

THE SEISMIC FRAGILITY ASSESSMENT OF THE FEED WATER TANKS PLANT USING ROBUST PREDICTION CONCEPT OF STRUCTURAL RESPONSE

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1 ABSTRACT

The computational task described in this paper is part of the updating effort of the Seismic Probabilistic Risk Assessment for Loviisa Nuclear Power Plant. Robustness in the prediction of structural response is an essential requirement for probabilistic fragility assessment. In order to develop the updated fragility curves for the feed water tanks in the Loviisa plant, which constitute the key element in assessing the core melt frequency of the plant, very detailed structural model incorporating the feed water tanks was developed. The fragility of a key plant component is defined as the conditional probability of its failure given a value of the response parameter, such as displacement, strain, stress or stress resultant. The first step in generating fragility is to develop a clear definition of what constitutes the failure of a component. It may be necessary to consider several modes of failure, and fragility is required for each mode. To assess the structural performance, it is important that robust predictions are made that treat all the uncertainties, from modeling applicable loads to modelling the structural behaviour. For large tanks, a failure of the support system or a plastic collapse of the pressure boundary is considered to be the dominant failure mode. Structures can be considered to fail functionally when the inelastic deformations under seismic loads are estimated to be sufficient to potentially interfere with the operability of equipment attached to the structure or fractured sufficiently for equipment attachments to fail. The event and fault trees should appropriately reflect these failure conditions. The fragility of large components is directly developed from the seismic response analysis results. The component fragility for a particular failure mode is expressed in terms of the ground-acceleration capacity A . The fragility is therefore the probability at which the random variable A is less than or equal to a specified value, a . The ground-acceleration capacity is, in turn, modelled as

$$\text{Equation 1 } A = \underline{A} \varepsilon_R \varepsilon_U$$

In Eq. (1) \underline{A} is the median ground-acceleration capacity, ε_R is variable representing the inherent randomness about A , and ε_U is a random variable representing the uncertainty in the median value. It is assumed that both ε_R and ε_U are log-normally distributed with logarithmic standard deviations β_R and β_U , respectively. As a result of the fragility evaluation the curves expressed with the aid of Equation 1 are given for the feed water tanks of Loviisa plant.

2 INTRODUCTION

The Loviisa Nuclear Power Plant obtained an extended operation license for the period of 2007 -2027 in July 2007. One of the conditions set in the safety assessment document that accompanied the license extension approval was the requirement to update the seismic probabilistic risk assessment of the plant dated from 1991. The text concerning the seismic PRA in the safety assessment of the given by STUK July 3, 2007 [1] was written as follows: "Except for the slow ground rising Finland's bedrock is steady. The dangerous earthquakes are considered in Finland extremely unlikely but the very weak earthquakes are perceived relatively often. The loads caused by the earthquakes were not taken into consideration separately in the design of the Loviisa nuclear power plant but the other load situations were expected to cover the seismic

loads well enough. Later it has turned out that the earthquakes may also be a significant risk factor to the nuclear power plants in the seismically low active areas if the horizontal loads caused by the earthquakes have not been taken into consideration at all in the design of the components or their supports. However, in the Loviisa nuclear power plant no especially seismically sensitive items have been identified. The seismic robustness of the Loviisa nuclear power plant has been estimated in a seismic risk analysis which has been completed in 1992. The central parts of the analysis are: 1) the evaluation of the annual occurrence frequency of the earthquakes of different sizes on the basis of seismological measurement data and on the basis of historical observations; 2) vibration analyses of buildings and determination of peak accelerations on separate floor elevations of the plant and 3) evaluation of the probability of the failure of the components and structures in earthquakes of different sizes. Generally speaking the seismic robustness of structures, systems and components in Loviisa nuclear power plant was estimated as good. The supports of feed water tanks and some direct current systems were estimated to be the most sensitive items. The core melt frequency caused by the earthquakes is relatively small on the basis of the analysis.

