REAL TIME SAFETY SYSTEM (RTSS) FOR NUCLEAR POWER PLANTS SUBJECTED TO EXTERNAL EVENTS

Victor Kostarev, Peter Vasilyev, Maxim Vayndrakh
CKTI-Vibroseism Co. Ltd., St. Petersburg, Russian Federation
E-mail of corresponding author: vvk@cvs.spb.su

ABSTRACT

CKTI-Vibroseism (CVS) has proposed a new approach in evaluation of a safety state of nuclear power plants (NPPs) subjected to seismic or other extreme dynamic events of a natural and malevolent origin. The approach is named as RTSS (Real Time Safety System) and uses state of the art practice in a safety and structural mechanical analysis of NPP's structures, systems and components. The RTSS proposal was formulated first time in August 2010 at the IAEA EBP/ISSC meeting in Vienna.

The initiation point for developing of RTSS were lessons learned from Kashiwazaki-Karima NPP seismic event happened on July 17, 2007 when losses due to a shutdown of all 7 Units of the plant has achieved several billions dollars. To mitigate such negative consequences RTSS allows to make a fast real time risk analysis of structures, systems and components included in a safe shutdown equipment list (SSEL) using actual time history external event's input.

RTSS allows providing for operator an actual safety state of the main structures, systems and individual components in terms of probability of failure of safety systems, core damage or radiation release probability. Using RTSS operator will obtain comprehensive data to make a weighted and cost effective decision concerning shut down of the plant or to extend plant's operation during and after impact. RTSS has some essential technical advantages in comparison with usual NPP's seismic safe shutdown systems based on peak acceleration, cumulative absolute velocity (CAV) or other damage indicating parameters (DIPs). RTSS gives an opportunity to prevent enormous losses due to unjustified shutdown of the plants subjected to external events of different origins.

1. REAL TIME IN-STRUCTURE SPECTRA GENERATION

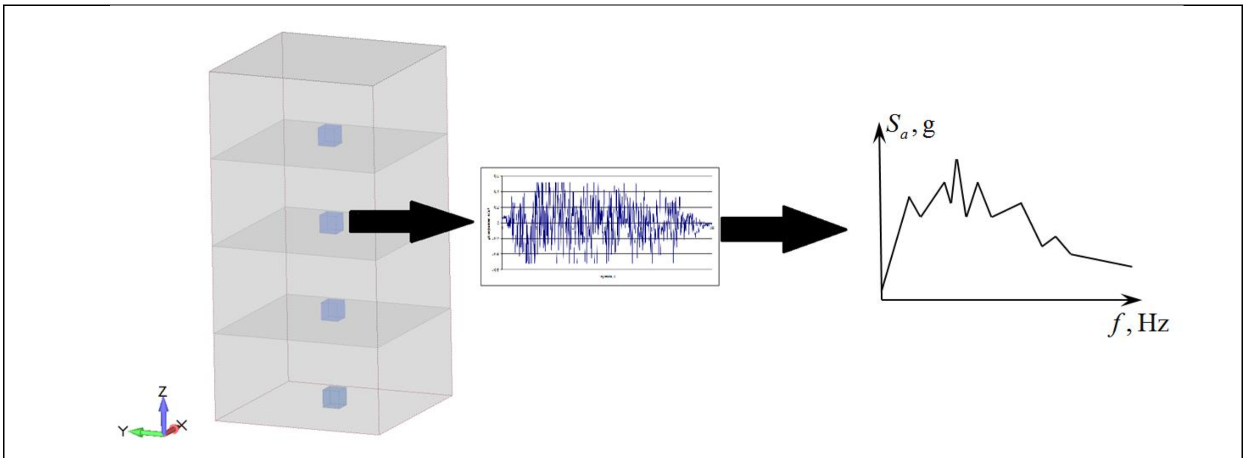

Figure 1 Spectra generation

It is supposed that initial dynamic impact on the building and components is measured by accelerometers installed at each elevation and/or in close proximity to critical equipment. The acceleration time histories for three orthogonal directions at each measuring point are used for in-structure spectra calculation for required frequencies and levels of damping (see Figure 1).

Thus resulting spectra is a posteriori demand information, free of uncertainty and conservatism inherent for priori general design seismic information as well of uncertainty related to a soil-structure interaction and other modeling issues. The proposed approach doesn't require any statistical processing (like peaks broadening and reduction) and calculation is performed in real time domain.

