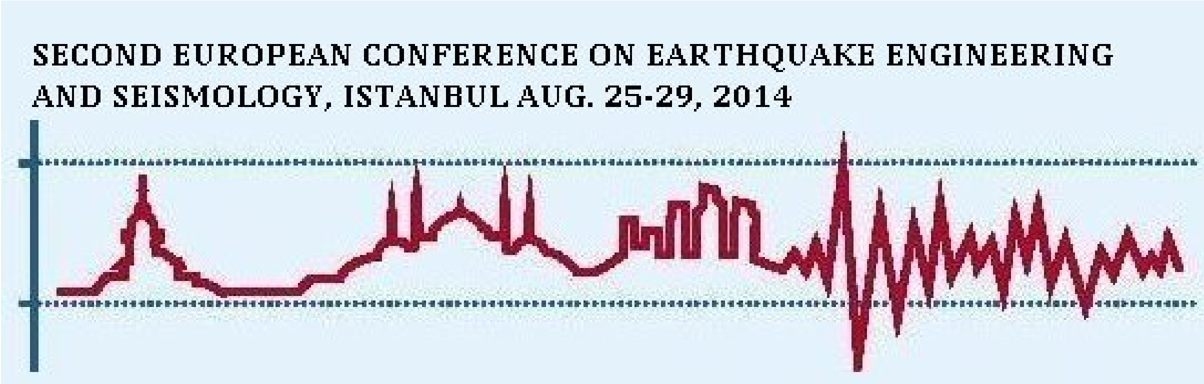

CRITICAL STRUCTURE SAFETY EVALUATION BASED ON DIP

Marin KOSTOV[1]

ABSTRACT

There are continuous attempts to describe the damaging potential of the seismic (or vibratory) motion by a single parameter or a set of damage indicating parameters (DIP). Recently CAV and I_{JMA} (*JMI)* are becoming two very promising parameters. Originally CAV was introduced as a parameter alongside spectral characteristics of ground motion for assessment of the operational state of a nuclear power plant after a seismic event. The aim is to shorten the time for evaluation of OBE exceedance and to provide guidance for the quick restart of a seismically affected plant. Meanwhile, there has been a growing experience and confidence that the DIP could be used not only as global indicator, i.e. assessment of the severity of excitation on the plant site but also as damage descriptor at equipment level, i.e. at each equipment location. The procedure proposed is similar to that for floor response spectra generation and safety evaluation against seismically induced forces. The current paper is presenting basic relations between damage parameters and structural damage derived from the European strong motion data base. The seismic experience data base is utilized to assess the capacity/damage of equipment.

A formalized approach is considered for evaluation of critical facilities subjected to dynamic vibratory loading. The following sequence of evaluation steps is discussed: Step One: For the safety equipment the standard in-structure CAV is calculated and compared with a threshold to screen-out the equipment for further considerations. An additional and optional threshold could be the in-structure I_{JMA} intensity estimate. Step Two: For all locations where standard CAV of in-structure vibrations is higher than the threshold, the floor response spectra are evaluated. They have to be compared with the equipment capacity spectra. The latter are represented by design floor response spectra multiplied by a safety factor or seismic ruggedness spectra. Step Three: Alternatively or simultaneously with the ultimate capacity assessment (force driven design) a displacement based evaluation of the ultimate drift capacity of the respective equipment can be performed.

It has to be stressed that under high frequency excitation the displacement (drift) estimated capacity is by far more realistic than the force based estimates.

If none of the above checks is positively answered, detailed conventional analysis can follow; however, a much smaller amount of equipment would remain for assessment.

INTRODUCTION

There are many cases in the earthquake engineering practice where significant efforts are needed in order to assess the seismic adequacy of building structures, systems, and equipment for higher seismic loading than the design base. In the nuclear engineering design phase this could be the case for extended design condition (DEC). According to the requirements of EUR (European Utility

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Requirements) the adequacy of the safety systems and components has to be proven for 1.4 times the design base seismic effects. Ideas for demonstration of higher seismic margin in the design phase of new nuclear power plants are introduced by EPRI and US NRC as well.

Another case is the airplane impact analysis where military and small commercial aircrafts are usually a design base case; the impact of large commercial aircraft (as a malevolent action) is, however, a separate analysis within the DEC requirements and involves significant additional efforts.

