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Division III

A COMPARATIVE STUDY ON DIRECT SPECTRA-TO-SPECTRA METHODS FOR FLOOR RESPONSE SPECTRA GENERATION

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ABSTRACT

For the seismic qualification of the Structures, Systems and Components (SSC's), the Floor Response Spectra (FRS) need to be generated. In the present work, FRS are generated for a structure categorized under Seismic Category 3 as per AERB/NPP-PHWR/SG/ D-23, using the direct spectra-to-spectra method as proposed by Wei Jang et al. (2016). A comparative study is also made by generating the FRS using the direct spectra-to-spectra method as proposed by Yasui, Y et al. (1993), and the time series method. A minor improvement is also proposed on the direct spectra-to-spectra method by Yasui, Y et al (1993). This work brought out the key findings using these direct spectra to spectra methods and the conclusions are drawn.

INTRODUCTION

For the civil structures categorized under Seismic Category 3 as per AERB/NPP-PHWR/SG/ D-23, the structures shall be qualified as per the Indian national code IS 1893 (Part 1,Part 4). In important cases, the SSC's housed under these structures shall also be seismically qualified for which there is a need to generate the FRS. The FRS generation using the conventional time series becomes tedious since the synthetic time histories for IS 1893 spectra are not readily available. In such cases the direct spectra-to-spectra methods for generating the FRS are effective since these methods require only the ground spectra and modal analysis information.

The main aim of this paper is to generate the FRS by using direct spectra-to-spectra methods and do a comparative study with the usual time series method. The FRS generated using direct spectra-to spectra methods proposed by Wei Jang et al. (2016), and Yasui, Y et al. (1993) are referred to DGM-1 and DGM-2 respectively and the FRS generated using the conventional time series is referred as TH hereafter in this paper. The details of improved DGM-2 are explained later and is referred as DGM-3 hereafter in this paper.

DESCRIPTION OF THE STRUCTURE

Geometry

The Reinforced Concrete (RC) structure considered is of length 42m, width 30m and total height is around 26m as shown in Figure 1. Raft type of foundation is provided, and the structure is resting on hard soil. The modelling and analysis are carried out using a Finite Element (FE) software.

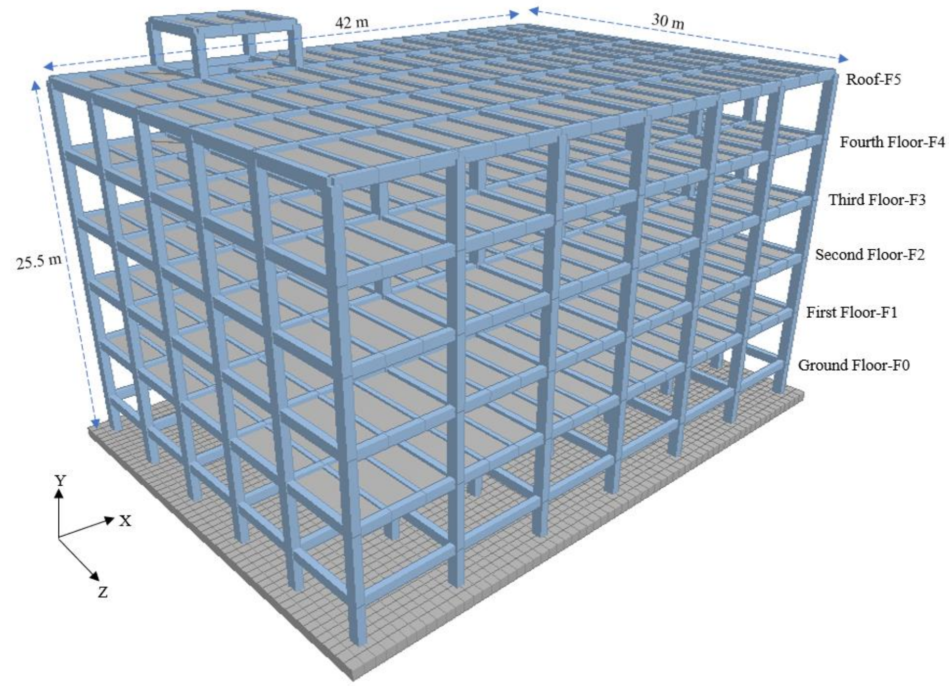

Figure 1. FE model.

