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Maximum Fragility Analysis of Loviisa Nuclear Power Plant Ventilation Stack for Wind Loads

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ABSTRACT

The task in this assignment is to analyze the ventilation stack fragility of the Loviisa NPP. The stack is 107.5-meter high reinforced concrete cylinder and it serves both units of the Loviisa plant. The foundation soil underneath the stack foundation is solid rock with only very moderate weathering. In this fragility analysis the rock stiffness characteristics are utilized for evaluating the spring constants for soil-structure interaction problem for evaluating the eigenfrequencies and natural mode shapes of the stack. The spring constants were developed using the elastic half-space theory. The obtained spring constants are frequency independent. The load for which the stack fragility is evaluated is the mean hourly wind speed load. This load parameter has a wide statistical database of measured values from various regions of the world and is therefore suitable for characteristic parameter against which the stack conditional failure probability is evaluated in all investigated stack sections. For Loviisa ventilation stack the result of the fragility analysis against the wind effects can be summarized in the following table:

Elevation	Mean hourly wind, v_b (m/s)	β_R	β_u
+45	30	0.1	0.2
+23	30	0.1	0.2
+4.2	48.5	0.1	0.2
overturning at base	49	0.125	0.25

According to the results obtained, the Loviisa plant ventilation stack has its weakest section at elevation +45 meters. At this section the median value of the mean hourly wind capacity of the stack is 30 m/s.

KEY WORDS: ventilation stack, reinforced concrete cylinder, foundation soil, solid rock, moderate weathering, fragility analysis, rock stiffness characteristics, spring constants, soil-structure interaction problem, eigenfrequencies natural mode shapes, mean hourly wind, conditional failure probability, weakest section, median value of the mean hourly wind capacity.

INTRODUCTION

The task in this assignment is to analyse the ventilation stack fragility of the Loviisa NPP. The stack is 107.5-meter high reinforced concrete cylinder and it serves both units of the Loviisa plant. The geometrical configuration of the stack is as follows. The outer diameter of the stack is constant for the whole length of the stack and its value is 6.8 meters. The uppermost segment of the stack is 62.5 meters high. Its wall thickness is 200 mm and its reinforcement percentage is 0.4. The middle portion of the stack is 22 meters high and its wall thickness is 400 mm and reinforcement percentage 0.4. The lowermost segment of the stack is 19 meters high to the top of the foundation and its wall thickness is 600 mm and its reinforcement percentage is 1.2. The side length of the rectangular foundation block is almost equal in both principal directions and the side length is about 12 meters. If the ribbed foundation is converted to solid rectangular block its height is about 2.5 meters and its total weight is 7.14 MN. The foundation soil underneath the stack foundation is solid rock with only very moderate weathering. In this fragility analysis the rock stiffness characteristics are utilized for evaluating the spring constants for soil-structure interaction problem for evaluating the eigenfrequencies and natural mode shapes of the stack. The load for which the stack fragility is evaluated is the mean hourly wind speed load at 23 meters height from ground, which in Loviisa stack condition is the same as the 10 meters height of the ground usually utilized in codes. This load parameter has a wide statistical database of measured values from various regions of the world and is therefore suitable for characteristic parameter against which the stack conditional failure probability is evaluated in all investigated stack sections. The sections chosen for fragility evaluation are the locations where the stack wall thickness varies discontinuously, namely, +45.00 meters and +23.00 meters and the section at the top surface of the foundation at elevation +4.20 meters as well as the bottom surface of the foundation block at elevation –0.70 meters.