2. DAMAGE INDICATING PARAMETER

The risk of failure of a component upon certain failure mode is governed by «damage indicating parameter» (DIP), representing the inverse value of the traditional factor of safety in the SPRA or SMA methods:

$$DIP = \frac{D_S}{C - D_{NS}} \tag{1}$$

Here D_S represents the calculated parameter of dynamic response of component, C – maximum allowable value of D_S based on the strength or functional limitations, D_{NS} – other non-dynamic loads, reducing the capacity (e.g., due to normal operational loads). Similarly to the SPRA approach it is assumed that D_S and C are random variables, D_{NS} – constant (nonrandom):

$$D_S = \hat{D}_S \varepsilon_R \varepsilon_U\ ,\ C = \hat{C}\lambda_R \lambda_U\ , \tag{2}$$

$\hat{D}_S$, $\hat{C}$ – median values, ε_R , ε_U , λ_R , λ_U – lognormal distributed variables with unit median and logarithmic standard deviations β_R , β_U , δ_R , δ_U representing, respectively, the scattering of the calculated dynamic response D_S and capacity C around their median values. Traditionally, β_R and δ_R are responsible for inherent variability which cannot be reduced through investigations (earthquake component combination, mode combination, etc.), β_U and δ_U – represents the scatter of values because of insufficient knowledge on component modeling (damping, material strength, strength equation, etc.).

Thus, DIP is also lognormal distributed parameter with a median

$$D\hat{I}P = \frac{\hat{D}_S}{\hat{C} - D_{NS}} = \frac{D_S^*}{C^* - D_{NS}} \cdot \frac{1}{\hat{F}_S \hat{F}_\mu} \cdot \frac{1}{\hat{F}_{QM} \hat{F}_D \hat{F}_M \hat{F}_{MC} \hat{F}_{ECC}} \tag{3}$$

and logarithmic standard deviations:

$$\beta_R = \sqrt{\varepsilon_R^2 + \delta_R^2}\ ,\ \beta_U = \sqrt{\varepsilon_U^2 + \delta_U^2} \tag{4}$$

The demand D_S^* is calculated by standard deterministic linear analysis. The capacity C^* depends on the considered type of failure mode: in case of stresses it is reasonable to use maximum allowable code values, in case of functional limitations C^* determined by technological or other aspects of the equipment under consideration. Median values $\hat{F}$ lead the equipment conservative, biased capacity and demand to their median values:

- **Equipment Capacity** (e.g. for plastic collapse of component):
  - F_S – Strength Factor ($\hat{F}_S$ = 1.2 - 2.0);
  - F_μ – Inelastic Energy Absorbtion ($\hat{F}_\mu$ = 1.0 - 2.0);
- **Equipment Response:**
  - F_{QM} – Qualification Method ($\hat{F}_{QM}$ = 1.0 for RTSS approach);
  - F_D – Damping ($\hat{F}_D$ = 1.0 for median damping);
  - F_M – Modeling ($\hat{F}_M$ = 1.0);
  - F_{MC} – Mode Combination ($\hat{F}_{MC}$ = 1.0 for SRSS, CQC methods);
  - F_{ECC} – Earthquake Component Combination ($\hat{F}_{ECC}$ = 1.0 for SRSS comb. method)

The way of obtaining of logarithmic standard deviations is identical to well-known calculation procedures of fragility curves parameters in the SPRA [1], [2].