Boundary Condition

The Soil Structure Interaction (SSI) is captured by modelling the soil springs based on the frequency independent spring formulation given in Appendix 2 of AERB/NPP-PHWR/SG/ D-23. The shear wave velocity is considered as 1500m/sec. The horizontal stiffnesses K_x, K_z are around 3 x 10^5 kN/m and the vertical stiffness is around 3.6 x 10^5 kN/m. Since the raft is modelled using plate elements, the vertical and horizontal soil springs are distributed over the plan area of the raft based on the influence area of each node of raft in the FE model. The rotational springs are not considered in this model.

Damping

The structural damping is considered as 5% based on the provisions of IS 1893-part 4. The soil damping percentages for rocking, horizontal and vertical are restricted to 7%, 20% and 30% respectively. The equivalent modal damping derived from these damping values shall not exceed 20%. For this study a 7% damping was conservatively adopted for vertical and horizontal equivalent soil springs.

Ground Spectra

The structure under consideration is in Zone III as per IS 1893-Part 4. Since the SSC's can have different Importance (I) factors and Response reduction factors (R), I and R are considered as unity for the purpose of FRS generation. Thereafter this FRS (with I and R equal to 1) can be multiplied with any (I/R) for the concerned SSC. The Peak Ground Acceleration (PGA) under the Design Basis Earthquake (DBE) for Zone III is equal to 0.08g.

The input horizontal DBE ground spectrum for 5% damping ratio as per IS 1893-Part 4 is given in Figure 2. The vertical spectrum is considered as 2/3 of the horizontal spectrum as per IS 1893-Part 4. The input horizontal DBE ground spectra for other damping ratios are obtained as per the provisions stated in IS 1893-Part 4.

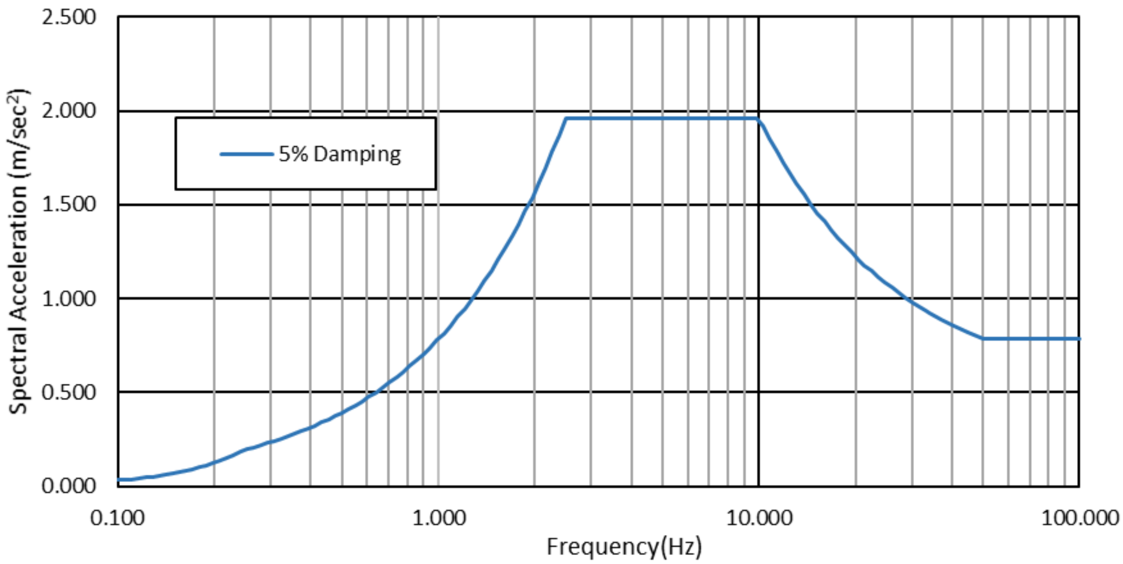

Figure 2. Horizontal DBE Ground Spectrum.

Modal Analysis Results

The major modes, mass participation in X, Y and Z directions and modal damping of the structure are given in Figure 3 and Figure 4 respectively.