The effects of wind can be divided to static effects of basic mean wind speed and dynamic effects of temporarily varying wind speed like gust effect and vortex shedding and the structural response to these effects. For the definition of long time average “mean” wind speed different time span have been used like 10 minutes average speed or hourly average speed. The gust effects are random in nature in both space and time. Davenport [1] has separated the gust effects as follows:

a) Wind “gust” loads which may be applied to only parts of the structure at any one time
b) Wind gusts at higher frequencies which are amplified by resonance at the natural frequencies of the structure

The structural responses for each this kind of wind load is potentially quite different and the modern research in wind engineering has been developing usable simplifications for different types of structures. One of these simplifications is so called static gust approach, which is used for structures with negligible resonant response. It takes into account the long time average “mean” wind speed and the wind gusts applicable only to parts of the structure at any one time. Sometimes this approach is enhanced by the use of the additional dynamic resonant factor to take into account the effects of item b) in the list above. The static gust method, which is adopted in the CICIND model code [2], involves more detailed knowledge of the wind structure, in particular, the intensity of wind turbulence. The wind loads therefore depend on two parameters the wind speed and wind turbulence. Reference [2] provides a method of calculating a wind load w(z), through the summation of a mean hourly wind load $w_m(z)$, and a static equivalent gust load, $w_g(z)$.

The gust load takes into account of wind fluctuations and depends on natural frequency, damping and height and width of chimney and is proportional to turbulence intensity. The basic mean wind speed to go along with turbulence intensity in the static gust models has been chosen to be either an “hourly” or “10 minute” mean wind speed.

Means are used because they are the most statistically stable measure of a randomly fluctuating value in any short-term record. The most modern wind codes such as Euro code 1 (EC1) [3] and UK standard BS 6399: Part 2 [4] use mean hourly wind speed. The map of mean hourly wind speeds that according to reference [3] will be exceeded only ones in a 50 year period with 10% exceedance probability is given in reference [3]. The mean return period for these wind loads is 475 years.

Wind models

Wind standards use a variety of different methods to describe how the wind speed or wind pressure varies with height. The most common are exponential function type profiles, which are used for numerical simplicity. Logarithm function type profiles provide a better physical fit to the boundary layer effect in fluid flows. The basic explaining character in practical wind profile models is that the profile depends only on local surface roughness. A model of a random process like wind must be based on statistically stable data. The local factors affecting the wind speed are:

a) Local obstructions
b) The general roughness of the ground upwind
c) Changes of the ground roughness with distance upwind of the site
d) Topography on site
e) Atmospheric stability on site

The storm mechanism by which strong winds are generated is also important. Most research has been of wind caused by large-scale extra-tropical cyclones. Other kind of wind gusts, for example gusts due to thunderstorms have different characteristics and different damage potential. Thunderstorm structure data have been classified from the nature of damage to trees. Site-specific information concerning thunderstorms is very difficult to obtain due to their infrequency at any particular site. Normal extra-tropical cyclonic winds are easier to study because they occur all the time in temperate latitudes and are very common all around the world.

The ESDU (Harris and Deaves) Wind model [5]

The work carried out by David Deaves and Ian Harris and Engineering Science Data Unit (ESDU) indicated the importance of two factors in developing the wind models. These factors are:

a) Displacement height, which is the direct and immediate effect of reasonable dense upwind obstruction, such as buildings or woods. This also causes the wind to be displaced upwards.

b) Distance (fetch) where the changes of ground roughness occur. This affects both mean speed and turbulence intensity

The ESDU methods give also a way of statistically relating gust and mean wind speeds at a particular location through an equation of the following form.

$$\underline{V}_{1s} = \underline{V}\,(1 + gI_u) \qquad (1)$$

In Equation (1) I_u is the turbulence intensity and for 1 second gust. The expected value of the peak factor, g, over one hour is 3.4. Using peak factor 3.4 and the Equation (1) , it is possible to derive gust speeds from information of mean speed and turbulence intensity. The equation for gust factor derived from ESDU model is as follows:

$$G = 1 + 2\,g\,I_u + (g\,I_u)^2 \qquad (2)$$

The CICIND model code model [2]

The CICIND model code, which with some minor corrections will be used in practical applications of this study, assumes a single surface roughness and ignores the displacement height. This study, however corrects the CICIND model by taking into account the varying roughness in the stack surroundings as well as the displacement height or “zero elevation transfer”. These are very reasonable simplifications given the height and typical location of chimneys. Using the exponential function type profile, the mean wind velocity at different heights is determined from the basic wind speed. A mean wind pressure load is calculated using the mean speeds, while wind load due to gusts is calculated through the Equation (3) given below.