3 FINITE ELEMENT MODELLING FOR THE COMBINED TURBINE /CONTROL BUILDING

3.1 General

A large finite element (FE) model of the turbine hall was constructed using mainly shell elements. Beam and truss elements were used in some selected regions in order to simplify the modeling task. For example the additional support structures of the feed water tanks were modeled with beam elements. The concrete pedestals of the feed water tanks were modeled with solid brick elements. The turbine hall concrete floors and walls were modeled using special continuum shell elements which are available in Abaqus software [2]. The feed water tank capacity is the most important aspect for turbine/control building seismic probabilistic safety assessment. In order to assess the feed water tank capacity against susceptibility for leak and support failure the local detailed model of the tank and the support structures were set up. The capacity analysis of the feed water tank was carried out by increasing the calculated floor response spectra and corresponding synthetic floor motion stepwise beginning from ground motion peak acceleration value of 0.056g with the step of 0.056g so that the analyzed PGA values would be 0.056g, 0.112g, 0.178g, 0.234g, 0.28g, 0.336g, 0.392g, 0.448g, 0.504g, 0.56g. The concrete post-cracking behavior used in detailed feed water tank analysis has been taken according to the presented in the ABAQUS documentation [2]. Local finite element model for feed water tank fragility analysis including the tank itself, the two de-aerator towers, the three steel box structures presenting the support accessories for fixed middle support and roller end supports as well as the reinforced concrete pedestals anchored to the steel frame of the turbine building was developed. The finite element model of turbine/control building is depicted in Figure 1.

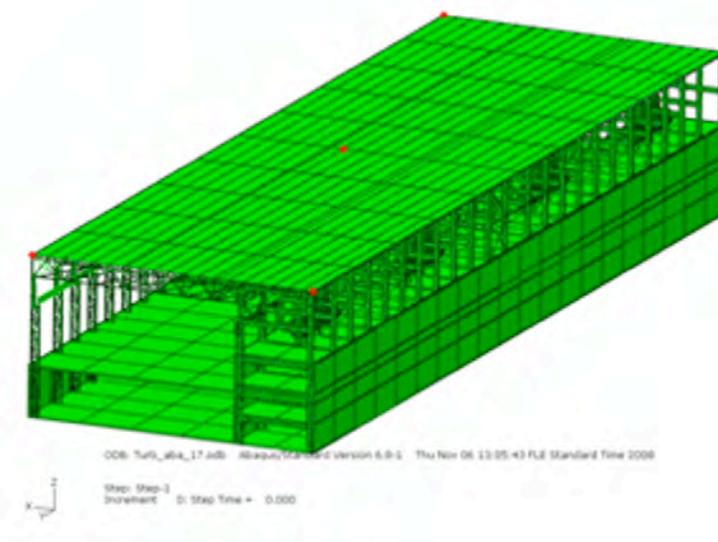


Figure 1. Turbine/control building FEM-model

3.2 Material Properties

General material properties are presented in Tables 1, 2 and 3 for each FE -model.

	ρ [kg/m ³]	E [MPa]	ν
Concrete	2500	30 000	0.2
Steel parts	7850	200 000	0.3

Table 1 Material properties for global linear model

	ρ [kg/m ³]	E [MPa]	ν	σ_Y [MPa]
Concrete	2500	30 000	0.2	10
Steel parts	7850	200 000	0.3	235

Table 2 Material properties for global model with perfectly plastic material model for steel and equivalent von Mises model for concrete

	ρ [kg/m ³]	E [MPa]	ν	σ_Y [MPa]
Concrete	2500	30 000	0.2	Brittle cracking shown in fig. 10
Concrete reinforcing bars	7850	200 000	0.3	250
Roller support	7850	200 000	0.3	Linear elastic
Feed water tank body	7850	200 000	0.3	250