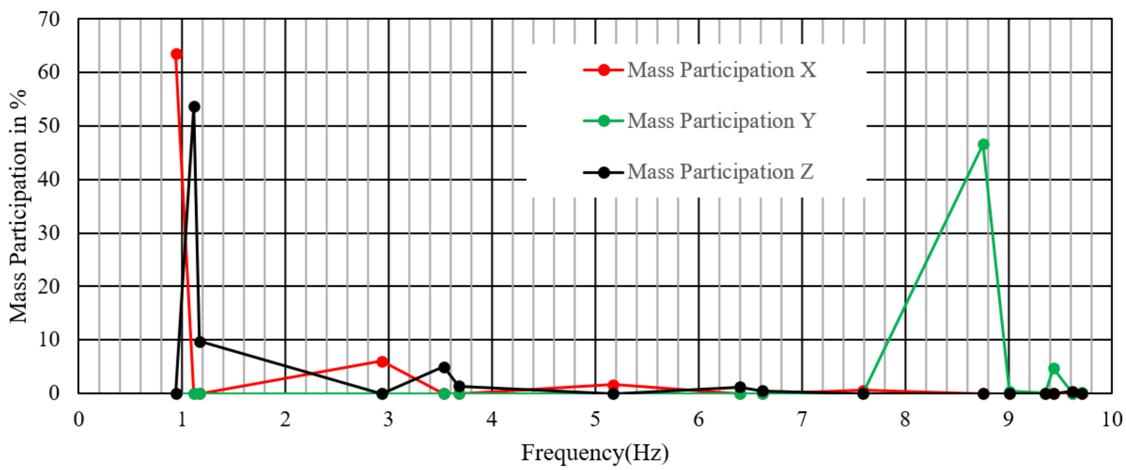

Figure 3. Mass participation of major modes.

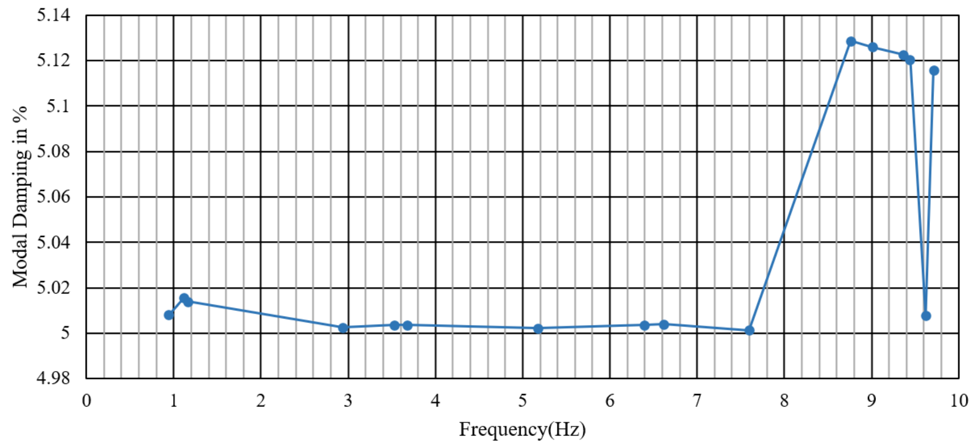

Figure 4. Modal Damping of major modes.

DIRECT SPECTRA-TO-SPECTRA METHODS

DGM-1(proposed by Wei Jang et al. (2016))

The basic inputs required by this method are the input ground spectra, nodes for which the FRS needs to be generated, frequencies and damping at which the FRS needs to be generated, frequencies and modal damping of the structure, mode shapes data and the mode participation factors. The PGA in horizontal and vertical directions and percentage of Non-Exceedance of Probability (NEP) are also required as an input.

With the above inputs and based on DGM-1 the amplification factors (AF's) for the oscillator and for the structure are computed for three cases, viz., non-tuning, near tuning and perfect tuning cases. The t-Response Spectrum which is the maximum acceleration response of a Single Degree Of Freedom (SDOF) oscillator mounted on top of a SDOF structure required for the estimation of AF's is also computed. The correlation coefficient between the responses of the oscillator contributed by two modal responses ($\rho_{k\kappa}$) is determined and is given in Figure 5.

