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A Seismic Response Time History Analysis for a Seismically Isolated Reactor Structure of PGSFR

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1. Introduction

PGSFR (Prototype Gen-IV Sodium Cooled Fast Reactor) has adopted a horizontal seismic isolation system [1]. Seismic response time history analyses for the seismically isolated reactor structure are performed for several cases. The maximum deformation of the isolator and the maximum acceleration responses of the isolated reactor building and reactor structure are calculated.

The influential factors considered in analyses are the structural damping, the skeleton curve of the bilinear model featured by the limiting value of the primary stiffness and vertical resisting weight of the isolators.

The full analysis model for the reactor, auxiliary and fuel buildings with the numerous elements[2] was simplified to shorten the computation time in the seismic response time history analysis using ANSYS[3].

Using the analysis model, the seismic response analyses for an artificial time history (ATH) earthquake of 0.3g are performed by replacing the influential parameters and the result responses are evaluated.

2. Configuration of analysis model

The reactor building has a circular dome shape, with 45,032 tons, as shown in Table 1, it is located at the center area of the PGSFR auxiliary building, which is connected to the reactor building at the common basemat and is excluded in analysis model. The reactor building includes a 1.5 m thick reactor support wall at the innermost side and a huge cylinder containment at the outside as shown in Fig.1.

A simple 8-node beam-mass model of the reactor structure is supported on reactor support wall at the innermost side [4]. This model weight is 1,997 tons.

Table 1 Weight and dead loads of reactor structure and building

Components	Element type	Thickness	Weight (ton)
RV base-mat	Solid185	2.0 m	4,230
Roof	Shell181	1.2 m	2,929
Outer wall	Shell181	1.5 m	21,094
Rx structure support walls	Shell181	1.5 m, 0.9 m	4,802
Floor slab	Shell181	0.6 ~ 0.9 m	4,972
Internal walls	Shell181	0.3 ~ 0.6 m	5,006
Rx structure	Beam4 & mass		1,997
Rx - building connections	cerig		
			45,032
Floor dead loads	Surf154	25% ~ 125% (97.65 kg/m^2)	1,512

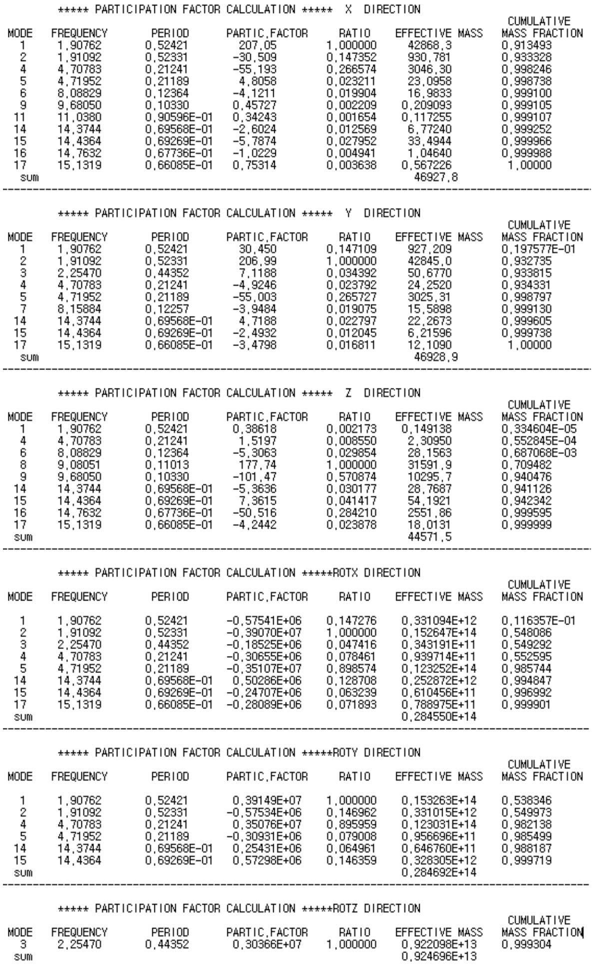
3. Seismic response time history analysis

3.1 Modal analysis

The natural frequencies of the analysis model was calculated with the primary horizontal stiffness (K1XY) of the isolator, which is about 100 times higher value than the secondary softening stiffness (K2XY) as shown in Fig.2. The natural frequencies are represented in Table 2. The first and second frequencies in horizontal are 1.9 Hz and 4.7 Hz, respectively. These are combined mode shapes of the horizontal isolation mode and the first bending mode of reactor building as shown in Fig.2. The first frequency in vertical direction is 9.08 Hz.

