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SEISMIC TESTING CHALLENGES IN RIM QUALIFICATION

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ABSTRACT

The nuclear standard IEEE 382 recommends required input motion (RIM) for seismic testing of items (such as actuators), installed on piping in a nuclear power plant (NPP), as an undamped series of single frequency sine-beats. The prescribed demand sine-beat accelerations are found to be unreasonably conservative in comparison to realistic seismic loading for low seismicity sites with peak ground acceleration below 0.25g. Response spectra generated from the sine-beats are not bounded by the device level spectra generated for a host of single-degree-of-freedom equipment in resonance with the structure. The prescribed 15s duration of testing at each dwell adds further conservatism because of unnecessary aging of a component owing to the long duration of repetitive testing in comparison to that of a realistic seismic event. The sine-beat response is found in an equipment at resonance to a narrow band seismic input, such as a component installed on a flexible support at higher elevation in a tall building. However, no sine-beats are present in response to a broad band seismic input, of components installed at lower elevations. This study revisits the sine-beat concept and explores the RIM testing process elaborating the challenges involved therein through the response to earthquake records and to the design basis response spectra compatible artificial time histories. Realistic examples from a NPP are studied and their responses are compared with single frequency sine-beats. The duration of realistic seismic loading is compared with that prescribed for RIM testing. An alternative solution to RIM testing based on enveloping the floor response spectra is presented. A solution for obtaining the RIM acceleration for low seismicity sites is suggested.

INTRODUCTION

Nuclear safety of a NPP depends on successful performance of a multitude of components subjected to design basis accidents including those caused by seismic events. Application of a design basis earthquake (DBE) at the foundation of a building results in response of various floors represented by floor response spectra (FRS). Spectral accelerations (SAs) of the DBE get amplified in the FRS at natural frequencies of the structures. While structures are designed for the DBE prescribed as a response spectrum at the foundation, various equipment such as electrical cabinets or piping situated inside at different elevations are seismically qualified for the applicable FRS. For brevity, piping is also referenced as equipment hereinafter. Devices located inside, or connected to, these equipment (such as a relay inside an electrical cabinet or a valve on piping) further experience amplification. Thus, seismic amplification is a cascaded process that takes place in two stages: 1. From the foundation to a floor and, 2. From the floor to the equipment. The first stage results in the floor response that is obtained in terms of the floor acceleration time history (FTH) and converted to FRS, whereas the second stage leads to the device level acceleration time history (DTH) leading to the device level spectrum (DLS). IEEE 382 (2019), prescribes the DTH of a line (typically piping) mounted component as sine-beats with minimum 15s duration regardless of their location in a structure or the seismic input's frequency content. The DTH is somewhat similar to a single frequency sine-beat when the equipment, considered as a single-degree-of-freedom (SDOF) oscillator, is in resonance with the supporting structure (Morrone, 1973). The DLS for such DTH comes out to be a sharp peak spectrum. However, due to uncertainties in resonant frequencies, the modern standards such as, ASCE 4 (2016) and CSA N289.3 (2020), recommend specifying peak broadened spectrum which constitutes the design basis. In several cases a broad band random vibration may contain sufficient energy and omitting it to impose pure sine test is not acceptable (DOD, 2008). This study revisits the sine-beat concept and its

prescribed duration by obtaining the response to earthquake records and artificial time histories (THs) in realistic scenarios from a low seismicity site. It is not known why IEEE 382 focuses only on line-mounted components but not on flexible cabinets which also respond essentially as SDOF oscillators.

HISTORY OF SINE BEATS TESTING

According to Morrone (1973), the idea of sine-beats being the device level seismic response was originally proposed by Fischer (1972) that was adopted in the IEEE guide (1971). Fischer (1972) concluded that "there are insufficient acceleration accelerograms available for power plant structures, let alone specific type of equipment, to establish an acceptable seismic risk" and "for test purposes it is necessary to apply the actual floor motion" or "else apply the conservative" sine-beats. Thus, the test criterion established by Fischer (1972) was influenced by limitations and conservatism rather than a sufficient number of real events. The effect of peak broadening was not discussed.