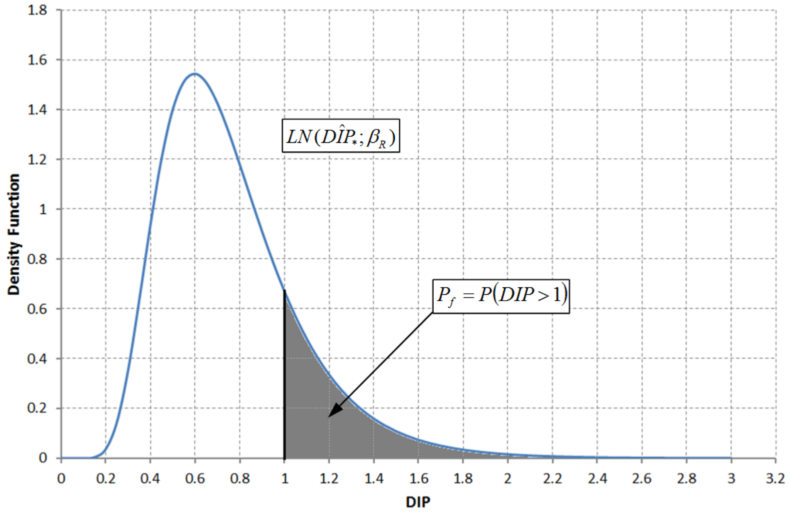

Figure 2 Example of density function of DIP distribution

Figure 2 shows a graph of density function of DIP with a median

$$D\hat{I}P_* = D\hat{I}P \cdot e^{u\beta_U} \tag{5}$$

and logarithmic standard deviation β_R. Here u - standardized normal variable corresponding to a given probability of non-exceedance for the median: $u = 0$ for 50% confidence, $u = 1.0$ for 84%, $u = 1.65$ for 95%.

An exceedance probability of unit by parameter DIP is the probability of failure of the component:

$$P_f = P(DIP > 1) \tag{6}$$

P_f is numerically equal to the area of the shaded sector under the curve (see Figure 2).

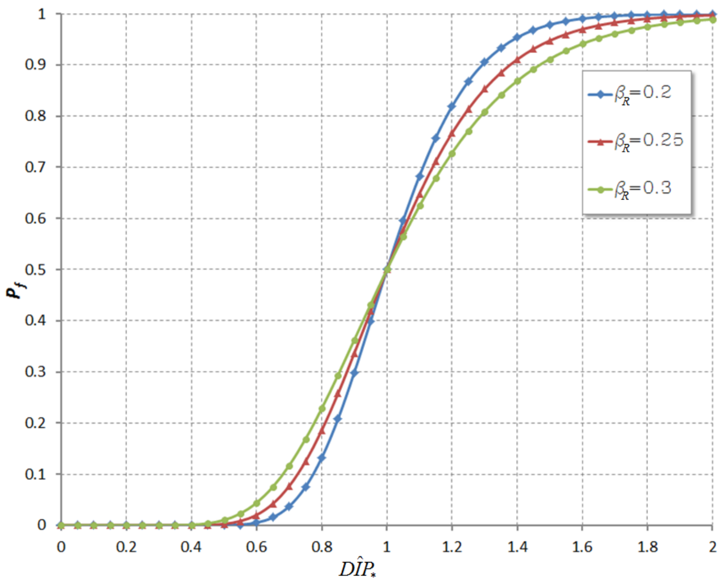

Figure 3 Dependence of failure probability P_f on the median $D\hat{I}P_*$ value for a specific deviations β_R

An example of DIP fragility curves is shown in Figure 3. The slope of curve determined by the measure of inherent uncertainty of response associated with β_R values.

The probability of failure at any non-exceedence probability level associated with standardized normal variable u can be derived as:

$$P_f = \Phi\left(\frac{\ln(D\hat{I}P) + u\beta_U}{\beta_R}\right) \tag{7}$$

where $\Phi(\ldots)$ is standard Gaussian cumulative distribution function.

The principal difference between RTSS and SPRA consists of knowing in-structure demand information in RTSS approach which allows to obtainmore accurate estimate of probability of component's damage after the earthquake. Table 1 shows the main parameters that define fragility curves of equipment in SPRA [1]. For RTSS composite logarithmic standard deviation in calculating of probability of failure is in the range 0.35-0.51, for the traditional fragility curve scattering is characterized by the values of 0.44-0.69.