The secondary softening stiffness (K2XY) of the isolator is actively influenced on the isolation response behavior for a strong seismic load over 0.3g.

Table 2 Natural frequencies of reactor structure and building of PGSFR



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        ***** PARTICIPATION FACTOR CALCULATION *****  X  DIRECTION
                                                                            CUMULATIVE
MODE   FREQUENCY        PERIOD       PARTIC,FACTOR     RATIO     EFFECTIVE MASS   MASS FRACTION
  1     1,90762        0,52421        207,05         1,000000     42868,3         0,913493
  2     1,91092        0,52331       -30,509         0,147352     930,781         0,933328
  4     4,70783        0,21241       -55,193         0,266574     3046,30         0,998246
  5     4,71952        0,21189        4,8058         0,023211     23,0958         0,998738
  6     8,08829        0,12364       -4,1211         0,019904     16,9833         0,999100
  9     9,68050        0,10330       0,45727         0,002209    0,209093         0,999105
 11     11,0380       0,90596E-01    0,34243         0,001654    0,117255         0,999107
 14     14,3744       0,69568E-01   -2,6024          0,012569     6,77240         0,999252
 15     14,4364       0,69269E-01   -5,7874          0,027952     33,4944         0,999966
 16     14,7632       0,67736E-01   -1,0229          0,004941     1,04640         0,999988
 17     15,1319       0,66085E-01    0,75314         0,003638    0,567226          1,00000
  sum                                                              46927,8
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        ***** PARTICIPATION FACTOR CALCULATION *****  Y  DIRECTION
                                                                            CUMULATIVE
MODE   FREQUENCY        PERIOD       PARTIC,FACTOR     RATIO     EFFECTIVE MASS   MASS FRACTION
  1     1,90762        0,52421        30,450         0,147109     927,209         0,197577E-01
  2     1,91092        0,52331        206,99         1,000000     42845,0         0,932735
  3     2,25470        0,44352        7,1188         0,034392     50,6770         0,933815
  4     4,70783        0,21241       -4,9246         0,023792     24,2520         0,934331
  5     4,71952        0,21189       -55,003         0,265727     3025,31         0,998797
  7     8,15884        0,12257       -3,9484         0,019075     15,5898         0,999130
 14     14,3744       0,69568E-01    4,7188          0,022797     22,2673         0,999605
 15     14,4364       0,69269E-01   -2,4932          0,012045     6,21596         0,999738
 17     15,1319       0,66085E-01   -3,4798          0,016811     12,1090          1,00000
  sum                                                              46928,9
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        ***** PARTICIPATION FACTOR CALCULATION *****  Z  DIRECTION
                                                                            CUMULATIVE
MODE   FREQUENCY        PERIOD       PARTIC,FACTOR     RATIO     EFFECTIVE MASS   MASS FRACTION
  1     1,90762        0,52421        0,38618        0,002173    0,149138         0,334604E-05
  4     4,70783        0,21241        1,5197         0,008550     2,30950         0,552845E-04
  6     8,08829        0,12364       -5,3063         0,029854     28,1563         0,687068E-03
  8     9,08051        0,11013        177,74         1,000000     31591,9         0,709482
  9     9,68050        0,10330       -101,47         0,570874     10295,7         0,940476
 14     14,3744       0,69568E-01   -5,3636          0,030177     28,7687         0,941126
 15     14,4364       0,69269E-01    7,3615          0,041417     54,1921         0,942342
 16     14,7632       0,67736E-01   -50,516          0,284210     2551,86         0,999595
 17     15,1319       0,66085E-01   -4,2442          0,023878     18,0131         0,999999
 sum                                                               44571,5
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        ***** PARTICIPATION FACTOR CALCULATION *****ROTX DIRECTION
                                                                            CUMULATIVE
MODE   FREQUENCY        PERIOD       PARTIC,FACTOR     RATIO     EFFECTIVE MASS   MASS FRACTION