For existing nuclear facilities there is frequently the need of seismic requalification analyses. A separate and different requirement is the quick assessment of an existing plant when subjected to earthquake excitation higher or close to the design base.

Lately, the “stress tests” of the nuclear facilities, which are required after the Fukushima Daiichi accident, are also an example of extensive beyond design base estimations being needed in a short timeframe.

We have similar cases when reassessing the seismic resistance of critical structures as dams, hydropower facilities or industrial installations due to change of the design base or regulatory requirements.

Another field of application of DIP based assessment is the seismic scenario or seismic risk analyses of urbanized territories supposed there are ground motion records on site.

In all of these cases the designer (or the analyst) most probably possesses information for the design seismic capacity of structures, systems, and equipment. The procedure that is proposed hereafter is aiming at limiting the scope of the repeated analyses by using damage indicating parameters developed on the base of site response or in-structure response and to screen out the most vulnerable buildings, equipment and systems. It was originally developed and applied for beyond design base excitations; however, it may also be used even in the design process. The CAV is already widely used in the assessment of the operability state of a nuclear power plant subjected to seismic impact; we would like to extend the application for other safety assessment as well.

The proposed procedure is applicable to engineered structures, i.e. there is a seismic design base and engineering rules (codes) applied in the original design and construction process has been conducted by state of art procedures and materials. In other cases, e.g. for scenario based assessment, only the statistics of the DIP and the related estimates could be used.

DATA BASE

The data is coming from the European Data Base developed within an EC sponsored project by Ambraseys et al. (2000) and subsequently upgraded. Additional data from Vrancea seismic sources is added to the data base. A summary of the data is presented in Tables 1 and 2. The seismic events are split in 3 groups according to the characteristics of the seismic source and the magnitude, i.e. local, regional, and Vrancea sources. The local earthquakes are these, characterized by low to moderate magnitudes (less than 5.5) and recorded on close distances. Such earthquakes are frequently excluded from the PSHA as not significant for engineered structures. In other cases they are considered as floating earthquakes (disperse seismicity). The regional sources are the ones that usually are the strongest contributor to the seismic hazard of a critical facility site. They generate earthquakes with magnitudes stronger than 5. The Vrancea sources (Romania) may influence large territories on the Balkans and also Ukraine, Moldova, and Russia. They are characterized by intermediate depth earthquakes (hypocenters deeper than 60km)

For most of the recorded data I_0 (MSK or EMS) is provided in the database. The site intensity is additionally estimated by an attenuation formulation (Koevesliethy et al., 1907). For these events where I_0 is not included in the data base, the epicentre intensity is calculated by relations, developed by Ambraseys (Ambraseys et al, 1991).

For these records where three components are available the I_{JMA} intensity is also computed by a numerical procedure kindly provided by Dr. Yoshimitsu Fukushima (2008).

The numerical procedure for CAV calculation is developed by the author Kostov (2005, 2003) and used for developing attenuation relationships. The computer code was kindly checked and improved by Dr. Kenneth Campbell (Campbell, 2008).

Table 1. Statistics of the database - components

Sources	Total number of records	Number of components CAV≠0	Number of records Ms≥5	Number of components Sa≥0.2g
REGIONAL 3 components 2 components	 229 651	1785	880	215
LOCAL 3 components 2 components	 164 292	748	8	146
VRANCEA 3 components 2 components	 22 9	83	83	24

Table 2. Statistics of the database – max/min values

Sources		Ms	PGA (g)	Sa (g)	Velocity (m/s)
REGIONAL	max	7.8	0.9	3.53	1.02
	min	5	0.025	0.0648	0.0057
LOCAL	max	5.7	0.525	1.5	0.26
	min	2.6	0.025	0.056	0.0027
VRANCEA	max	7	0.297	0.906	0.7
	min	6.2	0.0253	0.0142	0.013

The database shows that a wide range of seismic excitations are represented; however, the estimates for Vrancea source would be valid only for events with magnitude higher than 6, the local earthquake estimates may only apply for events with magnitude up to 5.5, and the estimates for the regional sources would apply for events with magnitude higher than 5. In the present analyses surface magnitude M_s is used.