$$G = 1 + 2g\, I_u\, (B + ES/\zeta)^{1/2} \qquad (3)$$

In Equation (3) g is the peak factor; g = sqrt(2 * ln (vT)) + 0,577 / (sqrt(2 * ln (vT))) with vT = 3600 * f_l / sqrt(1 + B*ζ/S/ E); I_u is the turbulence intensity; I_u = 0,311 - 0,089 $\log_{10}$ (h); B is the background turbulence; B = [1 + (h/265)**0,63]**-0,88; E is the energy density spectrum;

E = (123*(f_l/v_b)*h**0,21)/ [1+(330*f_l/v_b)**2*h**0,42]**0,83; S is the size reduction factor; S = (1 + 5,78 * (f1/vb)**1,14 * h**0,98)**(-0,88); ζ is the damping expressed as a fraction of critical damping. For the calculation of wind loads in the along direction a numerical value of ζ = 0,016 should be used; f_l is the natural frequency in 1/s of the chimney oscillating in its lowest mode; h is height of the chimney above ground elevation in meters; v_b is the basic wind speed in m/s.

Comparing ESDU and CICIND formulas (Equation (2) and Equation (3)) it can be seen the term 2g I_u is common for both. The non-linear squared term at the end of Equation (2) is omitted in Equation (3) but Equation (3) has a square root term, which includes the energy from low frequency gusts enveloping the chimney, B, and the resonant amplification of wind gusts at the natural frequencies of the chimney, ES/ζ. Despite the apparent differences, in practice these equations give similar results for a range of typical chimneys and typical heights.

Euro code 1 model [3]

The current EC1 model is based on the assumption that an equilibrium profile is achieved at distance of 1 km and that there is "displacement height" effect. In order to avoid conservatism resulting from this, artificially high surface roughness lengths are used. Peak gust speeds can be calculated by equivalent EC1 method using the following formula.

$$V_{gust} = V_{mean}\,(1+7I_u)^{1/2} \qquad (4)$$

The Euro code model significantly underestimates the gust speeds compared to ESDU [5]/BS 6399 Part 2 [4] model. N. J. Cook used the ESDU model in the analysis of wind speeds for United Kingdom [5]. This study used data from large number of wind velocity measurements. The dense velocity measurement grid made possible to compare the measurements from different measuring stations for all wind directions. The generally good comparison achieved validates the developed model. Apart from using standard wind velocity measurements there are few other ways to of deriving extreme winds speeds for standard exposure. These include:

a) Analysis of directly measured atmospheric pressure gradients
b) Analysis of meteorological, high-altitude balloon data
c) Using data from tall structures, which are less affected by surface roughness

Further information from wind effects on the structures and on wind models can be obtained from reference [6].

STACK FRAGILITY FOR LOVIISA VENTILATION STACK

In developing this case study following references in addition to the above mentioned are used: CICIND model code commentary [7], H. van Koten paper about stress distributions in chimneys [8], ACI design code for chimneys [9], German manual for concrete practice from the year 1988 [10].

FEM models for checking the lowest natural frequency and natural shape of the stack

The accurate determination of the lowest natural frequency is important for determining the wind profile and gust factor from the basic wind speed according to the reference [2]. In order to check calculate the lowest natural frequency the shell model was developed by using four node shell elements. The characteristic size of the shell element was about one square meter so that total amount of elements in the shell model was about 3000. The plot of the lowest natural shape of the shell model is given in the Figure 1.

Wind load Loviisa Stack

The basic wind load used in this study is based on hourly mean wind speed. The basic wind speed v_b is the mean hourly wind speed at 23 m above ground level in open flat country, which is exceeded with 10 % once in every 50 years. For the purposes of numerical evaluation in subsequent sections the value of v_b =30 m/s is adopted as reference. Basis for the determination of the wind loads is the design wind speed.