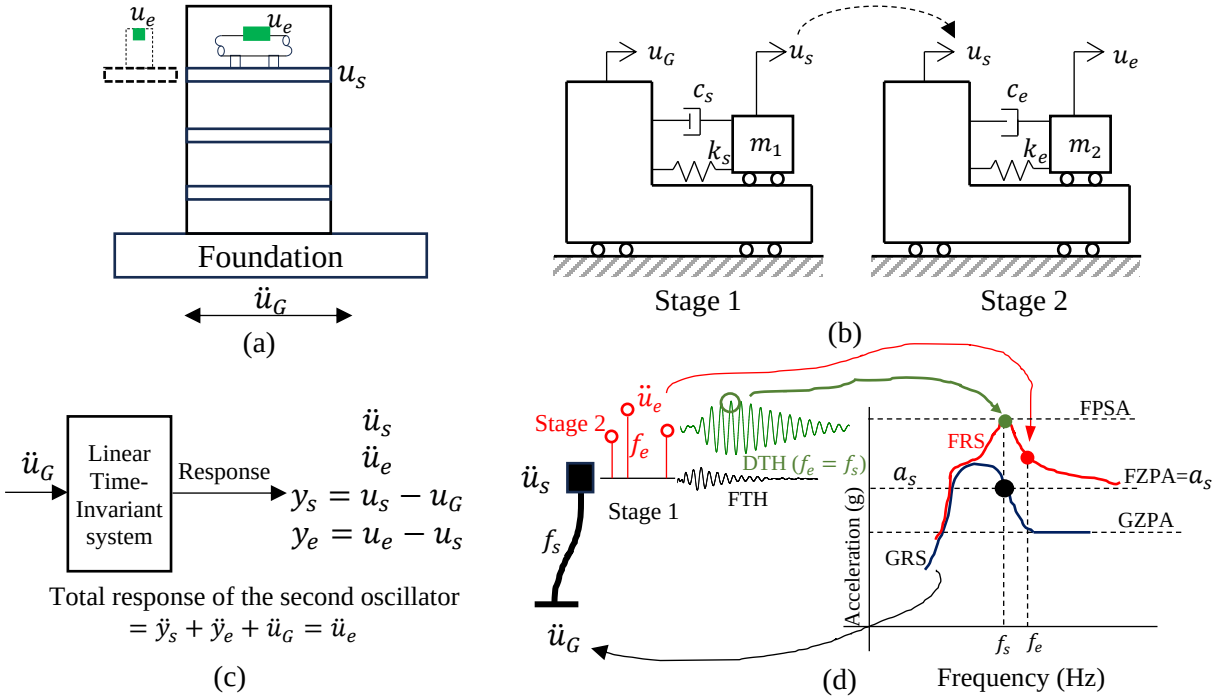

Figure 1: (a) Structure subjected to ground excitation, (b) two cascaded SDOF oscillators (Crandall & Mark, 1963), (c) amplification system, and (d) GRS and FRS relationship.

AMPLIFICATION

Figure 1 summarizes the process followed by Morrone (1973) with the help of two cascaded oscillators (Crandall & Mark, 1963). Figure 1(a) shows an equipment (piping or an electrical cabinet) mounted at the top floor of a structure with a device (or component, e.g., a valve) shown in green mounted on the equipment. The foundation excitation acceleration TH (addressed as 'ground' acceleration hereinafter) is depicted as $\ddot{u}_G$, floor displacement as u_s and the equipment displacement at the device location as u_e. For simplicity, conservatism and similarity with Fischer (1972) and Morrone (1973), the structure and equipment, both are considered as single-degree-of-freedom (SDOF) systems individually. The mass of an equipment being much smaller than that of the structure, both can be decoupled from each other, and the structure response can be considered as an input to the equipment (Morrone, 1973). Figure 1(b) shows two stages of amplification with decoupled SDOF spring-mass-damper oscillators (Crandall & Mark, 1963) with the spring and damping constants of the structure and equipment in two stages as k_s and c_s, and, k_e

and c_e, respectively. Stage 1 shows the response of the structure where the floor displacement, u_s, becomes input to the equipment in Stage 2. Considering, the relative displacements of the structure and the equipment as $y_s = u_s - u_G$ and $y_e = u_e - u_s$, the following equations of motion emerge.

$$\ddot{y}_s + 2\beta_s\dot{y}_s + \omega_s^2 y_s = -\ddot{u}_G \quad (1)$$

$$\ddot{y}_e + 2\beta_e\dot{y}_e + \omega_e^2 y_e = -\ddot{u}_s \quad (2)$$

Where, β_s, β_e, ω_s and ω_e represent percentage damping and natural angular frequencies of the structure and equipment respectively, and, $\ddot{u}_s = \ddot{y}_s + \ddot{u}_G$ and $\ddot{u}_e = \ddot{y}_e + \ddot{u}_s$. Equations (1) and (2) are the same as Equations (12) and (13) in Morrone (1973), and are utilized in this study to obtain the structure ($\ddot{u}_s$) and equipment ($\ddot{u}_e$) responses. Figure 1(c) shows the amplification system (Crandall & Mark, 1963). Figure 1(d) shows representation of the structure as a SDOF oscillator with natural frequency, f_s, subjected to the seismic input, $\ddot{u}_G$, represented by the ground response spectrum (GRS) shown as the black curve with its peak ground acceleration (PGA) or the zero-period acceleration (ZPA) marked as GZPA. The structure response time history, $\ddot{u}_s$, or, the FTH is shown in black whose absolute peak value, a_s, is represented as the black dot on the GRS, at frequency, f_s. The FTH, $\ddot{u}_s$, results in the FRS (shown in red with its ZPA marked as FZPA) which is the peak response of a spectrum of SDOF oscillators to the FTH. The peak response of a SDOF equipment to the FTH at frequency, f_e, is shown on the FRS as the red dot. Since the peak response of a rigid oscillator would be the same as the peak input, the FZPA is the same as a_s. The DTH at resonance ($f_e = f_s$) is shown as the green curve whose peak is denoted as the floor peak spectral acceleration (FPSA) of the FRS as the green dot. The ratio, FPSA/FZPA (the green dot over the black), is the so-called equipment 'amplification factor'(AF).

