaches at angles of 30°, 45°, 60° and 90° to the horizontal, but perpendicular to the line of the pipeline, were considered. From Figure 3 it can be seen that the blade approach angle greatly influences the levels of plastic strain observed in the pipeline. In the case of the 30° and 45° approaches, the blade would have failed before impacting the pipeline, although the stress plots indicated that stress waves propagating through the soil would induce stress in the pipeline. Localised areas of plasticity are generated but these are relatively low levels (~2-3% plastic strain) which are unlikely to cause rupture or complete failure of the pipe given the ductility of the material. At the higher approach angles, failure was predicted.

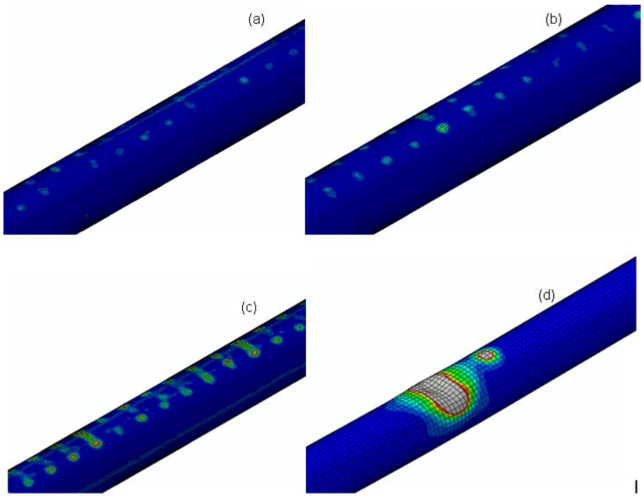


Figure 3: Plastic strains for varying blade approach angles; velocity 36 m/s. a) - 30°, b) - 45°, c) - 60° and d) – 90° (vertical)

2.2.7 Nacelle Impact Results

Figure 4 shows the Von Mises stresses for the pipeline after a nacelle impact. Given that the SMYS of a grade X46 pipeline is 320 MPa, large sections of the pipeline would yield and failure will occur. Simulations of the vertical blade impact with a concrete slab above the pipe showed that failure was not predicted to occur at any velocity, although at the highest velocity some yielding was predicted. These simulations show that for a blade impact the installation of protection will give benefits, although they may not be sufficient to prevent failure under all conditions. Simulations of the nacelle impact with a slab showed no benefits, as failure was still predicted to occur under all conditions.

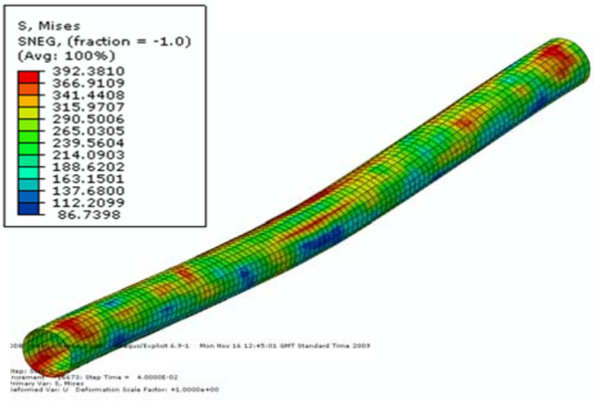


Figure 4: Stress contours for nacelle impact

2.2.8 Discussion

The finite element modelling has shown that direct vertical blade impacts at the maximum velocity considered and nacelle impacts will cause failure of the pipeline. For blade impacts at lower velocity and oblique angles, where there is a greater volume of soil to absorb the energy, failure is less likely to occur. It should be noted that the pipeline considered in this analysis is the same as the smallest diameter case detailed in the simple energy analysis in Section 2.1, which the results showed had the greatest difference between the energy available and the energy required to fail the pipeline. However, even for the larger pipelines the disparity in energy is such that a failure is very likely if the nacelle impacts the pipeline.

The modelling has also shown that protective measures such as concrete slabbing will give reductions in failure probability where blade impact is the concern. This is more likely to be the case at greater distances from the turbine than close to the base where a nacelle impact is credible. Slabbing will also give limited benefits in areas where the nacelle could strike the pipeline as it will give protection from the blade impacts that can also occur in these areas. However, slabbing cannot protect against a direct nacelle impact.

3 RISK MODEL

The wind turbine risk model was developed by GL Noble Denton from specified runs of a spreadsheet model owned by Gasunie. A detailed description of the model and results of the specified model runs were provided by Gasunie [3]. The model is based on a handbook for risk-based zoning of wind turbines produced by the Netherlands Agency for Energy and the Environment (NOVEM) [4]. The handbook uses data from two large wind turbine databases in Denmark and Germany and covers operation from the 1980s until 2001.