Table 1 Main factors governing fragility curves and logarithmic standard deviation estimates

Equipment Capacity	Equipment Response	Structure Response
• Strength Factor • Inelastic Energy Absorption	• Qualification Method • Damping • Modeling • Mode Combination • Earthquake Component Combination	• Ground Motion • Damping • Modeling • Mode and Component Combination • Time History Simulation • Soil-Structure Interaction • Inelastic Structural Response
$\beta_R = 0.10 - 0.18$ $\beta_U = 0.22 - 0.32$ $\beta_C = 0.24 - 0.37$	$\beta_R = 0.18 - 0.25$ $\beta_U = 0.18 - 0.25$ $\beta_C = 0.25 - 0.35$	$\beta_R = 0.2 - 0.32$ $\beta_U = 0.18 - 0.33$ $\beta_C = 0.27 - 0.46$
RTSS: $\beta_C = 0.35 – 0.51$		
SPRA: $\beta_C = 0.44 – 0.69$		

3. DEMAND CALCULATION

It is important in the frame of proposed approach to have an adequate latency of getting results – core damage or safety systems damage probability caused by actual past earthquake. Obviously the calculation of response on recorded seismic input by FEM methods with subsequent processing of results takes a lot of time and cannot be performed automatically during the relevance of this information with the current developing of technology. It is the task for the future. Because of such time limitations it is reasonable to use response spectrum analysis method as a very useful tool to calculate the response:

- Maximum relative displacements on mode i :

$$\left\{u_i^k\right\}_{\max} = \frac{1}{\omega_i^2}\Gamma_i^k S_a\left(\omega_i, \varsigma_i\right)\{\varphi\}_i \quad (8)$$

- Maximum stresses/forces/reactions on mode i :

$$\left\{R_i^k\right\}_{\max} = \frac{1}{\omega_i^2}\Gamma_i^k S_a\left(\omega_i, \varsigma_i\right)\{R\}_i \quad (9)$$

Here $S_a(\omega_i, \varsigma_i)$ – design response spectrum for the circular frequency ω_i and the damping ς_i, corresponding to mode i ; Γ_i^k – modal participation factor for mode i in direction k ; $\{\varphi\}_i$ –normalized vector with displacements for mode i ; $\{R\}_i$ – stresses/forces/reactions values for mode i .

The total response on impact in k direction and earthquake component combination are determined by standard summation rules (SRSS, CQC, «100-40-40»).

At the preliminary stage a model (FEM, analytic) of component is built and all cofactors of $S_a(\omega_i, \varsigma_i)$ – ω_i , Γ_i^k , $\{\varphi\}_i$, $\{R\}_i$ – in (8), (9) are founded by means of modal analysis. Further the most vulnerable points of component and related failure modes under dynamic loading are identified.

An equipment failure mode may consist of failure tofunction during impact, or pressure boundary collapse for vessels and pipelines. Some typical forms of failure for various types of equipment are listed in [2, 3, 4].

4. ACCOUNTING OF MULTIPLE POSSIBLE FAILURE MODES OF COMPONENT

The consideration of several possible failure modes of component leads to the definition of event «failure of component». Obviously it is a disjunction of events $A_1, A_2, \ldots, A_m$, each of them corresponds to the failure of a particular mode:

$$FP = A_1 \cup A_2 \cup A_3 \cup \ldots \cup A_m \quad (10)$$

Rather a complicated issue is a degree of correlation between events $A_1, A_2, \ldots, A_m$ of common initiating cause, however, it is assumed that failures of different modes are independent events. Then the probability of failure of component can be expressed by:

$$P_{FP} = 1 - \prod_{j=1}^{m} \left(1 - P_{A_j}\right) \tag{11}$$

5. SEQUENCE QUANTIFICATION AND DECISION MAKING

Further procedure flow partly overlaps with SPRA: developing a list of initiating events, event and fault trees, end states. Traditionally, event trees display the success or failure of various safety systems leading from initial event to an end state. For each of the systems in an event tree there is a corresponding fault tree which relates the various structure and equipment failures [2]. Having assessed the probabilities of failure of safety systems by means of fault trees, we come out to the probabilities of different types of end states realizations. The obtained values of the probability of failure can be grouped by type of end state (core damage, small release, large release etc.) and then for each type constructed its probability measure scale. Leaving for a future research and discussion its numerical performance, qualitative it can be divided into two states:

A. The operation can be continued without shutdown (for low failure probability of failure, $P < P_1$)

B. The operation can be continued after shutdown and detailed inspection of individual components or systems (for $P > P_1$)

For the case «B» the operator has an ability to see the main risk contributors among safety systems and then go down to the level of individual components that govern the failure of the whole system. The detailed inspections of these components can clarify further steps to a safe reactor start-up. At the same time the express-analysis of potential damage of safety systems allows the operator to choose the path of shutting down using the systems of minimal probabilities of failure.