Table 1: Earthquake records and amplification for $f_s = f_e = 5Hz$ and $\beta_s = \beta_e = 5\%$ (Morrone, 1973)

Earthquake	Station	Record	PGA (g)	Amp. Factor Figure 1(d), Green/black dot (FPSA/FZPA)
El Centro 1940	El Centro, Calif	N-S	0.313	6
Kern County 1952	Taft	S69E	0.16	5.9
San Francisco 1957	Golden Gate Park	N80W (or, S80E)	0.13	5.7

Morrone (1973) considered three earthquake records listed in Table 1. The last column of Table 1 shows the AF, as the ratio between the equipment's and structure's peak accelerations, FPSA/FZPA, obtained by Morrone (1973), at resonance ($f_e = f_s$), with $\beta_s = \beta_e = 5\%$, represented by the green and the black dots in Figure 1. Morrone (1973) proved that this ratio is maximum at resonance. Hence, the focus of this study is on the equipment responses when $f_e = f_s$. The records in Table 1 are included in the suite of those utilized by Newmark et. al (1973) to formulate the design basis earthquake of NPPs (USNRC, 1973).

AMPLIFICATION FACTOR

The seismic margin assessment methodology guide NP-6041 (EPRI, 1991) in its Table Q-1 (of Appendix Q) states the AF for flexible cabinets as 7.2. Some of the flexible electrical cabinets' fundamental frequencies are found to be as low as 3Hz. Also, according to the random vibration theory (Crandall & Mark, 1963), the AF at 5% damping in response to a 5% damped response spectrum comes out to be close to 7 (Dar & El-Dakhakhni, 2019). The AFs listed in Table 1 for the three cases are approximately 6. Thus, a 'practical' AF of 7 can be applied to flexible as well as other components. Fischer (1972) observed the overall AF, or the peak equipment acceleration to the GZPA ratio, to be equal to 21. Since the peak spectral acceleration of the USNRC DBE (USNRC, 1973) is approximately three times its ZPA, the overall AF of

21 (3x7) appears to be appropriate. Thus, the peak amplitudes of the sine-beats can be assessed as 21 times the GZPA as a reasonable approximation.

APPLICABLE DAMPING

It is to be noted that in most of the cases, the structure damping of 5% is justified in accordance with CSA N289.3 (CSA, 2020). Also, a 5% damped DLS is specified for testing at shake table because spectrum compatibility of the artificial TH generated for testing contains lesser variation in comparison to lower damping because of the jaggedness of the response spectrum that increases with decreased damping. Therefore, $\beta_s = \beta_e = 5\%$ is considered in the rest of the study.

IEEE 382 CRITERION

IEEE 382 essentially focuses on the peak amplitudes of the DTH and its waveform being a series of sine-beats. Figure 2(a) shows the seismic demand depicted as RIM expressed in terms of peak amplitudes of "single frequency sine-beat tests at one-third octave interval test frequencies" (IEEE, 2019). An 'octave' is the interval where frequency doubles. Thus, each doubling interval (2-4Hz, 4-8Hz, etc) is divided in three parts giving two additional frequencies in between resulting in total 13 frequencies ranging from 2 to 32Hz, listed in Table 2, as f_b, with their corresponding peak acceleration amplitude, a. According to IEEE 382 three additional frequencies between 32 and 64 Hz are required for rock sites. IEEE 382 also recommends 12-15 oscillations per beat and minimum 15s duration for each test. Sine-beats can be generated either by adding two sine waves with small frequency difference, or by multiplying two sine functions. Considering n number of oscillations per beat, the equation of sine-beat comes out to be (Morrone, 1973):

$$\ddot{u}_{es} = a[\sin(\omega_b t)\,\sin(\omega_b t/2n)] \tag{3}$$

Where, $\ddot{u}_{es}$ is the sine-beat acceleration, and $\omega_b = 2\pi f_b$. Figure 2(b) shows the shape of a typical sine wave with $n = 12$ cycles per beat.

Table 2: Peak accelerations of sine-beats (IEEE 382)

Dwell number	1	2	3	4	5	6	7	8	9	10	11	12	13
f_b	2	2.52	3.17	4	5.04	6.35	8	10.087	12.71	16	20.16	25.4	32
a(g)	1.14	1.44	1.81	2.28	2.87	3.62	4.5	4.5	4.5	4.5	4.5	4.5	4.5

DESIGN AND ASSESSMENT BASIS SPECTRA

The USNRC Reg. Guide 1.60 Revision 1 (1973) specifies the DBE spectrum for NPPs based on the NBK spectrum, named after its creators (Newmark, Blume, & Kapur, 1973). The USNRC Reg Guide specifies scaling of the specified spectrum on the basis of site-specific PGA. Figure 2 (c) shows USNRC spectrum scaled to 0.1g PGA. As evident from the figure, this is a broad-band spectrum because the SAs are practically constant between the frequency range 2.5-9Hz. Also shown is the high frequency spectrum (0.15g PGA) of the review level earthquake (RLE) utilized for seismic margin assessments of a NPP in Ontario, Canada (Dar, Konstantinidis, & El-Dakhakhni, 2014). The nuclear structures frequency range of interest is between 1-10 Hz (EPRI, 2012). Thus, the high frequency content of the RLE is filtered out through the structure except in the vertical direction at the column and shear wall locations and an equipment coinciding with such locations is a remote possibility. Hence this study focuses on the DBE. Response to the DBE is obtained in terms of the FRS or the DLS at various floors of a building. Due to uncertainties in resonant frequencies, such resulting spectra are peak broadened in accordance with nuclear

standards such as ASCE 4 (2016) and CSA N289.3 (2020). Peak broadened FRS or the DLS specified as seismic input, requires generation of artificial time histories whose frequency content will be different from that of the FTH and the DTH. Peak broadened FRS and the DLS constitute the design basis.