  1     1,90762        0,52421      -0,57541E+06     0,147276    0,331094E+12     0,116357E-01
  2     1,91092        0,52331      -0,39070E+07     1,000000    0,152647E+14     0,548086
  3     2,25470        0,44352      -0,18525E+06     0,047416    0,343191E+11     0,549292
  4     4,70783        0,21241      -0,30655E+06     0,078461    0,939714E+11     0,552595
  5     4,71952        0,21189      -0,35107E+07     0,898574    0,123252E+14     0,985744
 14     14,3744       0,69568E-01    0,50286E+06     0,128708    0,252872E+12     0,994847
 15     14,4364       0,69269E-01   -0,24707E+06     0,063239    0,610456E+11     0,996992
 17     15,1319       0,66085E-01   -0,28089E+06     0,071893    0,788975E+11     0,999901
 sum                                                              0,284550E+14
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        ***** PARTICIPATION FACTOR CALCULATION *****ROTY DIRECTION
                                                                            CUMULATIVE
MODE   FREQUENCY        PERIOD       PARTIC,FACTOR     RATIO     EFFECTIVE MASS   MASS FRACTION

  1     1,90762        0,52421        0,39149E+07     1,000000    0,153263E+14     0,538346
  2     1,91092        0,52331      -0,57534E+06     0,146962    0,331015E+12     0,549973
  4     4,70783        0,21241        0,35076E+07     0,895959    0,123031E+14     0,982138
  5     4,71952        0,21189      -0,30931E+06     0,079008    0,956696E+11     0,985499
 14     14,3744       0,69568E-01    0,25431E+06     0,064961    0,646760E+11     0,988187
 15     14,4364       0,69269E-01    0,57298E+06     0,146359    0,328305E+12     0,999719
 sum                                                              0,284692E+14
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        ***** PARTICIPATION FACTOR CALCULATION *****ROTZ DIRECTION
                                                                            CUMULATIVE
MODE   FREQUENCY        PERIOD       PARTIC,FACTOR     RATIO     EFFECTIVE MASS   MASS FRACTION
  3     2,25470        0,44352        0,30366E+07     1,000000    0,922098E+13     0,999304
 sum                                                              0,924696E+13
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3.2 Seismic response time history analysis

In the seismic response time history analysis using ANSYS, the artificial time history (ATH) earthquake of 0.3g was directly applied to the fixed lower basemat supporting the isolators of the analysis model.

The seismic response analyses were performed for 4 cases by changing the influential parameter values in Table 3.

Table 3 Seismic responses w.r.t analysis input parameters

Case No.	Influential input parameters			Maximum acceleration responses (g)						Max. LRB disps. (mm)
	#1	#2	#3							
	LRB, bilinear model, Q_d (ton)	Structural damping coefficients (α, β)	LRB vertical resisting force (ton)	RV support (330288)		RV bottom (330195)		Building top (137368)		Basemat center (130026-330026)
				x, y	z	x, y	z	x, y	z	x / y
1	25,044 (10%)	high structural damping α:1.736406 β:0.00119	1,268 (122 % of average)	0.051 0.041	0.389	0.102 0.043	0.594	0.057 0.044	0.957	240/250
2	250,442 (100%)					0.114 0.103	0.597	0.132 0.114	0.957	185/195
3		low structural damping α:0.30947 β:0.000475				0.181 0.130	0.689	0.136 0.167	1.122	310/250
4			1,036 (45 isolators, average)			0.186 0.152	0.71	0.210 0.179	1.17	277/223

3.3. Seismic response analysis summary results

The seismic response analysis results at selected points for the four model cases were evaluated with the expected ones.

The model of Case 1 is that the limiting value (FSLIDE, Q_d) of the primary stiffness in skeleton curve of the isolator's bilinear model is decreased to 1/10. The Q_d is a parameter affecting only for the horizontal response. The horizontal maximum acceleration response at the bottom of the reactor vessel (node 7) was about 0.1 g in Figs.4~5, and the maximum deformation of the isolators was calculated by 250 mm.

The model of Case 2 is that Q_d is set to the initial value (100%). The horizontal maximum acceleration response was increased by 10% to 0.11g from 0.1g at node 7 as shown in Fig.6, and the maximum deformation of the isolators was calculated by 195 mm.

The model of Case 3 is that the Q_d is the same as Case 2 and the structural damping coefficient [α, β] of the analysis model is set to be smaller than the initial value so that the structural damping ratio[5] is less than 5% for the frequency content between 3 Hz and 10 Hz as represented in Fig.3. As a result, the structural damping ratio applied is so high above 20% at the isolation frequency of 0.5 Hz. So, the damping coefficients are adjusted so that the maximum 5% structural damping is applied to the frequency content between 0.5 Hz and 33 Hz. Then, the horizontal maximum acceleration response was increased by 80% at node 7 to 0.18g, and the acceleration in the vertical direction was increased from 0.597g to 0.689g. The maximum deformation of the isolators was calculated by 310 mm, an increase of 59% over Case 2.