We decided to split the strong motion data in 3 groups, according to the macro seismic intensity (the effects observed), caused by the corresponding ground motion. The three groups represent intensity 6-7, 8-9 and 10 and higher. The statistics of the 5% damped acceleration spectra for each one of the groups are shown in figures 1 to 3.

We may also derive other statistics of the groups, e.g. CAV, I_{JMA}, velocity spectra, displacements, etc. This way we can have a statistical description of the damage parameters that are causing structural effects corresponding to the selected group of intensities as shown in Table.3, e.g. Japan seismic intensity (I_{JMA}), cumulative absolute velocity (CAV), averaged spectral acceleration (1-10Hz) - Sa, averaged spectral velocity (1-2Hz) - Sv, averaged spectral displacement (1-2Hz)- Sd, etc.

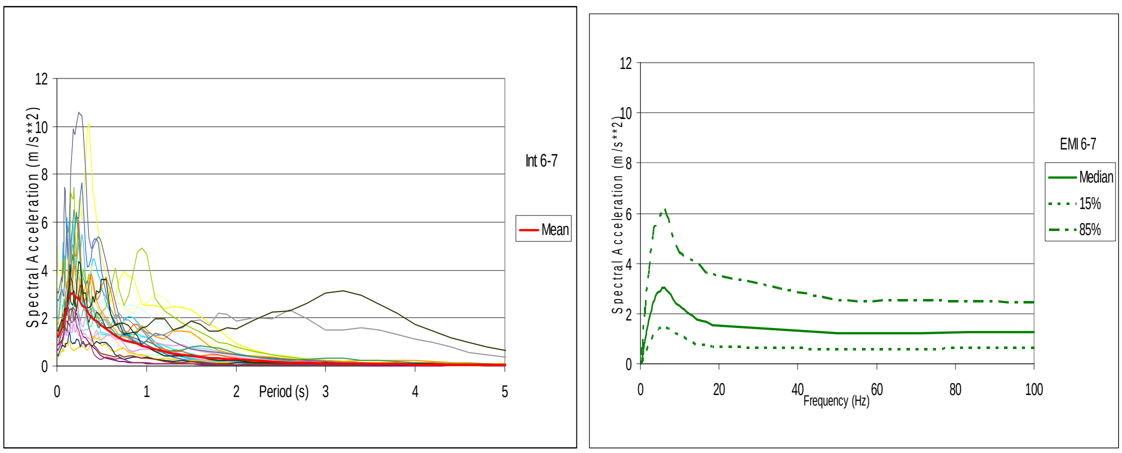

Figure 1. Acceleration response spectra, 5% damping, EMS intensity 6-7

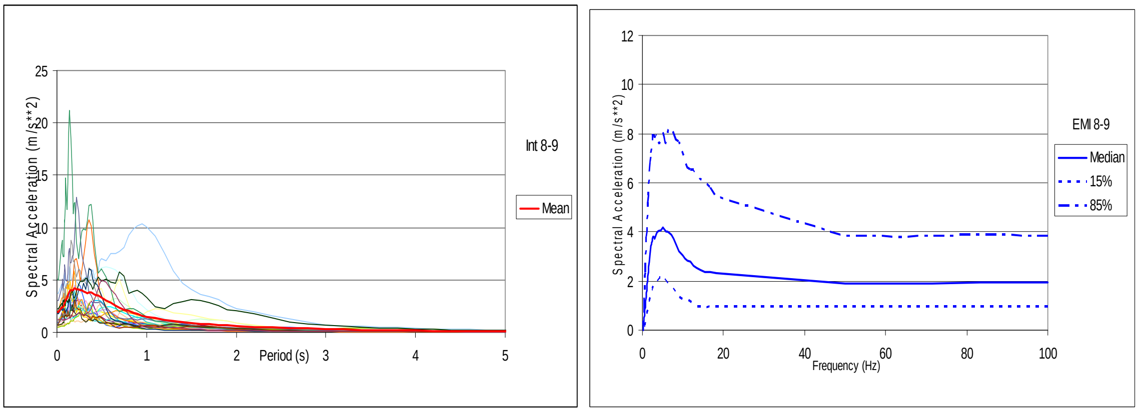

Figure 2. Acceleration response spectra, 5% damping, EMS intensity 8-9

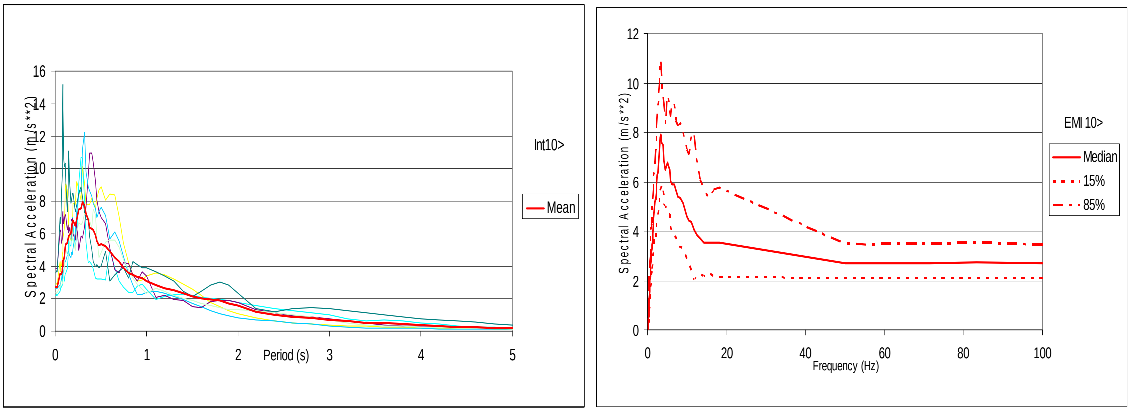

Figure 3. Acceleration spectra, 5% damping, EMS intensity 10

Table 3. Statistics of DIP, values correspond to 15% to 85% confidence interval

	Ijma	CAV [g.s]	Sa [m/s2]	Sv [m/s]	Sd [m]
Intensity 6-7	4.1-4.7	0.07-0.37	0.9-4.49	0.06-0.30	0.006-0.034
Intensity 8-9	4.6-5.2	0.12-0.47	1.51-7.13	0.10-0.60	0.012-0.07
Intensity >10	5.1-5.6	0.18-0.54	1.98-9.81	0.15-0.82	0.017-0.099

BUILDING STRUCTURE VULNERABILITY

The building structure damage indicating parameters are traditionally elements of the intensity scales. Unfortunately, they are rather defused and descriptive. Nevertheless, the only valuable and significant information collected so far for the structure behaviour under seismic excitation is in the seismic intensity records. We rely on the available information of the European Strong Motion Database to correlate the seismic structure behaviour (seismic intensity) with various strong motion parameters as maximum acceleration, maximum velocity, cumulative absolute velocity (CAV), various spectral ordinates, etc. The seismic structure behaviour is not firmly described by the seismic intensity; however, there are several features of the European