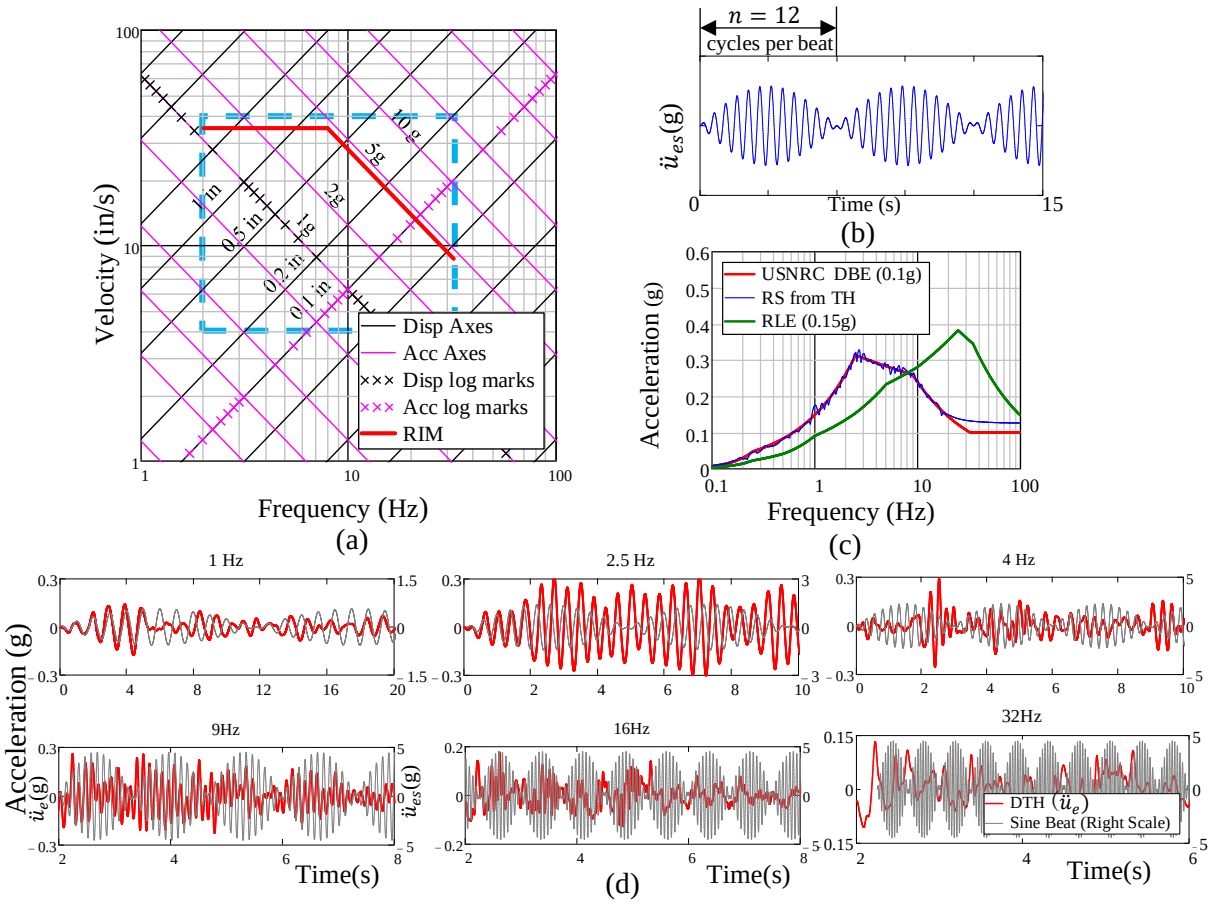

Figure 2: (a) RIM as in IEEE 382 (2019) and listed in Table 2. Blue dashed line depicts IEEE 382 figure boundary. (b) Typical sine-beat. (c) 5% damped DBE spectrum with PGA=0.1g (USNRC RG 1.60) and RLE. (d) DTH for SDOF oscillators in response to the DBE at frequencies as noted.

RESPONSE TO THE BROAD BAND DBE

An artificial spectrum compatible TH was generated for the DBE shown in Figure 2 (c). As illustrated, the response spectrum for the artificial TH is close to that of the DBE. An equipment installed at the foundation (or at lower elevations) will experience almost the same excitation as of the DBE and in such cases, $\ddot{u}_s = \ddot{u}_g$. Figure 2 (d) depicts the response of equipment to the DBE as DTHs ($\ddot{u}_e$) for various frequencies and the sine-beats ($\ddot{u}_{es}$ in Eq (3)), per IEEE 382, on the right axis or scale of each plot. As shown, none of the DTHs are close to the sine-beats, either in amplitudes or in duration. Thus, Figure 2 concludes that the DTH of an equipment subjected to the broad band USNRC excitation does not follow the IEEE 382 criterion.