In the model of Case 4, the parameter Q_d is the same as Case 2, and the damping coefficients of the structure are the same as Case 3, the vertical support load of the isolator was reduced to 1,036 tons, which is equivalent to 10% increase of the seismic isolation frequency. The analysis results were represented in Figs.7~8. The horizontal maximum acceleration response was increased by 8% to 0.186 g at node 7, and the vertical acceleration was slightly increased from 0.689g to 0.71g. The maximum deformation (277 mm) of isolators was reduced by 10%, compared to the Case 3.

The maximum deformation of the isolators and a slight increase in the horizontal acceleration in Case 4 were acceptable at the seismic isolation system design point.

4. Seismic isolation effects compared to non-isolation

For checking the seismic isolation effects, the seismic analysis results for two models of seismic isolation and non-isolation were compared. The vertical support load of the isolator is 1,036 tons and the Q_d is the same as Case 4. Both models have the low structural damping as follows.

- $\alpha = 0.30947$
- $\beta = 0.000475$

In the vertical direction, the acceleration response of 0.71g was recorded at node 7 for the isolation model, and 0.83g for non-isolation model as shown in Fig. 9. The results were caused by the overall amplification of the seismic response near 10 Hz of the natural frequency of the reactor building in vertical direction.

In the horizontal direction, the acceleration response of 0.19 g was recorded at node 7 for the isolation model, but the acceleration response of 1.3g for non-isolation model as shown in Fig.10. The seismic response acceleration in horizontal direction was reduced to 1/6 level by the seismic isolation system. Most of the seismic input energy in the horizontal direction was absorbed by the seismic isolators.

5. Conclusion

The several parameters affecting on seismic response time history analysis were identified by using the seismically isolated analysis model.

The acceleration response of the reactor structure is increased by the limiting value (Q_d) of the primary stiffness in the skeleton curve of the bilinear model for the isolator. The structural damping coefficients should be determined so that an over-damping value at the isolation frequency of an isolated structure system is not allocated.

The seismic response acceleration in the vertical direction was not affected by the horizontal seismic isolation bearings, while the seismic response acceleration in the horizontal direction was greatly reduced to 1/6 level by the seismic isolation system.

ACKNOWLEDGEMENT

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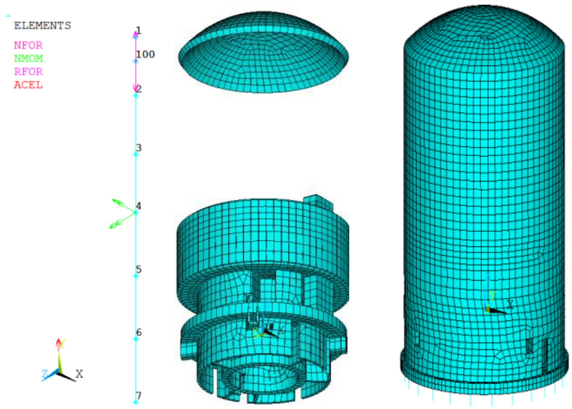
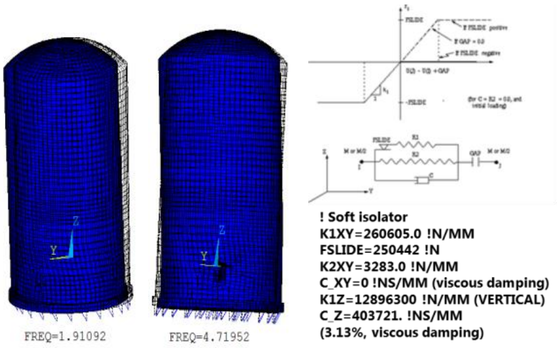