6. EXAMPLE

To illustrate the ideas of RTSS a simplified model of a single channel of the emergency core cooling system (ECCS) has been developed. The scheme of the channel is shown on the Figure 4. The main function of the system duplicated in three channels is a boron injection to the main loop. The channel consists of a tank, pipeline, two motor operated valves and a pump with electric motor. Failure of any of these elements leads to failure of the channel. The success of the whole system can be achieved when working one or two channels of three. Probability of failure of system elements depends on the probability of failure of other systems, as shown on the Figure 4. For example, the normal operation of the pump requires water cooling system for cooling the pump bearings, ventilation system to cool the motor, power supply and control system. In the given model these interactions are not accounted, but when a real RTSS is built, of course, it should be considered.

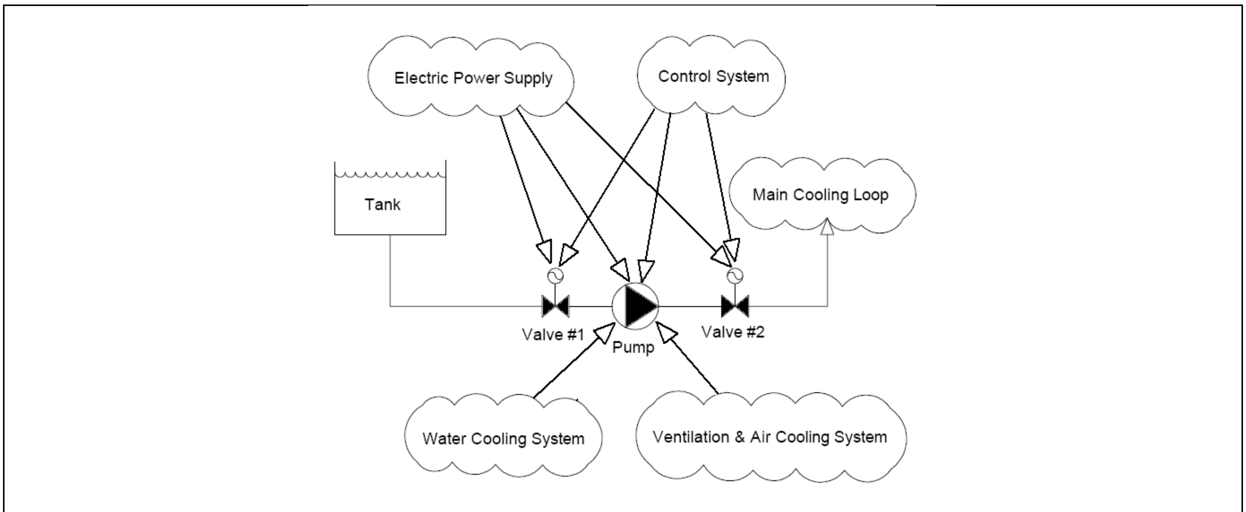

Figure 4 Mocked-up scheme of the single channel of ECCS

A FE model of the pipeline is shown on Figure 5. A collapse of supporting steel construction is chosen as a failure mode for the tank; for the valve – absolute acceleration on the body or drive exceeding the value 3g (can lead to malfunction); for the pump – inertia load on the thrust bearing and the load on the pump nozzles; for the pipeline – break of the rod hangers and pipeline plastic collapse.