RESPONSE TO EARTHQUAKE RECORDS

Figure 3 (a) shows the response spectrum of the GGP record (Table 1) with two peaks at: 4.5 and 7.5Hz. For comparison, the USNRC RG 1.60 spectrum (USNRC, 1973) scaled to the ZPA of the record is also shown. Figure 3 (b) and (c) illustrate the 2% and 5% damped FTH ($\ddot{u}_s$) and the DTH ($\ddot{u}_e$) respectively at $f_s = f_e = 4.5$Hz.

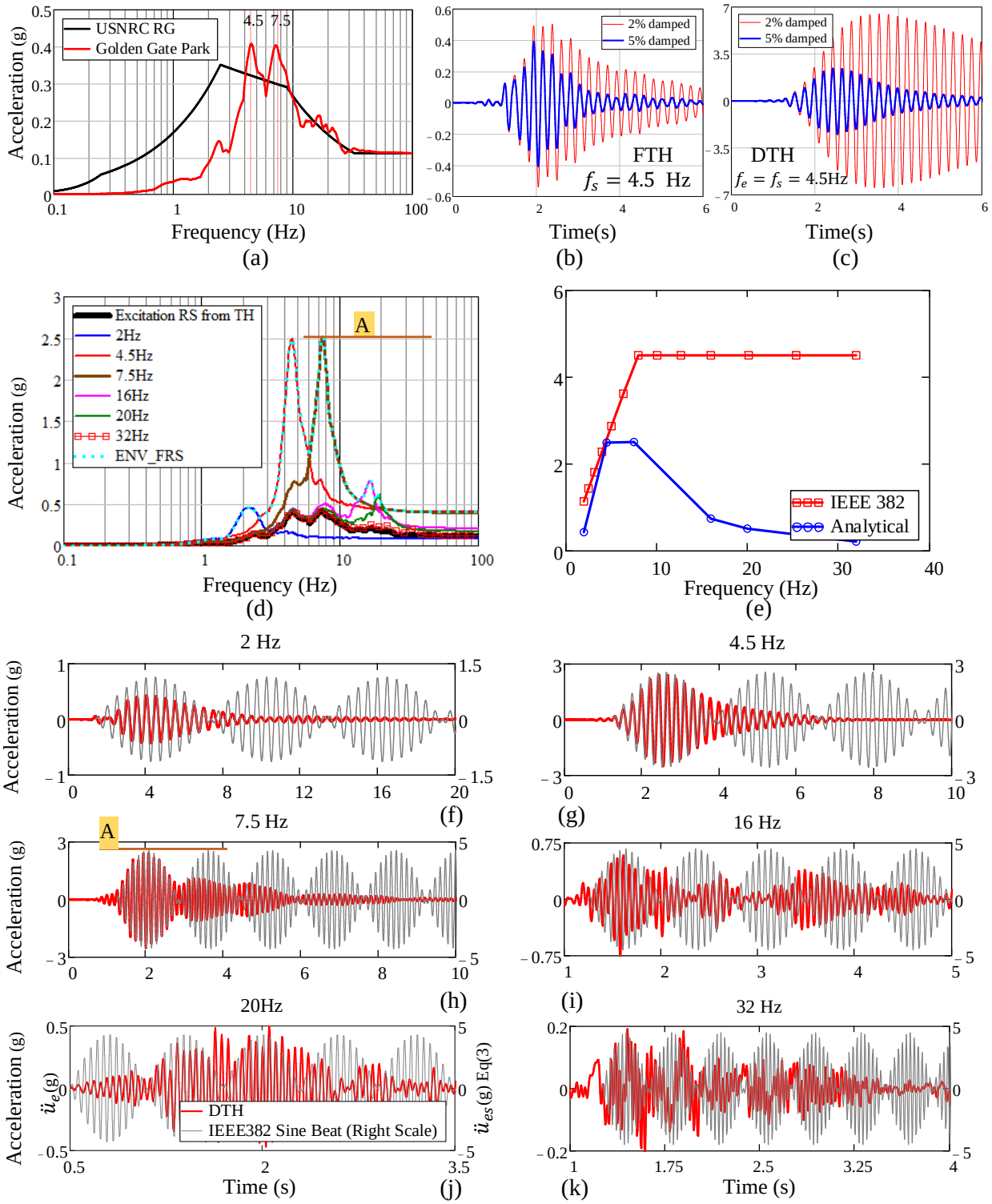

Figure 3: 5% damped response to GGP record (Table 1): (a) 5% damped GGP and USNRC response spectra, (b) 2% and 5% damped structure response (FTH) at $f_s = 4.5$ Hz, (c) 2% and 5% damped equipment response (DTH) at $f_s = f_e = 4.5$ Hz, (d) FRS at various frequencies, (e) Peak accelerations of the FRS compared with the IEE 382 recommendation. (f) to (k) DTH at various frequencies.