Figure 1 Reactor structure (8 nodes) and building models of the PGSFR



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! Soft isolator
K1XY=260605.0 !N/MM
FSLIDE=250442 !N
K2XY=3283.0 !N/MM
C_XY=0 !NS/MM (viscous damping)
K1Z=12896300 !N/MM (VERTICAL)
C_Z=403721. !NS/MM
(3.13%, viscous damping)
```

Figure 2 Mode shapes of the analysis model and isolator stiffness

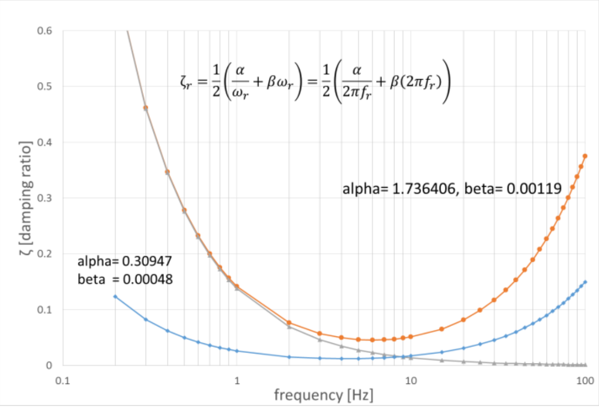


Figure 3 Rayleigh structural damping ratios for two coefficient parameter sets (low & high)

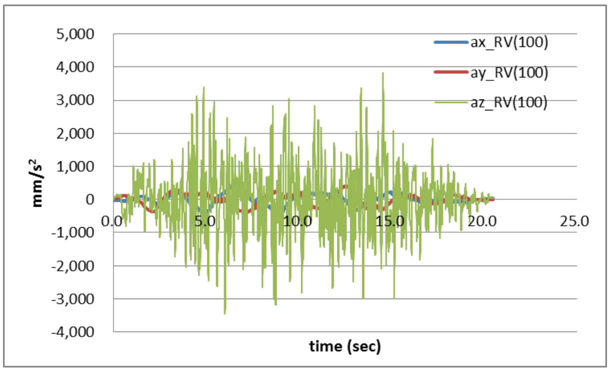


Figure 4 Seismic acceleration responses at support of reactor vessel (low damping of LRB)

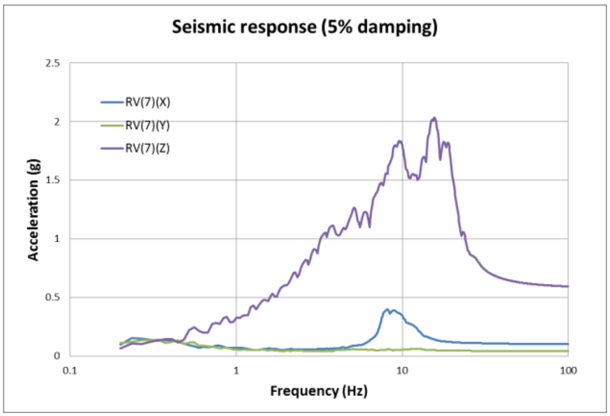


Figure 5 Seismic acceleration responses at bottom of reactor vessel (low damping of LRB)