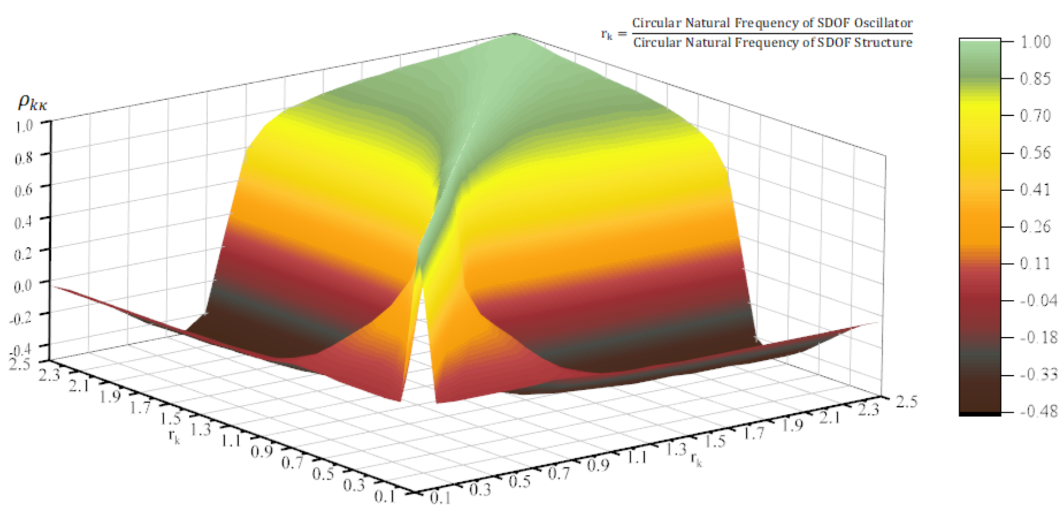

Figure 5. 3D view of FRS-Complete Quadratic Combination correlation coefficients.

DGM-2(proposed by Yasui, Y et al. (1993))

The basic inputs required for this method are the same as DGM-1 except that the PGA and NEP are not required. Based on DGM-2, the amplification factors for the structure and the oscillator are determined.

DGM-3(minor improvement to DGM-2)

The basic inputs required for this method are the same as DGM-2. However, a minor improvement is proposed on DGM-2 and is explained here.

As per DGM-2 the FRS generated at a node of the structure in the direction X,Y or Z is given by Equation (1).

$$S_E = \sqrt{\sum_i (\beta U_i S_{Ei})^2} \tag{1}$$

where $\beta U_i S_{Ei}$ is the FRS for each mode of the structure.

The Square Root Sum of Squares (SRSS) modal combination rule stated in Regulatory Guide 1.92 is reproduced below:

$$R_{pI} = [\sum_{i=1}^{n} R_{p_i}^2]^{1/2} \tag{2}$$

where R_{pI} is the combined periodic response for the I^{th} component of seismic input motion (I = 1, 2, 3, for one vertical and two horizontal components), R_{pi} is the periodic response or periodic component of a response of mode *i*.

Comparing Equations and (1) and (2) it is evident that the modal combination rule used in Equation (1) in DGM-2 is SRSS and the response in mode *i* , R_{pi} is equal to $\beta U_i S_{Ei}$. In DGM-3, it is proposed to use Complete Quadratic Combination (CQC) modal combination rule as stated in Regulatory Guide 1.92 instead of the SRSS rule as used in DGM-2 and Equation (1) is modified as given below.

$$R_{pI} = S_{EI} = [\sum_{i=1}^{n}\sum_{j=1}^{n} \varepsilon_{ij}\, R_{pi} R_{pj}]^{1/2} \tag{3}$$

where ε_{ij} is the modal correlation coefficient given in Equation (4)

$$\varepsilon_{ij} = \frac{8(\lambda_i \lambda_j f_i f_j)^{1/2}(\lambda_i f_i + \lambda_j f_j) f_i f_j}{(f_i^2 - f_j^2)^2 + 4\lambda_i \lambda_j f_i f_j (f_i^2 + f_j^2) + 4(\lambda_i^2 + \lambda_j^2) f_i^2 f_j^2} \tag{4}$$

In Equation (4) λ_i, λ_j are the modal damping ratios and f_i, f_j are the modal frequencies for modes i and j respectively. , R_{pi} and R_{pj} are equal to $\beta U_i S_{Ei}$ and $\beta U_j S_{Ej}$ respectively. It may be noted that the correlation coefficient used here is quite different than the one used in DGM-1.

In all of the above direct spectra-to-spectra methods, since the FRS at a given location and in a given direction has contributions from more than one spatial component of earthquake, these contributions are combined by the SRSS rule as per AERB/NPP-PHWR/SG/ D-23. The above direct spectra-to-spectra methods are coded using Python Software.

TIME SERIES METHOD(TH)

For the FRS generation using the TH method three statistically independent synthetic time histories are generated meeting the requirements of AERB/NPP-PHWR/SG/ D-23. The comparison of mean compatible spectra and IS 1893 DBE spectra are given in Figure 6.

This set of three time-histories are applied in the FE model to generate three different responses in a given direction by using the combinations (a, b, c), (b, c, a) and (c, a, b) in X, Y and Z directions respectively and the FRS are generated using the FE software. Thereafter the FRS is calculated as the average of all the spectra corresponding to the different time-histories as per AERB/NPP-PHWR/SG/ D-23.