The 2% damped response is similar to that reported by Morrone (1973) at $f_s = f_e = 5$Hz. Morrone (1973) reported only these two figures commenting that the DTH is similar to a sine-beat but without showing the DTH plot over full excitation duration. The FTH ($\ddot{u}_e$) were obtained for the GGP record (at 2, 4.5, 7.5, 16, 20 and 32Hz frequencies) but are not shown for brevity. The resulting FRS, from these FTHs, are shown in Figure 3 (d) along with their envelope marked as ENV_FRS. As evident, maximum amplification is visible only at the peak frequencies 4.5 and 7.5Hz. Figure 3 (e) depicts the comparison between the peak SAs of various FRS, named 'Analytical', plotted against their corresponding frequencies, and, the IEEE 382 recommendation given in Table 2. Since the GGP is a comparatively a low ZPA record, it is not expected to meet the acceleration values given in IEEE 382. However, the shape of the Analytical plot is quite different from that recommended by the code. The IEEE 382 plot assumes constant acceleration beyond 8Hz, whereas the 'Analytical' plot shows a dramatic decrease past 9Hz. Figure 3 (f) to (k) compare the DTH response plots (at 2, 4.5, 7.5, 16, 20 and 32Hz frequencies) with the sine-beats (plotted on right axis or 'scale' as $\ddot{u}_{es}$ in Eq(3)) having amplitudes according to Table 2. As evident, the peaks of the DTH match with their corresponding FRS peaks. The DTH for 2Hz (Figure 3 (f)) corresponds to the peak of the 2Hz FRS (Figure 3 (d)), the DTH of 4.5Hz (Figure 3 (g)) to the 4.5Hz FRS peak and so on. For example, the peak acceleration of the DTH for f_e =7.5Hz in Figure 3 (h) is marked as A which matches with the peak of the FRS for f_s =7.5Hz in Figure 3 (d). The DTH plots in Figure 3 (f) to (h) (i.e., up to 7.5Hz) resemble the sine-beats only for the first cycle. This is in contrast not only with the 15s duration recommendation in IEEE 382 but also the number of beats. In Figure 3(i) to (k), there is no resemblance of the DTH with sine wave or beats. In Figure 3 (k), at 32Hz, the response does not experience any amplification. Also, there is a significant difference between the amplitudes of the DTH (left scale) and those of the sine-beats (right scale). Both amplitudes match only in Figure 3 (g) corresponding to 4.5Hz. Thus, Figure 3 proves that the acceleration amplification is visible only at peak frequencies of the FRS, DTH resembles sine waves at only lower frequencies but without continuous beats, the duration of sine waves is much lesser than 15s, the acceleration values recommended in IEEE 382 for sine-beats are much higher than those obtained from analysis. In short, Figure 3 defies the IEEE 382 criterion.

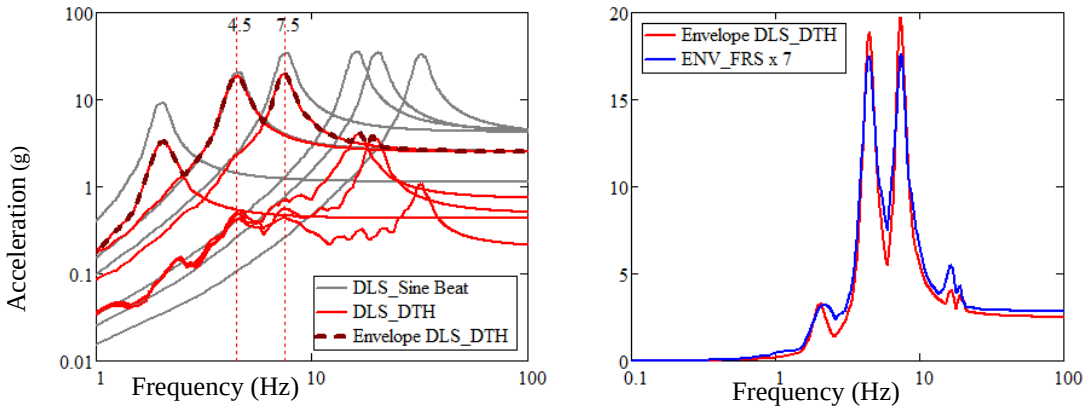

Figure 4: 5% damped response to the GGP record. Left: DLS comparison. Right: FRS envelopes

Figure 4 shows the response spectra, or the DLS, obtained for the DTH and the sine-beats in Figure 3. The left diagram in Figure 4 shows families of the DLS for the sine-beats and the DTH, marked as 'DLS_Sine-beat' and the 'DLS_DTH' respectively. As depicted, DLS_Sine-beat plot peaks are higher than the DLS_DTH peaks except at 4.5Hz but unreasonably conservative at higher frequencies. Also shown is an envelope of the family of the DLS_DTH plots, marked as 'Envelope DLS_DTH'. The right diagram in Figure 4 compares the 'Envelope DLS_DTH' with 7 times the FRS envelope curve from Figure 3 (d) marked as 'ENV_FRS x 7'. As depicted, the 'ENV_FRS x 7' plot is more conservative than 'Envelope DLS_DTH' except at peak frequencies with maximum ~11% difference. It can be shown that this gap

disappears for the peak broadened response spectrum. Also, peaks can be clipped in accordance with NP-6041 (EPRI, 1991).