3.1 Accident Scenarios

Three accident scenarios as detailed in Section 2 are considered within the wind turbine risk mode i.e.

- The rotor blade breaking off
- Fall of the wind turbine due to mast failure
- Fall of the nacelle or of the rotor

The failure frequencies associated with these scenarios are shown in Table 2 below.

Accident scenario	Failure frequency per turbine per year
Rotor blade breaking off:	**Total: 8.4 x10^{-4}**
Blade breaking off during normal use (nominal rotational speed)	4.2 x10^{-4}
Blade breaking off by mechanical braking (~1.25 times the nominal rotational speed)	4.2 x10^{-4}
Over rotation (~2.0 times the nominal rotational speed)	5.0 x10^{-6}
Fall of the wind turbine due to mast failure	**1.3 x10^{-4}**
Fall of the nacelle or of the rotor	**3.2 x10^{-4}**

Table 2: Wind turbine failure frequencies

3.2 Overview of the Model

The model calculates both the hit frequency and critical hit frequency of underground gas transmission pipelines. These frequencies are defined by Gasunie as:

- **Hit frequency**: frequency with which the pipeline route is hit by the wind turbine, or part of the wind turbine
- **Critical hit frequency**: frequency with which a serious gas calamity (pipeline rupture) occurs due to the pipe being hit by the wind turbine, or part of the wind turbine.

These frequencies are calculated for each of the three accident scenarios to give the total frequency with which a wind turbine is expected to cause pipeline rupture. The methodology used to perform the calculations is described below.

Rotor blade breaking off

It is assumed by the risk model that a broken blade can only impact a pipeline if its centre of gravity hits the pipeline route. The width of the pipeline route is defined as:

$$W_r = 2h + D$$

where: h – depth of the pipeline (depth of cover + half the diameter)

D – diameter of the pipeline.

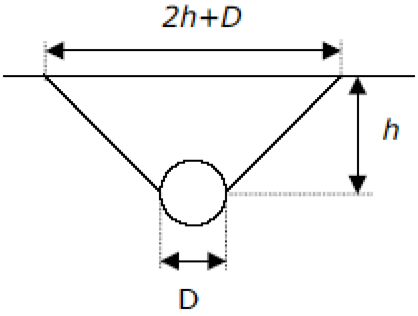


Figure 5: Underground pipeline, showing pipeline route width

The hit frequency is expressed as:

$$f = (2h + D)\int_S p_{cg}(s)\mathrm{d}s$$

where: p_{cg} - probability per m^2 that the centre of gravity of the blade reaches a specific 1 m x 1 m square at ground level (calculated using a ballistic model), assumed to be constant along the width of the pipeline route

s - length parameter along the pipeline route.

It is further assumed by the risk model that a broken blade can only damage the pipeline if it satisfies the following conditions:

- The blade will only penetrate the ground if the angle between the velocity vector of the centre of gravity and the longitudinal axis of the blade is not too large. The probability that the blade hits the ground with the correct angle is assigned a value of 0.1 within the Dutch model.
- To hit the pipeline, the longitudinal axis of the blade must approximately hit the centre line of the pipeline, otherwise it will only graze it. This is assumed to happen 1/10th of the time.
- To damage the pipeline, the blade must also have enough kinetic energy when impacting. It is assumed that the probability of the blade having sufficient kinetic energy decreases with increasing depth of the pipeline. For a depth of cover of 1 m, the probability is assumed to be 0.1.

The critical hit frequency of the pipeline is therefore:

$$F_{cr} = 0.1 * 0.1 * 0.1 * f = 0.001f$$

Fall of the wind turbine due to mast failure

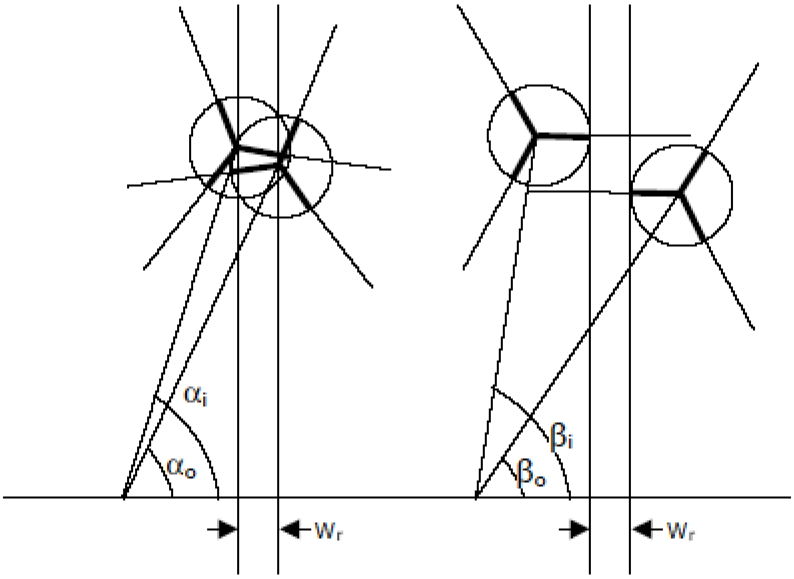
The model only takes account of the case where the mast breaks at the flange of the foundation and the nacelle or the blade roots (the section of blade from the rotor to the centre of gravity) fall on the pipeline route. Therefore no account is taken of cases where the nacelle and blades' roots fall next to the pipeline route.

The frequency with which the pipeline route is hit is given by:

$$f = 2 \cdot f_{mb} \cdot \frac{\left(\frac{\beta_i - \alpha_i}{2} + \alpha_i - \alpha_o + \frac{\alpha_o - \beta_o}{2}\right)}{2\pi} = 2 \cdot f_{mb} \cdot \frac{\left(\frac{\beta_i - \beta_o}{2} + \frac{\alpha_i - \alpha_o}{2}\right)}{2\pi}$$

where: f_{mb} – failure frequency of the mast

α *and* β are the angles shown in Figure 6.



Note: the root portion of the blade (the section of blade from the rotor to the centre of gravity) is shown by the thick line on the diagram

Figure 6: Situations in which the nacelle or the blade roots fall on the pipeline route

It is assumed that a 1 m depth of cover would be insufficient to protect the pipeline and therefore the critical hit frequency is considered to be equal to the hit frequency.

Fall of the nacelle or of the rotor

For the scenario whereby the nacelle or the rotor falls from the turbine, the same method is employed as used for the previous case of mast failure, except that the mast height is assumed to equal zero. This means that the hit frequency will only be non-zero if the wind turbine is on the pipeline route, or very close to it.

4 CALCULATED RISK LEVELS AND RECOMMENDED SEPARATION LEVELS

The Dutch model was used to calculate pipeline rupture frequencies for three sizes of wind turbine (mast height, blade length) Turbine 1 (30m, 13.5m), Turbine 2 (35m, 22m) and Turbine 3 (50m, 26m). The variation in the expected pipeline rupture frequency due to the wind turbines is shown as a function of distance from the turbine for 457 mm, 914 mm and 1219 mm diameter pipelines in Figure 7, Figure 8 and Figure 9 respectively. The failure frequencies are given in units of ‘per year’ as they were calculated for 200 m long sections of pipeline. Calculations were performed for 200m sections of pipeline as this was the longest distance over which there was potential for interaction with a wind turbine for the pipeline/wind turbine combinations studied. Also shown on these graphs for comparison purposes, are typical rupture frequencies for pipelines in Rural (R) areas as a result of third party interference damage calculated using FFREQ. Generally, third party interference damage dominates the risk associated with gas transmission pipelines. FFREQ is a structural reliability model that is used by UKOPA members to predict pipeline failure frequency as a result of third party interference [4]. The pipeline parameters assumed in the calculation of these values are shown in Table 3 and have been chosen to represent typical pipelines that would be expected to operate in R areas in the vicinities of the wind turbines.

Pipe diameter (mm)	Operating pressure (barg)	Wall thickness (mm)	Material grade	Area Type	Failure frequency (per million km years)	Failure frequency of 200m section (per year)
457.2	38	9.52	X52	R	1.416	2.83×10^{-7}
	70	9.52	X52	R	10.012	2.00×10^{-6}
914.4	70	12.7	X60	R	3.569	7.14×10^{-7}
1219	75	14.3	X80	R	1.891	3.78×10^{-7}