The basic wind speed for design load determination is corrected by three factors taking into account the height of the chimney, the topography of its surroundings and the existence of adjacent objects. These three factors are the height factor k(z), the topographical factor k_t, and the interference factor k_i.

The difference in corrected and original CICIND wind models for the vertical profile of mean hourly wind speed used in this study is in the expression for the height factor k(z). According to the original CICIND wind model the height factor for mean hourly wind speed is given by following formula

$$k(z) = (z/10)^{0.14} \qquad (4)$$

In Equation (4) z is the height of the monitored point in meters and 10 m is the reference height of basic wind speed. In this study the corrected CICIND model is used and the vertical profile of mean hourly wind speed is the function of surface roughness and the elevation of the monitoring point and the height factor is expressed by the following formula

$$k(z) = u(z)/u(z_{ref}) = \ln((z-6.66*z_0)/z_0)/\ln((z_{ref}-6.66*z_0)/z_0) \qquad (5)$$

In Equation (5) $u(z_{ref})$ is the observed wind velocity at elevation z_{ref}. u(z) is the vind velocity to be calculated at elevation z. z_0 is the roughness of the ground surfaře. The design wind speed is determined by multiplying the basic wind speed with correction factors. The design wind load per unit height of the stack is determined by adding to the mean hourly wind load per unit height the static equivalent of the wind load due to gusts per unit height. The mean wind load per unit height is obtained as a product of the square of the wind speed at investigated height multiplied by air density, chimney outer diameter, shape factor and by the coefficient 0.5.

The static equivalent of the wind load due to gusts is assumed to vary linearly with the height according to the original CICIND wind profile. The difference of corrected and original CICIND wind profiles for the static equivalent of the wind load due to gusts used in this study is in the expression for turbulence intensity I_u in gust factor Equation (3). According to the original CICIND wind profile the turbulence intensity factor is given by following formula

$$I_u = 0{,}311 - 0{,}089 \log_{10}(h) \qquad (6)$$

In Equation (5) h is the height of the chimney above ground level in m. The turbulence intensity used in this study as a correction to the CICIND model has been calculated as follows. The basic profile of the turbulence intensity is given by the formula:

$$I_u(z)/I_u(z_{ref}) = \ln((z_{ref}-6.66*z_0)/z_0)/\ln((z-6.66*z_0)/z_0) \qquad (7)$$

In Equation (6) $I_u(z_{ref})$ is the observed wind velocity turbulence intensity at elevation z_{ref}. The z_{ref} for Loviisa stack is the stack height 107.5 meters and the reference turbulence intensity value at this elevation is taken to be 0.1. z_0 is the roughness of ground surface.

The wind load due to gusts per unit height can be determined by multiplying the height of the investigated point with two factors, namely, the integral of mean hourly wind speed weighted with height and integrated over the chimney height above the ground and the quotient, where the nominator is 3 times the gust factor decreased by one and the denominator is the cube of the chimney height above the ground. The gust factor will be calculated according to CICIND model code wind model with the aid of Equation (2). In the Figure 2 is given wind load profile for Loviisa ventilation stack, based on mean hourly wind speed of 30 m/s. In this study the CICIND wind model [2] described above is corrected as follows: the vertical profile of mean hourly wind speed is the function of surface roughness and the elevation of the monitoring point.

Figure 1 The lowest natural shape of the shell model. The natural frequency is 0.375 Hz