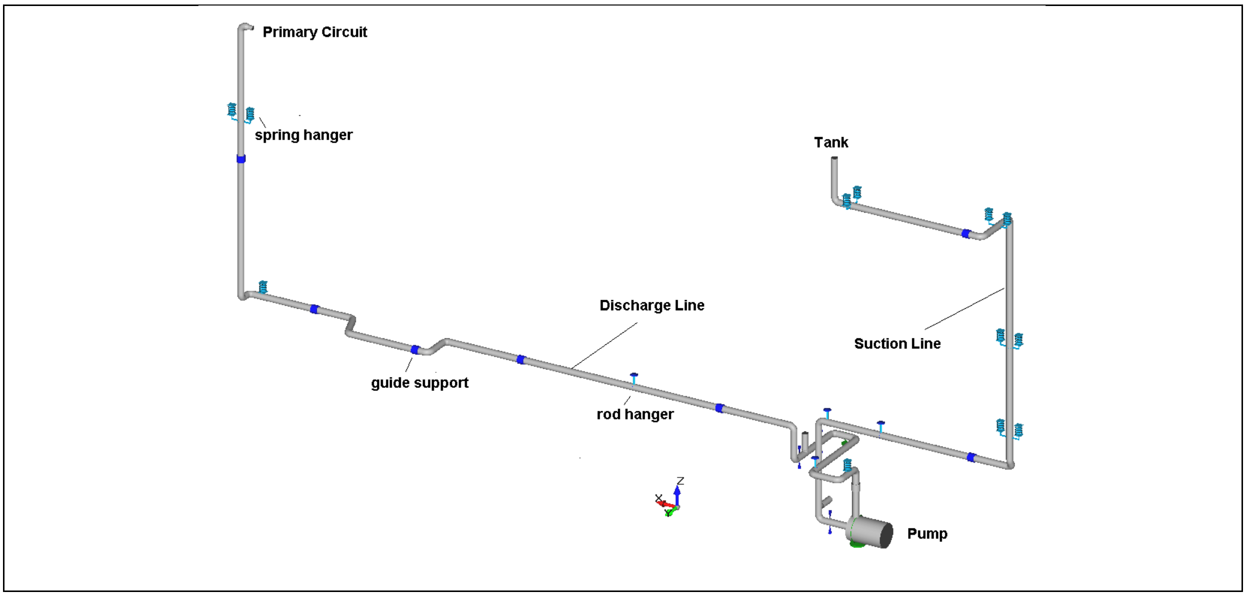

Figure 5 FE model of the pipeline

The formulas for DIP calculations are shown on the Table 2. They contain the following notations for the spectral response: $S_{3x}(12,5)$ means the value of the acceleration response spectra (m/s^2) for the oscillator with a natural frequency of 12 Hz and relative damping of 5% on impact on the third floor in the X-direction. Spectra values are the functions of time and will grow up during the earthquake.

Table 2 Equipment failure modes and corresponding formulas for DIP

Element	Failure mode #	Failure mode	Formulas for DIP
Tank	1	Collapse of supporting steel construction	$DIP := 0.045\sqrt{S_{3x}(4,5)^2 + S_{3y}(2.5,5)^2}$
Valve #1 (suction line)	2	Malfunction due to valve body high acceleration	$DIP := 0.0131\cdot\sqrt{S_{1x}(1.06,5)^2 + (0.69\cdot S_{1z}(9.99,5))^2}$
Valve #2 (discharge line)	3	Malfunction due to valve actuator high acceleration	$DIP := 0.0322\cdot\sqrt{(0.16\cdot S_{1y}(2.86,5))^2 + S_{1z}(13.7,5)^2}$
Pump	4	Malfunction of the thrust bearing due to overloading in axial direction	$DIP := 0.12\cdot S_{1x}(8.9,4)$
	5	Malfunction due to overloading of suction nozzle	$DIP := 0.128\cdot S_{1y}(2.86,5)$
	6	Malfunction due to overloading of discharge nozzle	$DIP := 0.121\cdot\sqrt{S_{1x}(1.06,5)^2 + (0.91\cdot S_{1x}(5.42,5))^2}$
Pipeline	7	Rod hanger break in node A15	$DIP := 0.0325\cdot\sqrt{S_{2y}(1.06,5)^2 + (0.79\cdot S_{2x}(11.03,5))^2}$
	8	Rod hanger break in node B1	$DIP := 0.0177\cdot S_{2z}(9.99,5)$
	9	Rod hanger break in node 87	$DIP := 0.0214\cdot\sqrt{S_{2x}(4.12,5)^2 + (0.43\cdot S_{2x}(2.29,5))^2 + (0.42\cdot S_{2y}(2.29,5))^2 + (0.6\cdot S_{2z}(17,5))^2 + (0.54\cdot S_{2x}(3.03,5))^2}$
	10	Plastic collapse of suction line	$DIP := 0.0608\cdot\sqrt{S_{2y}(2.86,5)^2 + (0.29\cdot S_{2x}(2.29,5))^2 + (0.28\cdot S_{2y}(2.29,5))^2 + (0.2\cdot S_{2x}(1.91,5))^2 + (0.16\cdot S_{2y}(1.91,5))^2 + (0.33\cdot S_{2x}(3.03,5))^2}$
	11	Plastic collapse of discharge line	$DIP := 0.175\cdot S_{2y}(1.06,5)$

The in-structure motion was calculated using a simple stick model of the reactor building and records of the earthquake made by Zarand station (Iran) in February 22, 2005. One of three ground motion acceleration time histories (direction N-S (X) and the stick model is shown on Fig. 6.