Figure 5 (a) shows the response spectrum of the El Centro (ELC) record (Table 2) (having three significant peaks at, 2.15, 4 and 7.5Hz) and that in the USNRC RC 1.60. Figure 5 (b) shows the FRS at various frequencies. Figure 5 (c) to (e) depict the DTH at 2.15, 4 and 20Hz. Only the 4Hz response in Figure 5 (d) is somewhat similar to a sine wave but only in the first cycle that is for a single beat. Figure 5 (f) shows significant difference between the DTH peaks and the IEEE 382 recommendation. At lower frequencies, the analytical solution is much higher than the IEEE 382 criterion but at higher frequencies, it is much lower. Figure 5(g) shows the DLS from the DTH to be higher than the sine-beat spectra at lower frequencies whereas at higher frequencies the trend reverses. Figure 5(h) compares the envelope of the DLS spectra with seven times the FRS envelope. As shown the 7xFRS envelope plot is higher than the DLS except at the sharp peak where it is 14% lower. This gap disappears as demonstrated in the next section.

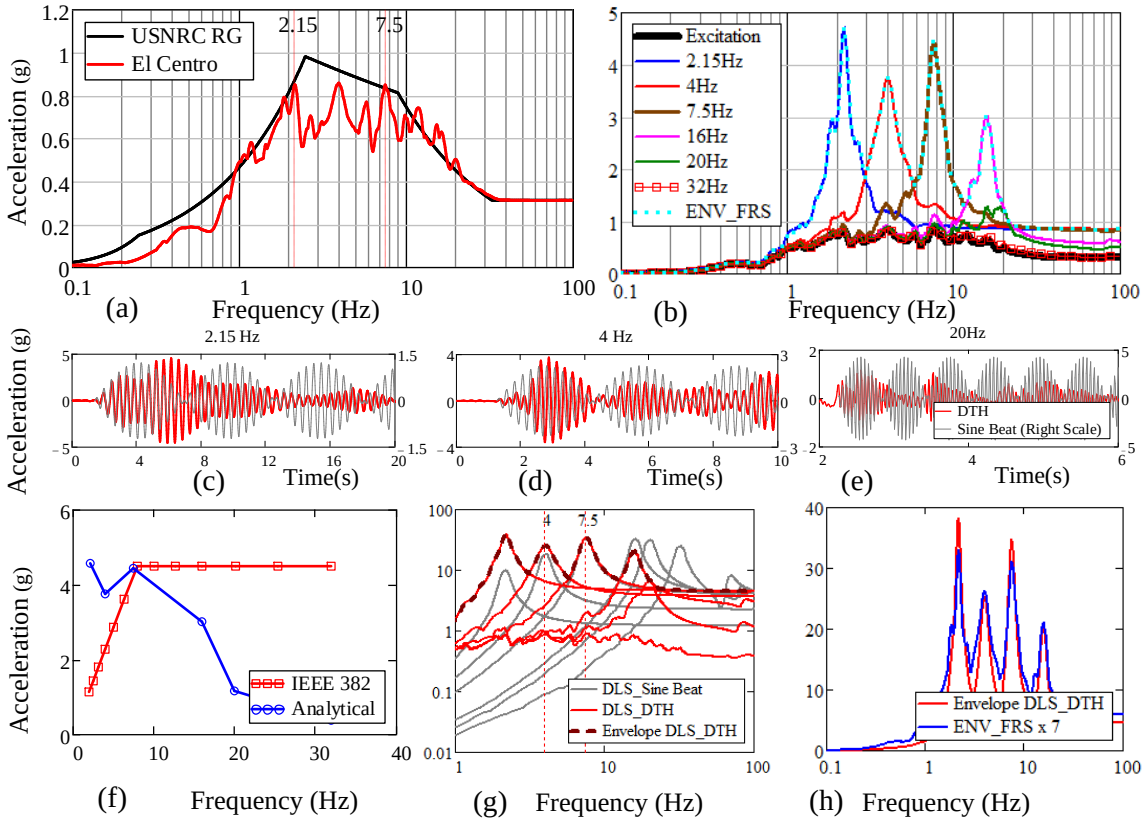

Figure 5: 5% damped response to the ELC record (Table 1): (a) 5% damped ELC and USNRC response spectra, (b) FRS at various frequencies, (c) to (e) DTH plots, (f) Peak accelerations of the FRS compared with the IEE 382 recommendation, (g) DLS comparison (h) FRS envelopes

FLOOR RESPONSE SPECTRA IN A REALISTIC SCENARIO

The left column in Figure 6 shows the lumped mass model considered in EPRI guides 1002988 (EPRI, 2002) and 3002012994 (EPRI, 2018) that was analysed for the 0.1g PGA DBE shown in Figure 2 (c) as the seismic input at Node 2. The top row of the middle column shows the FRS at Node 12 along with its peak broadened version and the response spectrum of an artificial TH that was generated for the peak broadened spectrum. The bottom row in this column shows the response DLS at various frequencies to the artificial TH of the peak broadened spectrum. As shown, the DLS Envelope is bounded by the seven times peak

broadened FRS. Thus, for a peak broadened FRS, the 7xFRS bounds the DLS envelope everywhere including the peak. The right column shows the response at Node 4. Here too the DLS Envelope is bounded by the 7xFRS except at the left sharp peak where it is about 15% shorter. This difference disappears once this peak is broadened as explained above (not shown for brevity).