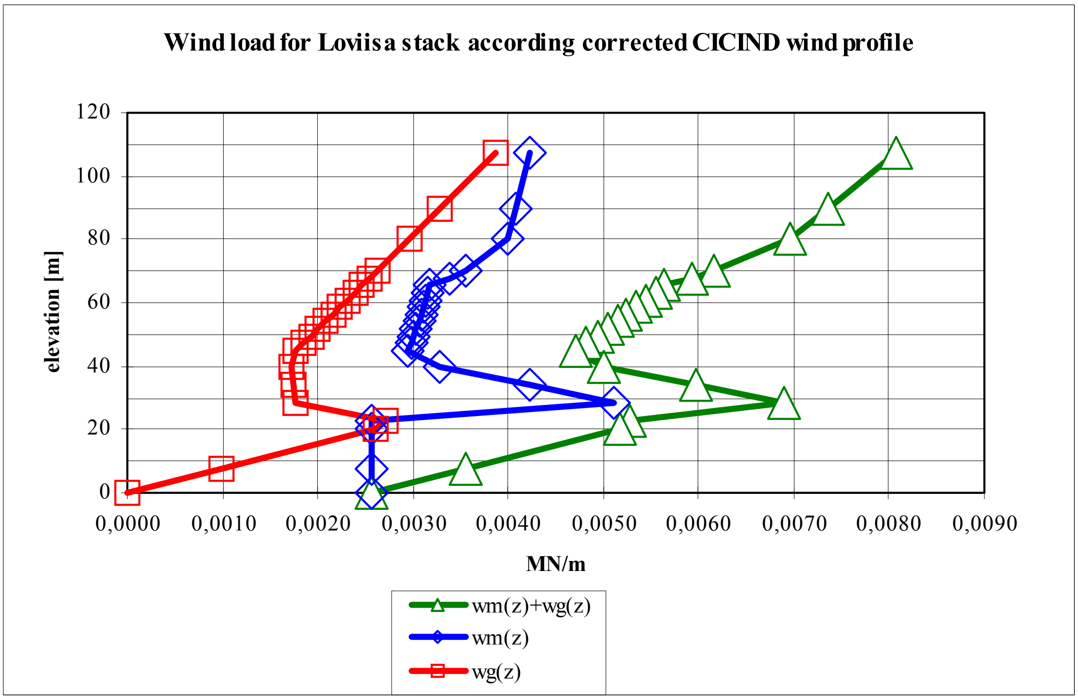

Figure 2 Wind load profile for Loviisa ventilation stack , basic mean hourly wind speed v_b = 30 m/s based on corrected CICIND model code wind profile

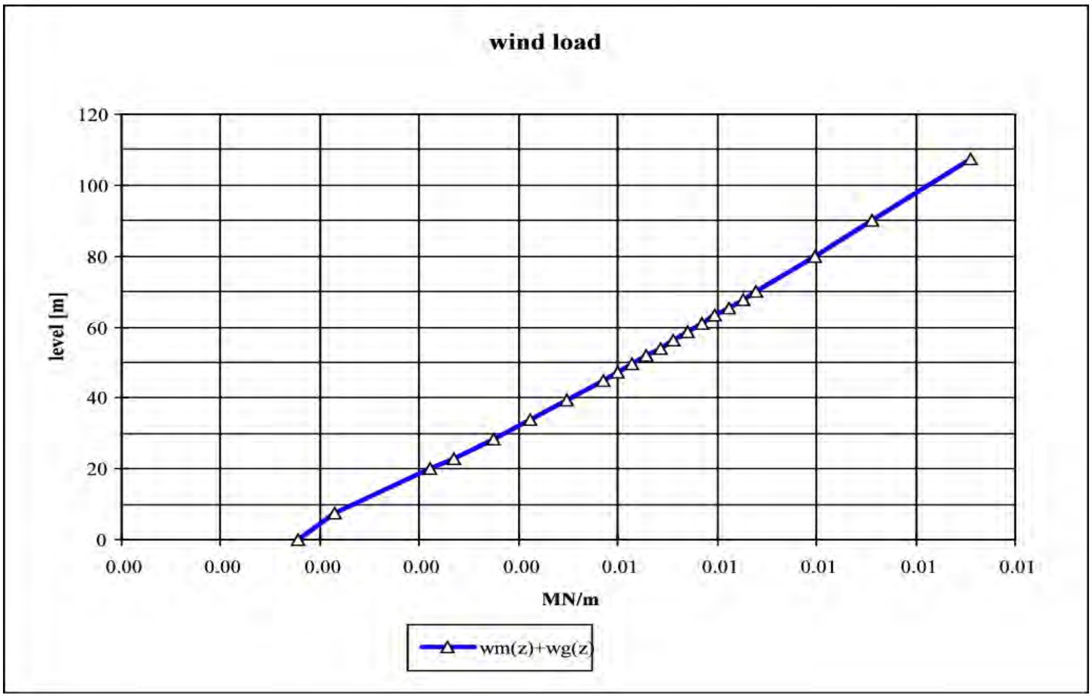

Figure 3 Wind load profile for Loviisa ventilation stack, basic mean hourly wind speed v_b = 25 m/s based on original CICIND model code wind profile