Macro-seismic Scale (EMS) that could be very useful for engineering assessments. The building structures in EMS are grouped in 6 vulnerability classes (VC) according to their bearing structure, materials, horizontal diaphragms, seismic design code used, etc. We assume that nuclear structures are designed and built with high code requirements for quality and therefore possess high seismic ruggedness and belong to vulnerability classes E and F, i.e. they are less vulnerable structures. The damages in EMS are also grouped in 6 damage grades (DG), including grade 0 – no damage. The damage grade 5 corresponds to failure. Damage grade 1 corresponds to light architectonic damages and damage grade 2 to light structure damage. As an example, the damage probability matrix for intensity 10 excitations is shown in Table.4. That table shows a probability of 10% for having minor structural damage for buildings of vulnerability class F when subjected to shaking intensity corresponding to seismic intensity 10. A large number of different seismic motions may cause seismic effects corresponding to seismic intensity 10.

Table 4. Damage probability matrix for EMS intensity 10

VC/DG	A	B	C	D	E	F
0	0	0	0	0	20	50
1	0	0	0	20	30	40
2	0	10	20	30	40	10
3	10	20	30	40	10	
4	20	30	40	10		
5	70	40	10			

If there is a seismic ground motion recorded on a site we may quickly estimate most of the damage indicating parameters and based on these estimates make a preliminary assessment of the effects in terms of seismic intensity and consequently also conclusions regarding the behaviour of the building stock. All these could be done with a certain confidence level to account the variability of effects. These assessments could significantly be improved if we may split the building stock to acceleration sensitive and drift sensitive group respectively. A rough measure for that could be the first natural frequency of the building structure. We should also take into account that most of the structures are acceleration sensitive, if we consider DG 1 to 2, but also most of the structures are displacement sensitive if we consider DG 3 to 5. Additionally most frequently, the vulnerability classes A to C are acceleration sensitive and those from D to F are displacement sensitive.