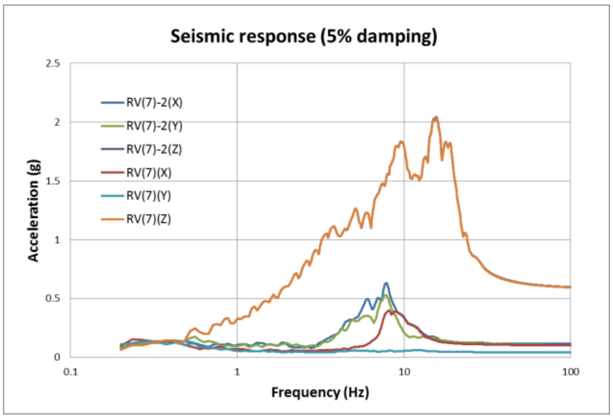
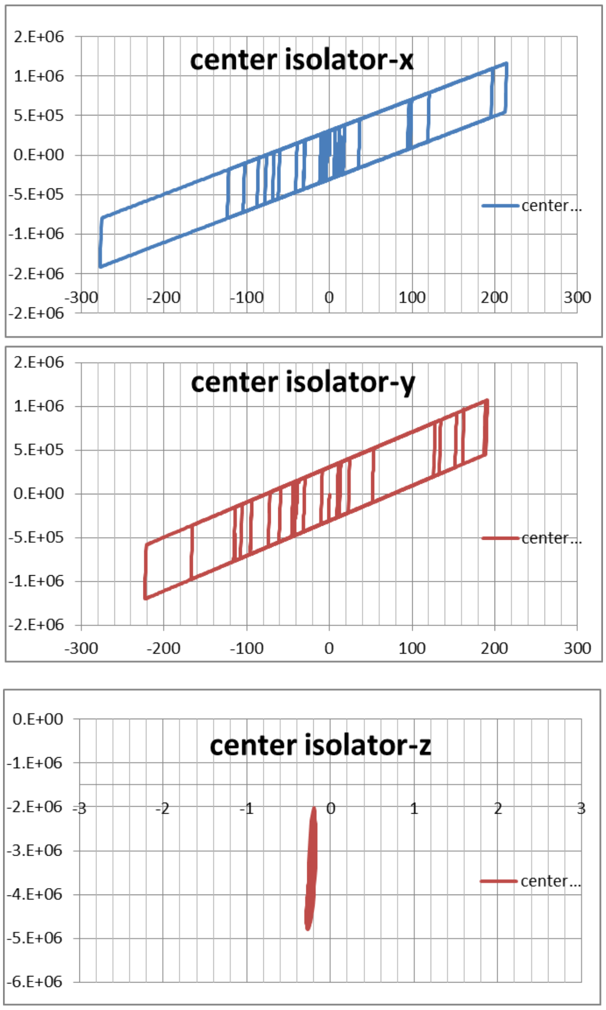


Figure 6 Seismic acceleration responses at top of reactor vessel (low and high damping of LRB)



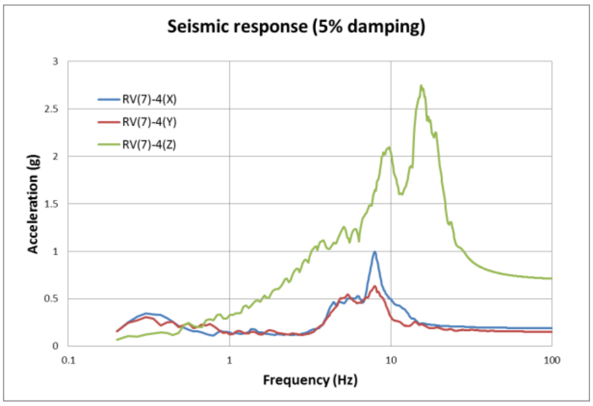


Figure 7 Seismic acceleration responses at bottom of reactor vessel (low structural damping & high damping of LRB)

Figure 8 Seismic response deformation hysteresis of isolator (tons vs. mm)

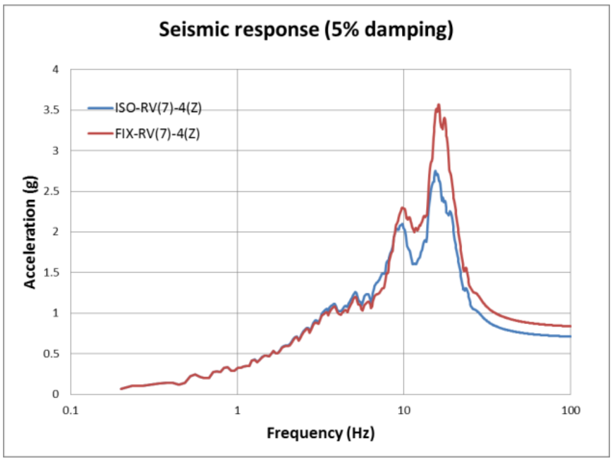


Figure 9 Vertical seismic acceleration responses at bottom of reactor vessel (isolation & non-isolation)

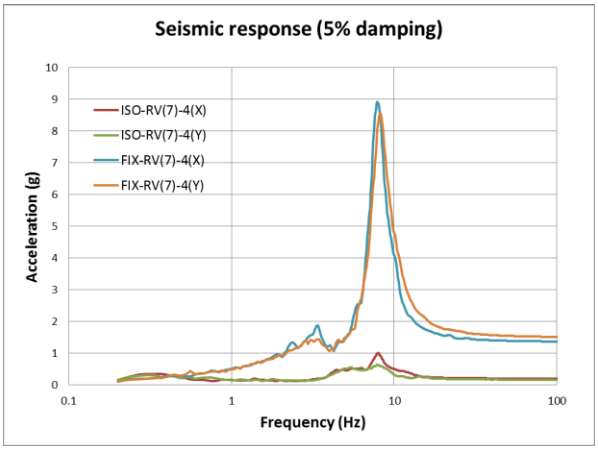


Figure 10 Horizontal seismic acceleration responses at bottom of reactor vessel (isolation & non-isolation)