INTERNAL SECTION STRESS RESULTANTS AND THE STACK SECTION CAPACITIES

In order to assess the stack fragility the internal stress and resultant distribution because of wind has to be determined. Statically the stack is relatively simple structure and the stress resultants can be determined with Excel-spreadsheet for different basic mean hourly wind speeds by having v_b as a parameter in the sheets. For evaluating the fragility in different sections of the stack the section stress resultants were also evaluated using basic wind speeds v_b as parameter. For the sake of brevity these calculations are not presented in this report. To assess the random variability of the section stress resultants as well as the uncertainty in the modeling of the structure for the determination of section forces, the internal force distribution was also determined with two different finite element models, namely, shell model and stick model.

The elevations, where the stack capacities against bending mode failure and overturning failure were investigated, were chosen to be the locations, where the stack stiffness changes abruptly. These locations are +45 meters, +23 meters, +4.2, meters and the bottom of the base slab –0.7 meters, where the overturning capacity is checked.

The section bending moment capacities were evaluated according to methods of the references [9] and [10].

FRAGLITY EVALUATION

The fragility of a structure or equipment is defined as the conditional probability of its failure at a given value of characteristic load value. The methodology for evaluating fragilities of structures and equipment is documented PRA Procedures Guide (1983) and has been developed and applied in over 20 Probabilistic Risk Assessments of Nuclear Power Plants (PRA). The objective of fragility evaluation is to estimate the load capacity of a given structure component.

At any load parameter value, the structure or component fragility (i.e., conditional probability of failure) varies from 0 to 1; this variation is represented by a subjective probability distribution. On this distribution we can find a fragility value (say, 0.01) that corresponds to the cumulative subjective probability of 5%. We have 5% cumulative subjective probability (confidence) that the fragility is less than 0.01.

Similarly, we can find a fragility value for which we have a confidence of 95%. Note that these statements can be made without reference to any probability model. Using this procedure, the median and high (95%) and low (5%) confidence fragility curves can be drawn. On the high confidence curve, we can locate the fragility value of 5%; the load parameter corresponding to this fragility on the high confidence curve is the so called HCLF capacity of the component. By characterizing the component fragility through a family of fragility curves, the analyst has expressed all his knowledge about the capacity of the component along with the assessment of uncertainties. Given the same information, two analysts with similar experience and expertise would produce approximately the same fragility curves.

The entire fragility family for an element corresponding to a particular failure mode can be expressed in terms of the best estimate of the median load parameter capacity, Am and two random variables.

Thus, the ground acceleration capacity, A, is given by

$$A = A_m \varepsilon_R \varepsilon_U \qquad (8)$$

In Equation (5) ε_R and ε_U are random variables with unit medians, representing, respectively, the inherent randomness about the median and the uncertainty in the median value. In this model, we assume that both ε_R and ε_U are log-normally distributed with logarithmic standard deviations, β_R and β_U, respectively.

The formulation for fragility, given by Equation (5) and the assumption of lognormal distribution allows easy development of the family of fragility curves, which appropriately represent fragility uncertainty. The uncertainty in fragility needs to be expressed in a range of conditional failure probabilities for a given load parameter value.