Table 3: 3rd party interference rupture failure frequencies

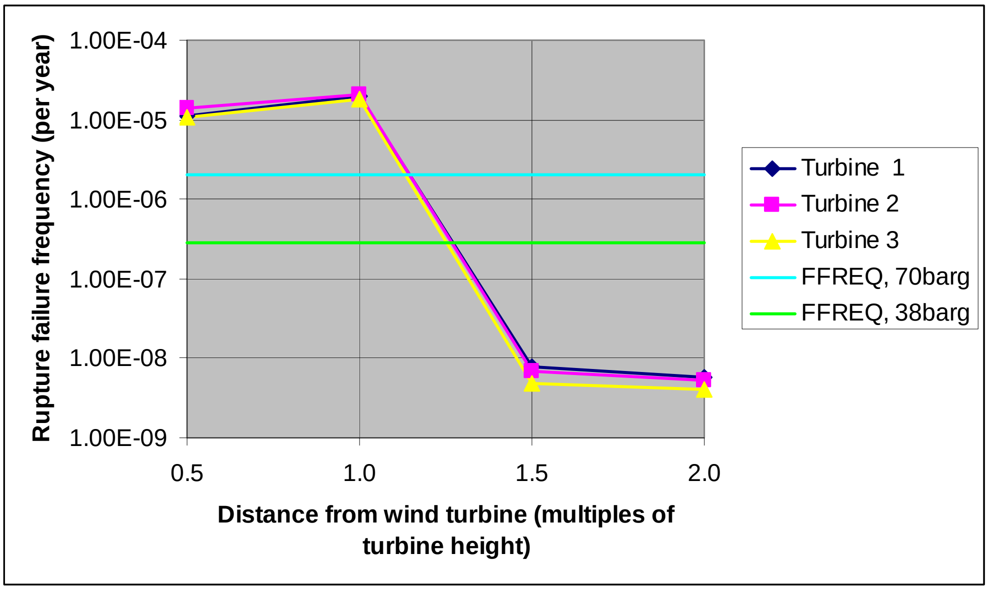


Figure 7: Failure frequency for a 200 m section of pipe due to wind turbines as a function of the distance from the turbine (457 mm pipeline)

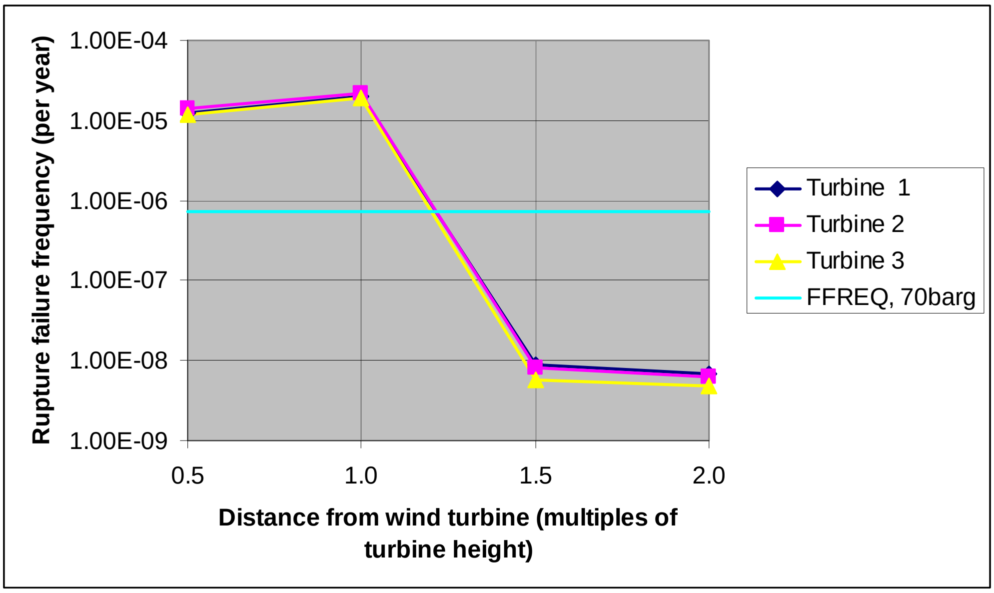


Figure 8: Failure frequency for a 200 m section of pipe due to wind turbines as a function of the distance from the turbine (914 mm pipeline)