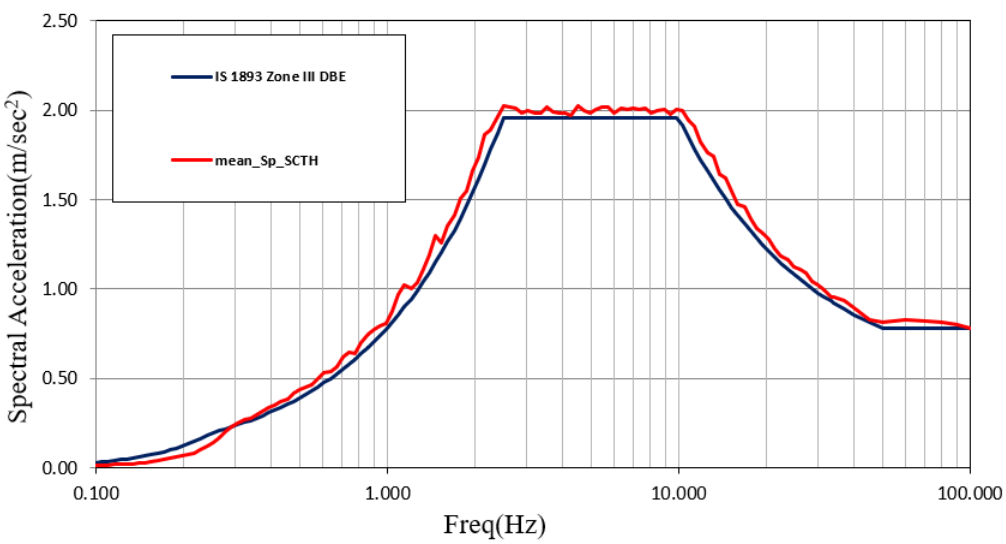

Figure 6. Comparison of mean compatible spectra and IS 1893 DBE spectra.

RESULTS AND DISCUSSION

Results

The FRS are generated at 5% damping for all the floors; however, the results are provided at the roof (F5) level for the purpose of discussion in Figure 7 through Figure 9. It shall be noted that the FRS presented is the raw FRS and not a broadened one. All the nodes in F5 are considered and the average of all these nodal response spectra is done for the calculation of FRS. The FRS generated using DGM-1 is generated for 50% and 84.1% NEP.

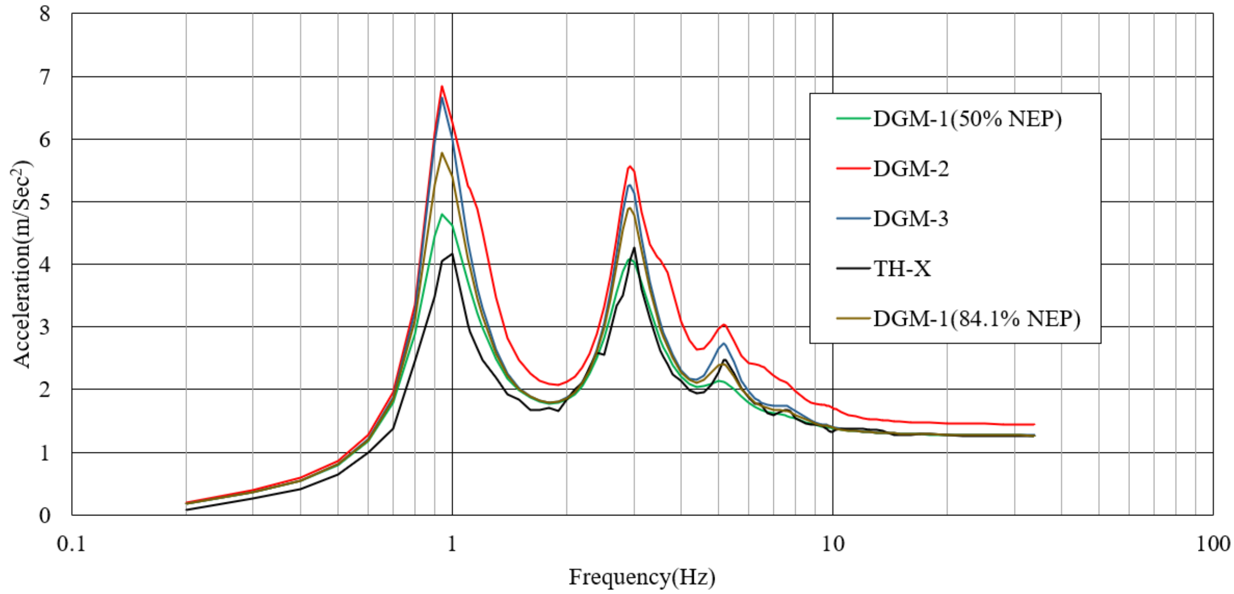

Figure 7. FRS in X (horizontal) Direction at Roof level.