With perfect knowledge (i.e., only accounting for the random variability, ε_R), the conditional probability of failure, f_o, for a given load parameter level, a, is given by

$$f_0 = \Phi[\ln(a/A_m)/\beta_R] \qquad (9)$$

In Equation (6) Φ (.)is the standard Gaussian cumulative distribution function. The relationship between f_0 and a is the median fragility curve. When the modeling uncertainty ε_U is included, the fragility becomes a random variable (uncertain). At each load parameter value, the fragility f can be represented by a subjective probability density function. The subjective probability, Q (also known as "confidence") not exceeding a fragility f' is related to f' by

$$f' = \Phi[\{\ln(a/A_m) + \beta_U \Phi^{-1}(Q)\}/\beta_U] \qquad (10)$$

$Q = P[f<f'|a]$ i. e., the subjective probability (confidence) that the conditional probability of failure, f, is less than f' for a peak load parameter value a; $\Phi^{-1}()$ = the inverse of the standard Gaussian cumulative distribution function.

The median load parameter capacity A_m , and its variability estimates β_R and β_U are evaluated by taking into account safety margins inherent in capacity predictions in structural analysis and uncertainty structural modelling.

For Loviisa ventilation stack the result of the fragility analysis against the wind effects can be summarized in the following Table 1 and plotted in Figure 4:

Table 1 Summary table of the stack fragilities

Elevation	Mean hourly wind, v_b (m/s) according to corrected CICIND wind profile	Mean hourly wind, v_b (m/s) according to original CICIND wind profile	β_R	β_u
+45	30	25	0.1	0.2
+23	30	25	0.1	0.2
+4.2	48.5	40	0.1	0.2
overturning at base	49	43	0.125	0.25

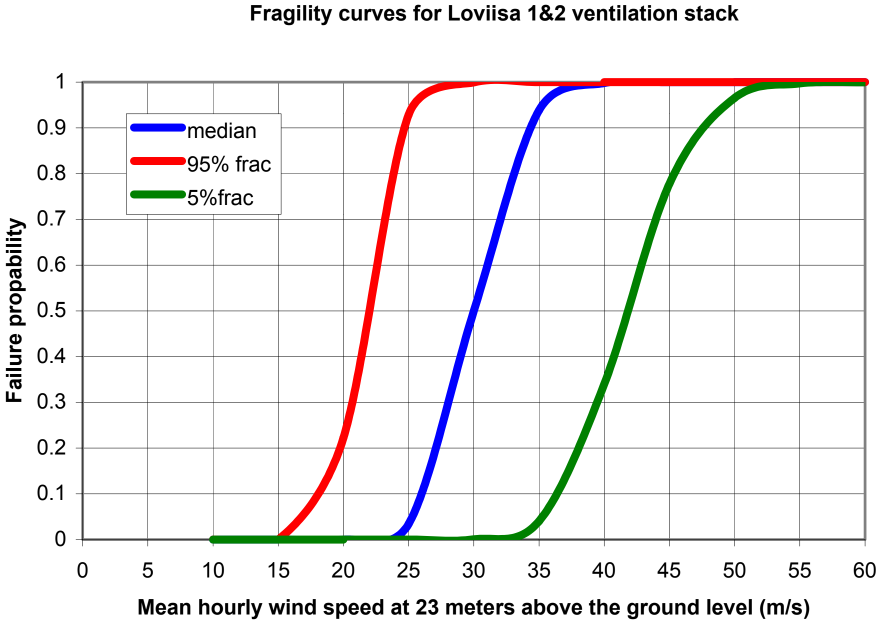

Figure 4 Plot of stack fragility curves against mean hourly winds

CONCLUSION

According to the results obtained, the Loviisa plant ventilation stack has its weakest section at elevation +45 meters. At this section the median value of the mean hourly wind capacity of the stack is 30 m/s if the assessment is based on corrected CICIND model code wind profile. The median value of the mean hourly wind capacity of the stack is 25 m/s if the assessment is based on original CICIND model code wind profile

This study has not made any attempt for evaluating the wind hazard at Loviisa plant site. To assess the risk of stack failure the wind hazard has to be evaluated. To be consistent with this fragility study the wind hazard should be evaluated in mean hourly wind speeds and the gust speeds should be measured as one second means.

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