Table 3 Material properties for local linear model of the feed water tank

3.3 Seismic Load

The ground motion response spectra shape used in the structural response analysis of the turbine building model has been taken from the YVL 2.6 – guide [3]. This spectral shape represents the envelope ground response spectrum for Southern Finland corresponding to the median annual occurrence frequency of 10^{-5} . The accepted spectral shape in YVL 2.6 is determined as follows. The acceleration values of the ground response spectrum are directly proportional to the peak acceleration of the ground surface (PGA), which corresponds to the spectral acceleration on high, over 50 Hz frequencies. With the frequencies which are smaller than 50 Hz the accelerations decrease in proportion to the relative damping of the oscillator supposed to be located in the bedrock surface. The suitable bedrock spectrum form corresponding to region south of the sixty third latitude in continental Finland and corresponding to the values of 0.056g (median value for 100 000 year frequency) for PGA and 5% for the relative damping of the oscillator is used as the definition of ground motion to be used as the excitation in structural models.

4 RESULTS

The functional failure mode of the tank is the loss of tightness. The yield limit of the tank steel material is 250 MN/m^2 . Since strain is the best measure of energy absorption and material rupture, energy limited events need to be based on acceptance criteria that are related to Strain Limits not

Stress Limits. The failure limit used in this report is the cumulated plastic strain of 8% in the reinforcing bars or anchor bolts. This failure limit has taken from the reference [4]. In this reference the proposed NRC strain-based acceptance criteria for energy-limited events are given. The failure strain limits e_u (strains at maximum load) are given for high strength carbon steel and for austenitic stainless steel 304L are given in the reference [4]. The recommendations given in reference [4] for the criteria to limit the average through the thickness equivalent plastic strain (EPS) for local and non-local strain values are:

Equation 2 $EPS < 0.9 \epsilon_{ut} / TR$ (local)

Equation 3 $EPS < 0.7 \epsilon_{ut} / TR$ (non-local)

In Equation 2 and in Equation 3 the parameter $TR = \text{Triaxiality Factor} = \text{Mean Stress} / \text{Octahedral Shear Stress}$ and

Equation 4 $\epsilon_{ut} = \ln(1 + e_u)$

In Equation 4 the e_u is the engineering strain. Following the reference [4] the cumulative plastic strain limit against loss tightness for the feed water tank steel material was taken to be 8%. The parameter to be followed and monitored in the numerical simulation of the failure modes local feed water tank model is called work equivalent plastic strain and its meaning is explained in the reference [4].

The seismic fragility of a component is defined as the conditional probability of its failure given a value of peak ground acceleration. Using the lognormal-distribution assumption, the fragility (i.e., the probability of failure, f') at any non-exceedance probability level Q can be derived as

Equation 5 $f' = \Phi[(\ln(a/A) + \beta_U \Phi^{-1}(Q)) / \beta_R]$

In Equation 5 $Q = P(f < f' | a)$ is the probability that the conditional probability f is less than f' for a peak ground acceleration a . A is the median ground acceleration capacity, β_R is the logarithmic standard deviation representing the inherent randomness about A , and β_U is the logarithmic standard deviation representing the uncertainty in the median value. The quantity $\Phi(\cdot)$ is the standard Gaussian cumulative distribution function, and $\Phi^{-1}(\cdot)$ is its inverse. The median value A for the feed water tank is obtained from failure criteria of 8% for the work equivalent plastic strain in the anchor bolts of the center support of the four feed water tanks modelled explicitly in global finite element model depicted in Figure 1 and the coefficients β_R and β_U are derived as in the following Table 4:

	β_R	β_U
Capacity Factor	0.00	0.23
Equipment Response Factor	0.08	0.17
Structural Response Factor	0.27	0.25
Ground Acceleration Capacity	0.28	0.38

Table 1 The derivation of logarithmic standard deviations $\beta_R = 0.28$ for randomness and $\beta_U = 0.38$ for uncertainty in Equation 4

Using the median peak ground acceleration capacity of 0.28g and logarithmic standard deviations $\beta_R = 0.28$ for randomness and $\beta_U = 0.38$ for uncertainty the graphical presentation of the fragility definition of the Equation 4 can be depicted as follows in Figure 2:

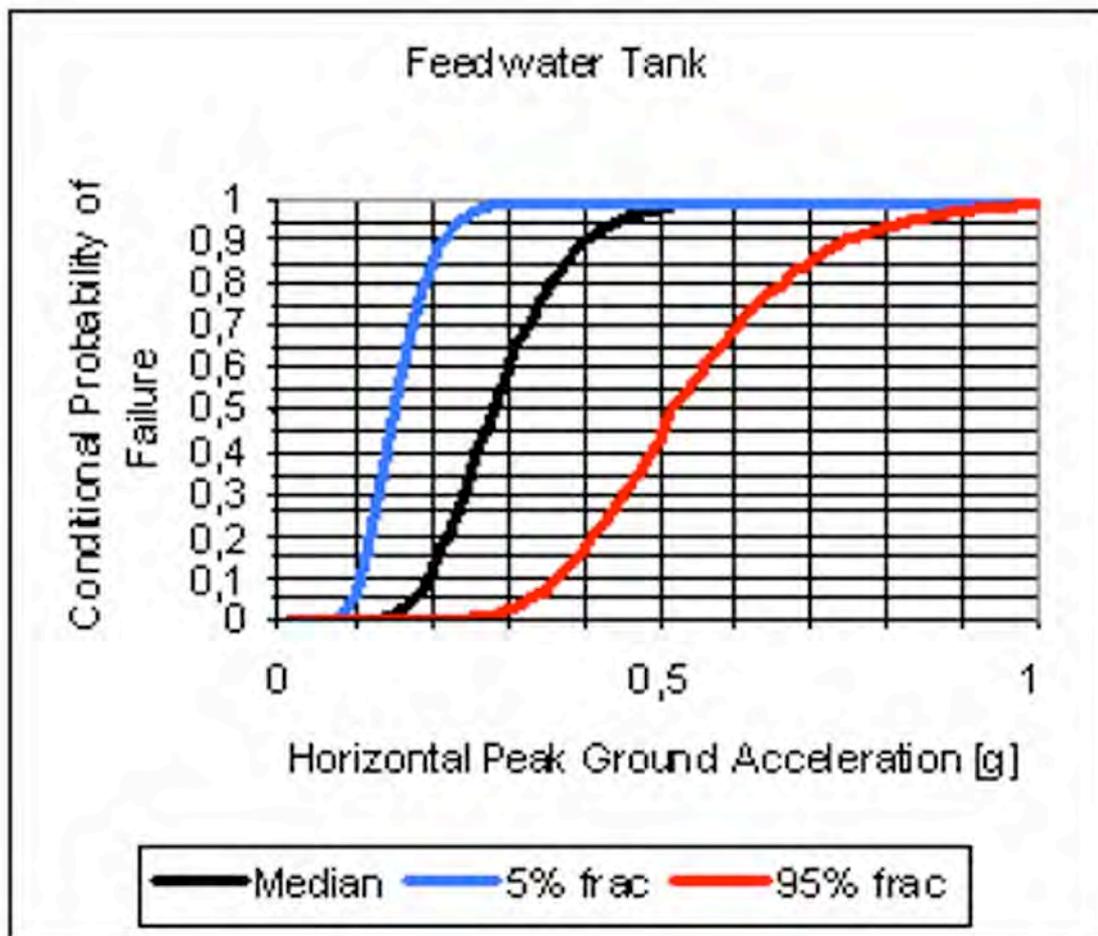


Figure 2 The updated fragility of the feed water tanks showing the median failure capacity of 0.28g in peak ground acceleration and the logarithmic standard deviations $\beta_R = 0.28$ for randomness and $\beta_U = 0.38$ for uncertainty

5 CONCLUSIONS

As a consequence of more accurate geometric modeling and more advanced material modeling as well as the use of new strain based failure criteria in estimating the component capacity the median value of the estimation for peak ground acceleration capacity of the Loviisa NPP main feed water tanks was increased from 0.15g obtained in the seismic PSA study from 1991 [5] up to the value of 0.28g obtained in the current study..

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