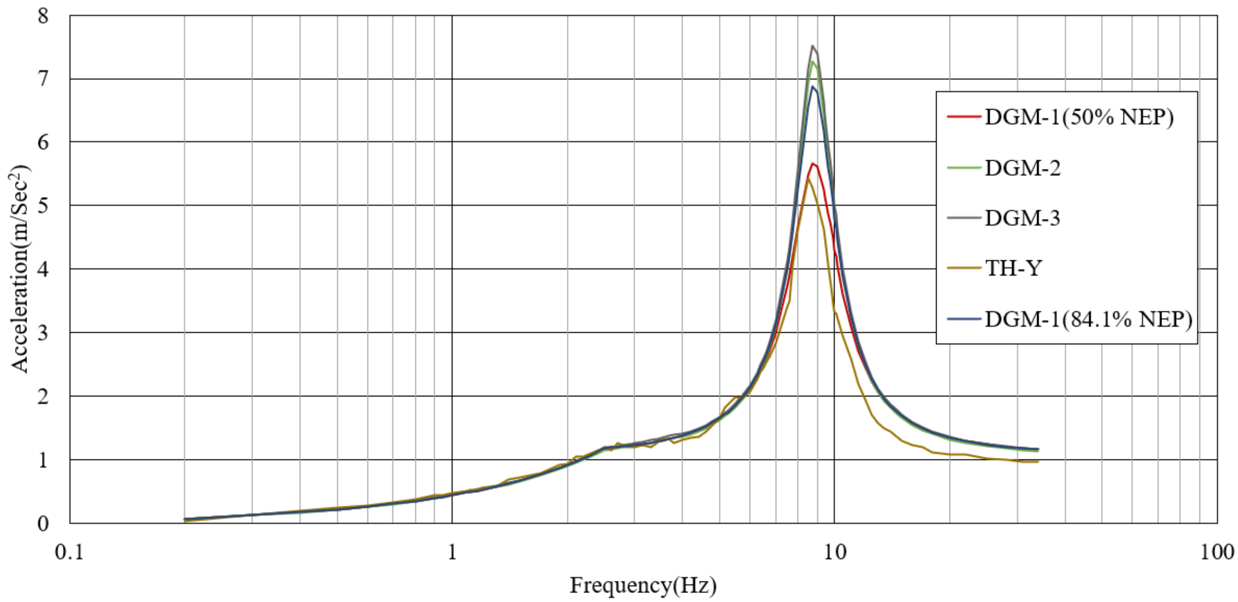

Figure 8. FRS in Y (vertical) Direction at Roof level.

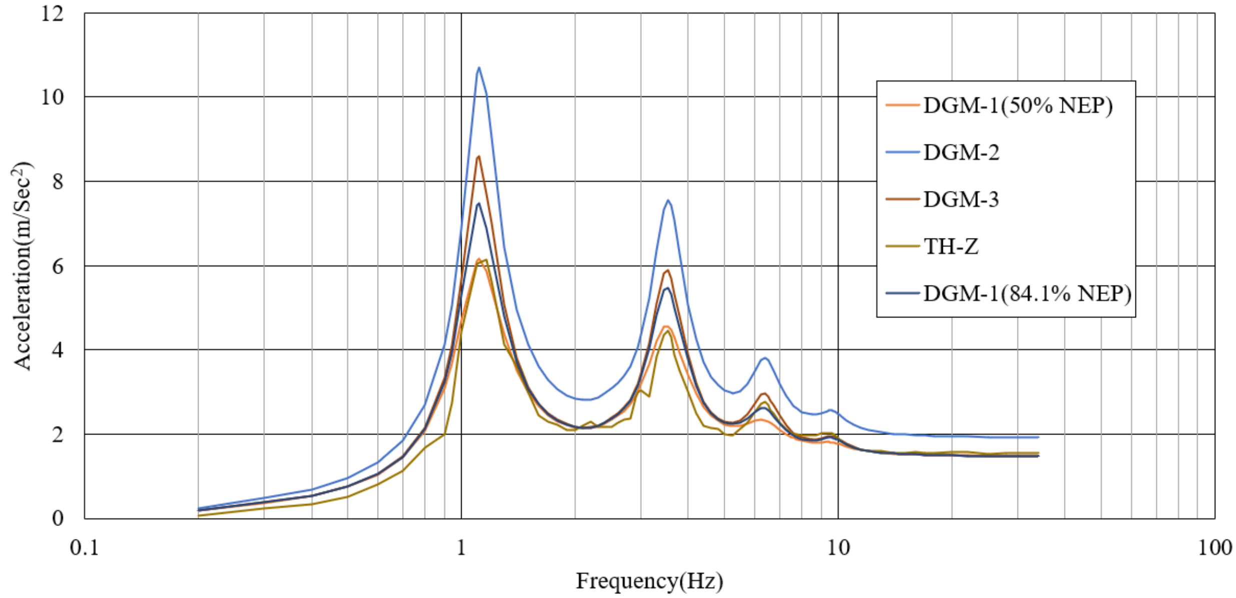

Figure 9. FRS in Z (horizontal) Direction at Roof level.