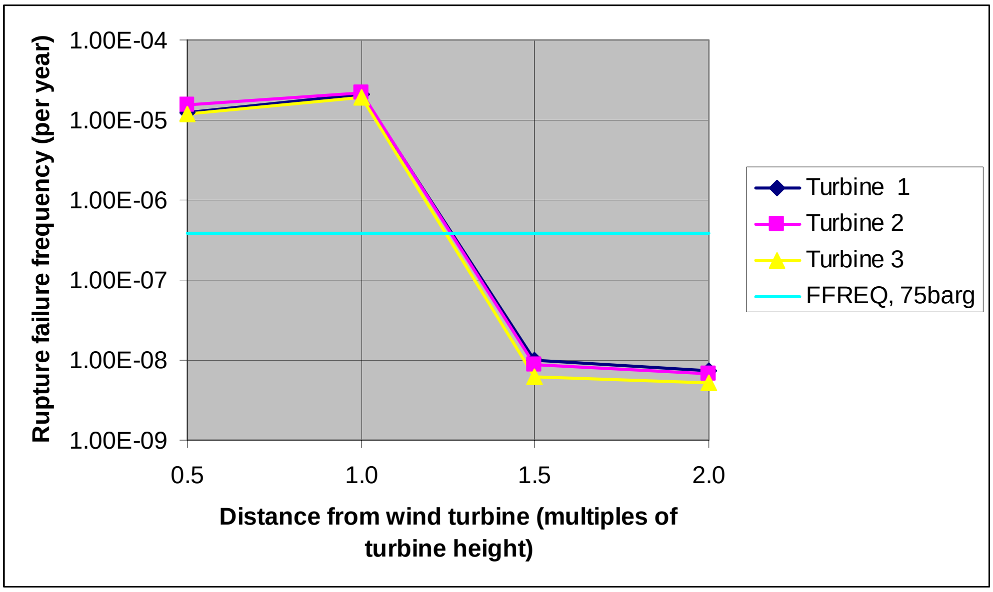


Figure 9: Failure frequency for a 200 m section of pipe due to wind turbines as a function of the distance from the turbine (1219 mm pipeline)

From these results, it can be seen that the calculated failure frequencies are all of the order of 10^{-5}/year for the 200 m section of pipeline within approximately one mast height of the turbine, and therefore it can be concluded that the failure of a pipeline due to a wind turbine is a credible event. The failure frequencies predicted by the model are the sum of the contributions from three failure scenarios discussed above. The 3rd party interference failure frequencies shown on the graphs also suggest that for short separation distances between the pipeline and a wind turbine, the turbine may be a significant contributing factor to the expected failure frequency of a pipeline.

Within the Dutch model, the pipeline parameters do not have a significant effect on the predicted failure frequency due to failure of a nearby turbine. However, it should be noted that the model only requires details of the diameter of the pipeline and its depth of cover. Other factors relating to the likelihood of pipe damage if the pipe is hit (for example wall thickness and material grade) have not been taken into account.

In addition, several assumptions have been made in the Dutch model that could be refined. For example, the probability that a turbine blade has enough kinetic energy to damage the pipe is assumed to be 0.1, based on an assumed depth of cover of 1 m. This assumption appears to be reasonable based on the results of the finite element modelling which showed for oblique impact angles pipeline failure is less likely. However, this factor will be dependent on the actual depth of cover of the pipeline and this aspect of the model could be refined to take account of the specified pipeline depth of cover.

Other assumptions made in formulating the risk model may also limit its applicability in certain situations. In particular, the model assumes that the ground between the pipeline and the base of the wind turbine is nominally flat. In cases where there are strong topographical features present, the effect of topography may need to be accounted for (e.g. a wind turbine sited in an elevated position relative to the pipeline route which would tend to increase the horizontal effect distances).

The graphs show that the size of the wind turbine has little influence on the magnitude of the expected pipeline failure frequency due to the turbine. The failure frequencies are plotted as a function of the wind turbine height and the hazard ranges due to the turbines increase with increasing mast height.[1] The failure frequency does, however, fall away quickly between 1.0 and 1.5 mast heights away from the turbine to below 10^{-8} per year for the 200 m section. At these levels, the contribution to the total failure frequency predicted for a pipeline will generally be less than that predicted for third party interference, and so an appropriate exclusion zone for wind turbines would be a minimum distance of 1.5 times the turbine mast height from the pipeline (measured from the nearest point on the base of the turbine mast to the nearest point on the pieline circumference).

5 CONCLUSIONS

The rupture of a transmission pipeline that is situated close to a wind turbine installation, due to the failure of the wind turbine is a credible event. Direct vertical turbine blade impacts at high velocity and nacelle impacts involve significant amounts of energy and are able to cause pipeline failure. If a wind turbine is situated close to a pipeline (within approximately 1.5 mast height) then the presence of the turbine could be a significant contributing factor to the expected failure frequency of the pipe. The finite element modelling has also shown that protective measures such as concrete slabbing may provide some reduction in failure probability where blade impact is the only concern however it is not able to provide any benefit in protecting the pipeline in locations where the nacelle falls.

An appropriate exclusion zone for wind turbines around transmission pipelines is considered to be 1.5 times the turbine mast height. This separation distance ensures that the contribution to the overall pipeline failure frequency as a result of wind turbine failure is not significant compared to the expected background third party interference failure frequency.

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[1] The model was not designed for very small turbines and there is no lower limit threshold for size. It is likely that some small turbines would be too small to fail certain pipelines, even if there was direct nacelle impact over the pipeline and, hence, the recommended separation distances will be cautious in such cases.

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