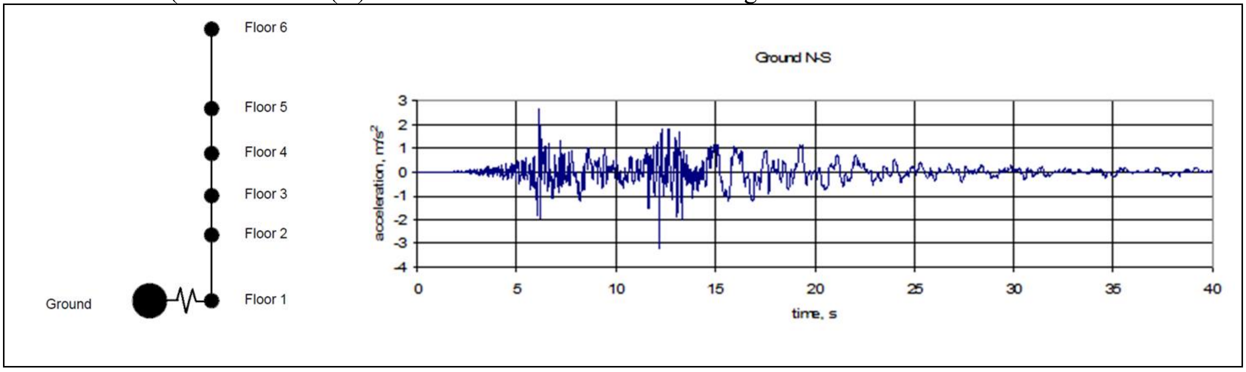

Figure 6 Stick model of the reactor building and N-S accelerogram of ground motion

Fig. 7 shows the acceleration time history of the first floor and the time variation of the spectral response at frequencies 1.08 Hz and 5.42 Hz, which determine the load of pipeline on the pump discharge nozzle.

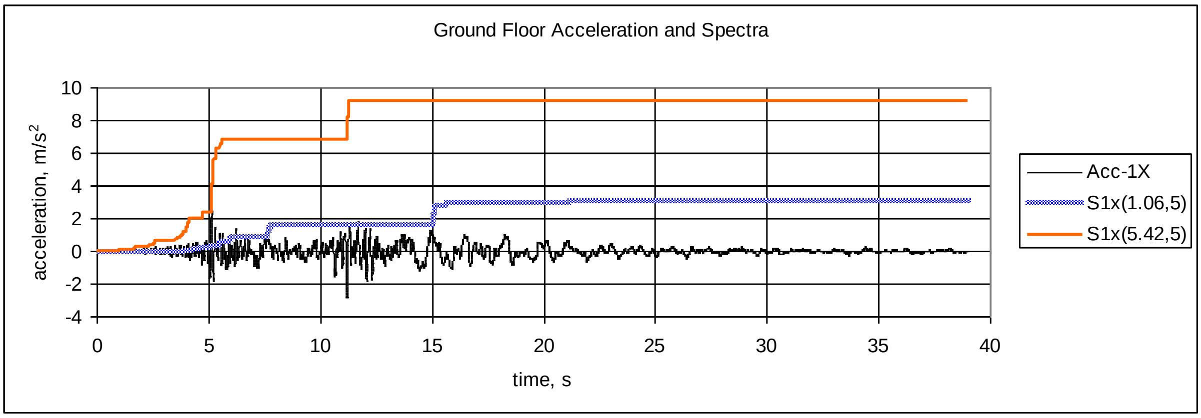

Figure 7 Accelerogram of the first floor and spectral response at frequencies 1.08 Hz and 5.42 Hz

Fig. 8 shows the time variation of DIP related to the load on the pump nozzle and a corresponding variation in the probability of failure (here $\beta_R = 0.25$, $u = 0$, see formula (7)).