The percentage errors at major peaks for the FRS generated using spectra-to spectra methods (DGM-1, DGM-2, and DGM-3) are calculated with respect to TH FRS and are given in Figure 10 through Figure 12. A positive error indicates that the FRS generated using spectra-to-spectra methods is higher than the FRS generated using the time series method and a negative error indicates that the FRS generated using spectra-to-spectra methods is lesser than the FRS generated using time series method.

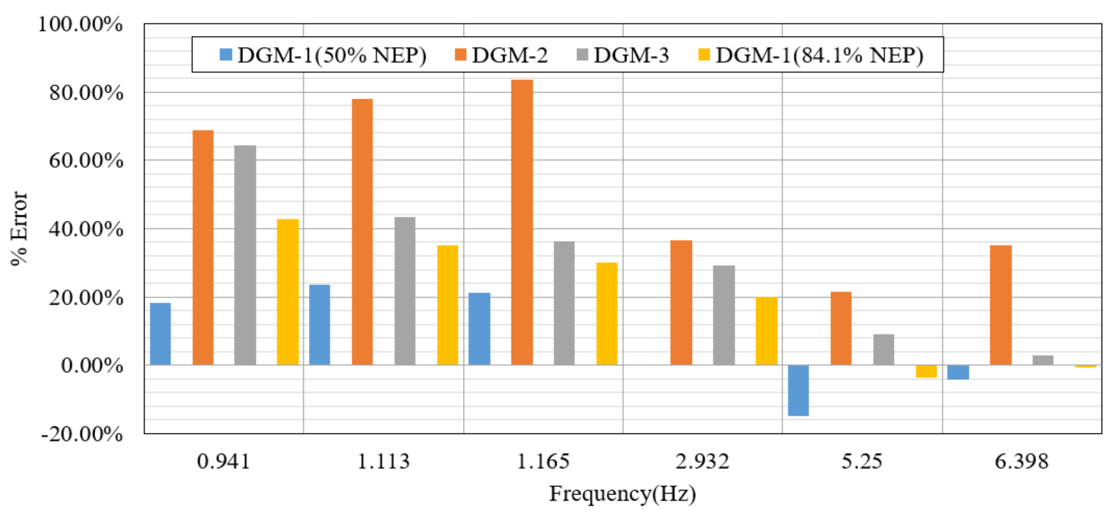

Figure 10. Percentage Error-FRS X.

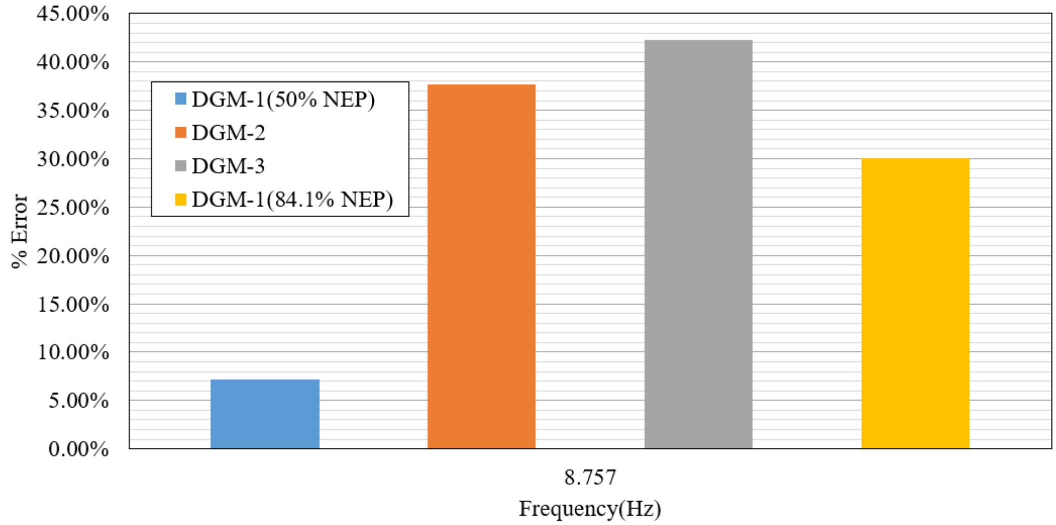

Figure 11. Percentage Error-FRS Y.