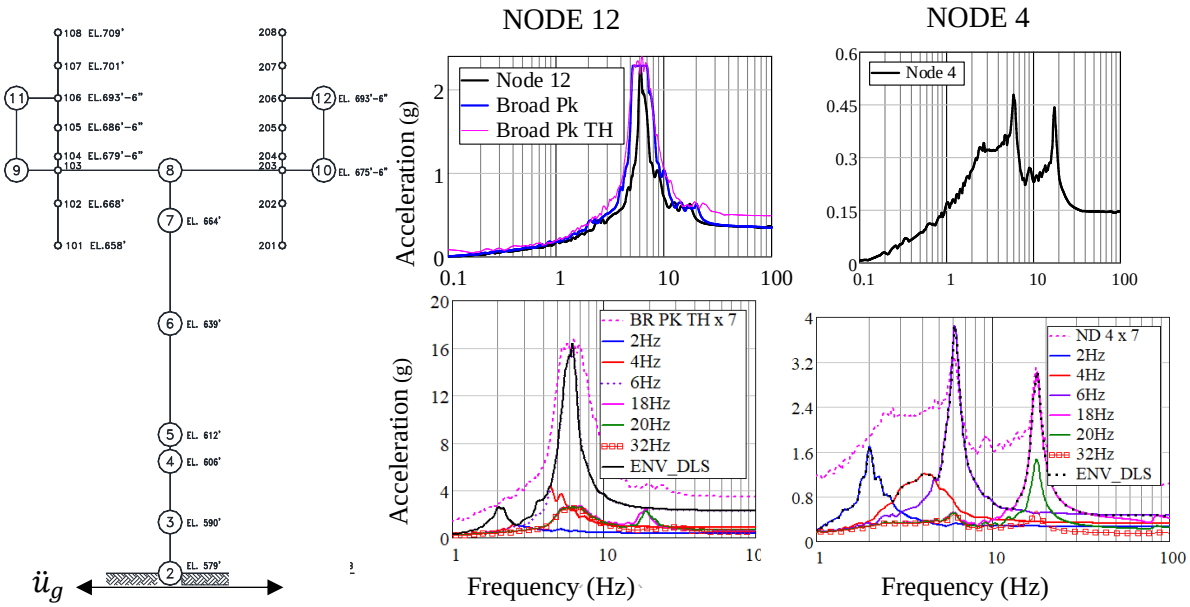

Figure 6: Left: Lumped mass model in EPRI guides 1002988 and 3002012994. 5% damped responses at Node 12 in the middle column and at Node 4 in the right column.

CONCLUSIONS

It is concluded that the IEEE 382 RIM criterion is based on research carried out almost half a century ago when sufficient earthquake records were not available, computer processing cost was prohibitive, the DBE for NPPs was yet to be created, and, seismic standards and industry guides such as CSA N289.3 and EPRI NP-6041 were yet to be written. As pointed out in the literature, it is always better to prescribe the floor motion rather than the sine-beats. This study demonstrates that this indeed is true by means of several examples constituting response to earthquake records and artificial time histories. None of the equipment response in this study was found to have sine-beats except for somewhat similar curve in the first cycle in some cases. None of the examples resulted in repetition of beats to 15s duration. It is also concluded that the IEEE 382 RIM acceleration levels are too conservative for low seismicity sites with the PGA <0.25g, the shape of the RIM curve (with constant accelerations beyond 7.9Hz) does not match with reality and the 15s RIM duration in each test is unrealistic that contributes to unnecessary aging of the specimen under test. It is concluded that the AF of 7 on the FRS at a floor in a NPP is a practical and realistic option that bounds the response of the equipment. It is recommended that the sine-beat criterion in IEEE 382 should be made optional rather than mandatory. If at all a sine-beat test is to be carried out, its amplitude can be considered as 21 times the PGA of the input motion. However, that may be unrealistic and overconservative especially at high frequencies.

NOMENCLATURE

AF	Amplification Factor
DBE	Design Basis Earthquake
DTH	Device Level Time History
FRS	Floor Response Spectrum
FTH	Floor Time History
CSA	Canadian Standards Association
DLS	Device Level Spectrum
EPRI	Electric Power Research Institute
FPSA	Floor peak spectral acceleration
FZPA	Floor zero period acceleration

GRS	Ground Response Spectrum	GZPA	Ground zero period acceleration
NBK	Newmark, Blume and Kapur	NPP	Nuclear Power Plant
PGA	Peak Ground Acceleration	RLE	Review Level Earthquake
SDOF	Single-Degree-of-Freedom	SA	Spectral Acceleration
USNRC	United States Nuclear Regulatory Commission	ZPA	Zero period acceleration

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