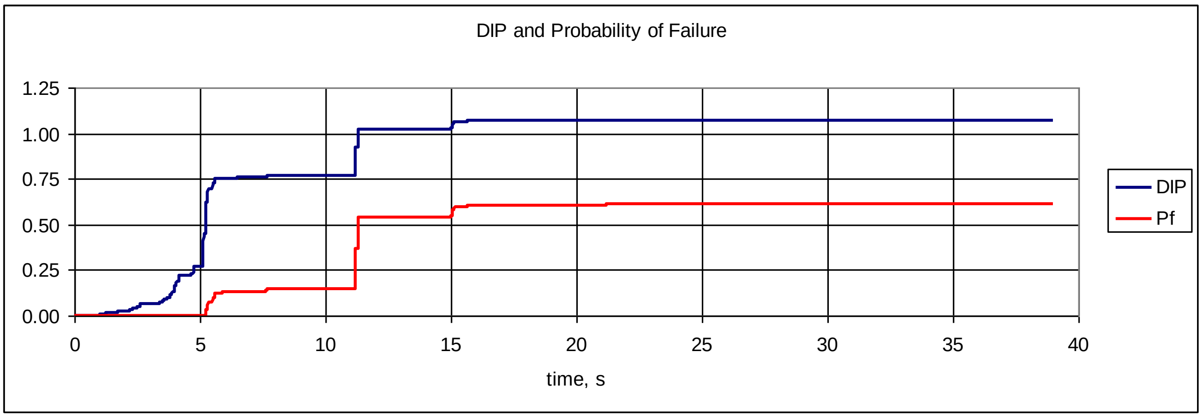

Figure 8 Time variation of DIP related to the load on the pump nozzle and corresponding probability of failure

To illustrate the sensitivity of the proposed approach to the spectral characteristics of earthquake ground motion two calculations has been carried out. In the first case the records of Zarand ground motion used as is, in the second case accelerograms was modified by multiplying the time step by 1.15. Thus, the frequency was reduced by 13%. ZPGA of both cases exactly the same, response spectrum and parameter CAV differ slightly. The results are presented in Tables 3-4.

Table 3 Equipment failure modes and corresponding probabilities of failure for original ground motion

DIP #	Equipment	DIP	P_f	Equipment P_f	Channel P_f	System P_f
1	Tank	0.781	0.1610	0.1610	**0.6943**	**0.3347**
2	Valve #1	0.060	1.4E-29	1.4E-29		
3	Valve #2	0.149	1.4E-14	1.4E-14		
4	Pump	0.640	0.0370	**0.6282**		
5		0.535	0.0062			
6		1.073	**0.6115**			
7	Pipe	0.137	1.0E-15	0.0200		
8		0.312	1.6E-06			
9		0.250	1.5E-08			
10		0.457	0.0009			
11		0.596	0.0191			

Table 4 Equipment failure modes and corresponding probabilities of failure for modified ground motion

DIP #	Equipment	DIP	P_f	Equipment P_f	Channel P_f	System P_f
1	Tank	0.871	**0.2897**	**0.2897**	**0.5189**	**0.1397**
2	Valve #1	0.069	4.7E-27	4.7E-27		
3	Valve #2	0.149	1.3E-14	1.3E-14		
4	Pump	0.644	0.0393	**0.3222**		
5		0.493	0.0023			
6		0.873	**0.2928**			
7	Pipe	0.130	1.8E-16	0.0008		
8		0.230	2.0E-09			
9		0.301	7.7E-07			
10		0.444	0.0006			
11		0.415	0.0002			

The results show that in the first case the threat of pump failure prevailed and in the second case there are two roughly equally probable threats: breaking the pump and collapse of the tank supporting frame.

However, in the second case the probability of system failure, i.e. all three of its channels proved to be lower by more than two times.

CONCLUSION

The Real Time Safety System (RTSS) is proposed for the existing NPPs and nuclear installations to mitigate risk of a nuclear accident and/or in order to prevent possible losses in result of seismic and other extreme dynamic events of natural, man-made or malevolent origins.

RTSS allows to perform a real time safety analysis of a nuclear installation safety path and provides to the Operator valuable information in probabilistic form of actual safety state of structures, systems, components and distribution systems included in safe shutdown equipment list (SSEL). On the basis of this information the Operator would be able to make a weighted decision and to do real time determining of the weakest SSEL elements during and after extreme dynamic event.

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