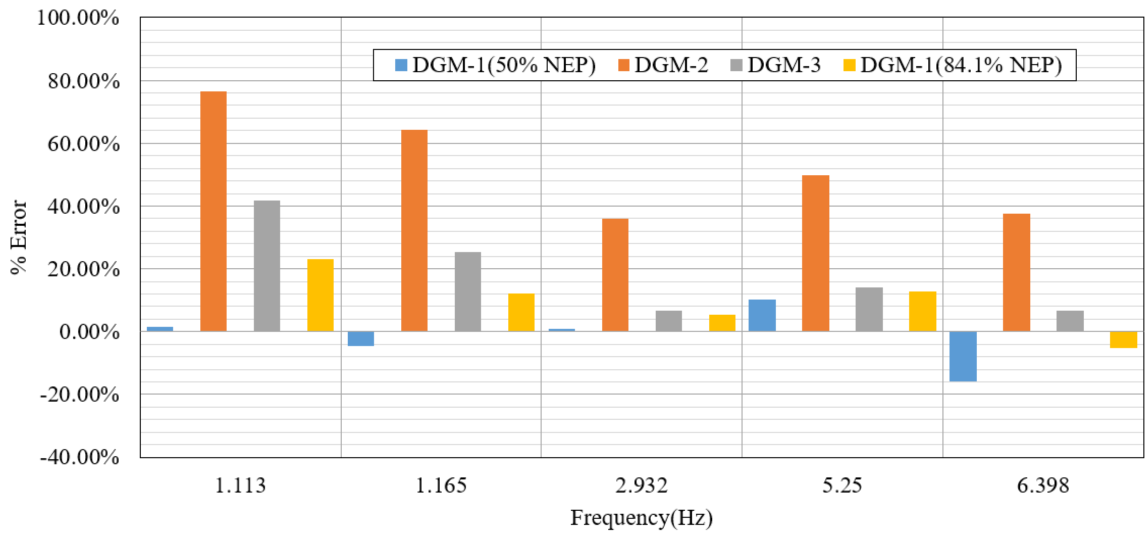

Figure 12. Percentage Error-FRS Z.

Discussion on the results

Based on the results obtained it is observed that the shapes of the FRS generated using DGM-1, DGM-2 and DGM-3 are similar and are smoothened as compared to the FRS generated by TH. In general, DGM-1 with 50% NEP has the least error when compared to DGM-2, DGM-3 and DGM-1 with 84.1% NEP in X,Y and Z directions. The FRS generated using DGM-3 method using CQC modal combination rule instead of the SRSS rule as used in DGM-2 provides more accurate results when compared to the DGM-2.

Though the comparison of spectra-to-spectra methods is done with time series method, the FRS generated though time series method shall not be taken for benchmarking as the synthetic time histories may have a wide variability within them and using only three-time histories may not be sufficient for the generation of FRS.

CONCLUSION

It can be concluded that in general FRS generated using the methodology proposed by Wei Jang et al. (2016) with 50% NEP agree well with the FRS generated using the time series method. The analysts and designers can generate the FRS for any design NEP using this method. The DGM-3 which is a minor improvement to the methodology proposed by Yasui, Y et al. (1993) can also be used as a preferred option for the FRS generation.

As the spectra-to-spectra methods are simple and effective than compared to time series methods, these spectra-to-spectra methods can very well be used for the FRS generation in practice, for first level (preliminary check) of qualification for equipment to be housed in the building.

REFERENCES

Combining modal responses and spatial components in seismic response analysis, U.S. NUCLEAR REGULATORY COMMISSION REGULATORY GUIDE 1.92 Revision 2,2006.

Criteria for design of earth resistant design of structures-Part 1 (2016), IS 1893.

Criteria for design of earth resistant design of structures-Part 4 (2015), IS 1893.

Seismic qualification of structures, systems and components of pressurized heavy water reactors, (2009), AERB/NPP-PHWR/SG/D-23.

Wei Jiang (2016). *Direct method of generating Floor Response Spectra*, Ph.D. thesis, University of Waterloo at Ontario, Canada.

Yasui, Y., Yoshihara, J., Takeda, T., Miyamoto, A., (1993). *Direct generation method for floor response spectra*. Proceedings of the 12th International Conference on Structural Mechanics in Reactor Technology 13 (4).