EQUIPMENT VULNERABILITY

Unfortunately, the seismic intensity scales do not contain information and do not require collection of information for equipment seismic behaviour. Such information, however, is available and broadly used in the seismic experience data base, developed by SQUG and EPRI. This data base is not publically available but some of the integral features and the equipment group characteristics of the EPRI data base are available in DOE documents (DOE/EH0545, 1997). The seismic experience database includes the response of systems and components in about 100 (typically non-reactor) facilities located in areas of strong ground motion from 20 earthquakes. The earthquakes have magnitudes 5.2 to 8.1, PGA from 0.10g to 0.85g and are 3 to 50 s in durations. Soil conditions, building structure types, and location of equipment vary considerably within the data base. The SQUG GIP consists of four sets of criteria, i.e:

1) the experience-based capacity spectrum must bound the plant seismic demand spectrum,

2) the equipment item must be reviewed against certain inclusion rules and caveats,

3) the component anchorage must be evaluated,

4) any potentially significant seismic systems interaction concerns that may adversely affect component safe shutdown function must be addressed.

If we assume that the last three criteria are fulfilled, i.e. there are no interactions affecting equipment safety, the anchorage is adequate, and the specific requirements are all met, then the equipment capacity will be described only by the corresponding equipment ruggedness spectrum, supposing that the experienced based capacity spectrum bounds the seismic demand.

The capacity spectra for the different kinds of equipment for which the GIP apply are based on real observation and/or seismic testing (Fig.5 left). These spectra should apply to equipment at a specific location and should be compared with the specific in-structure response (seismic demand).

Just for simplicity we assume the general term “equipment” that statistically represent all groups of GIP equipment; the generalized “equipment” will have capacity spectrum with statistics as presented in Fig.5 (right).

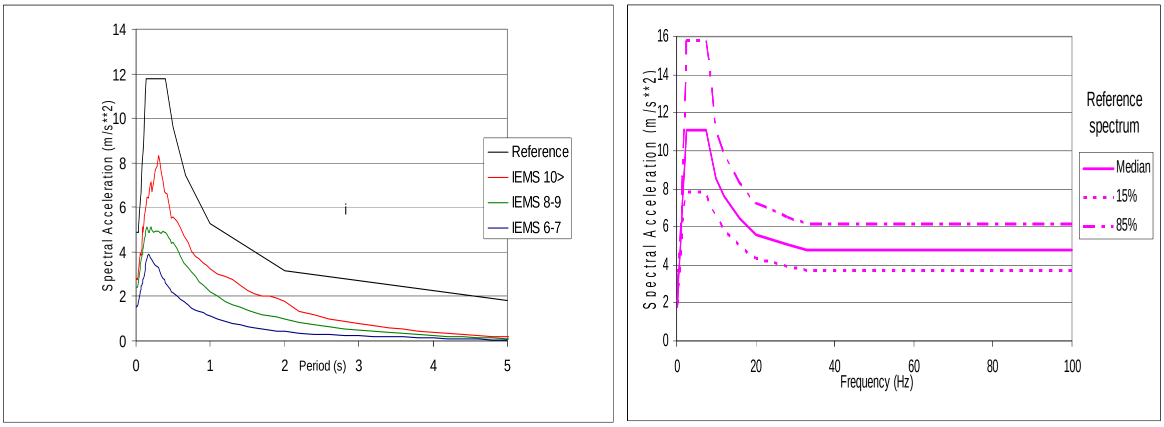

Figure 4. Comparison between mean acceleration response spectra for intensities 6 to 10 and the reference spectrum

As it is shown in Fig. 4 (left), the reference spectrum (mean) is higher than the mean spectra for all intensity groups, i.e. the rules of GIP are applicable. On Fig. 4 (right) the statistics of the reference spectra are given.

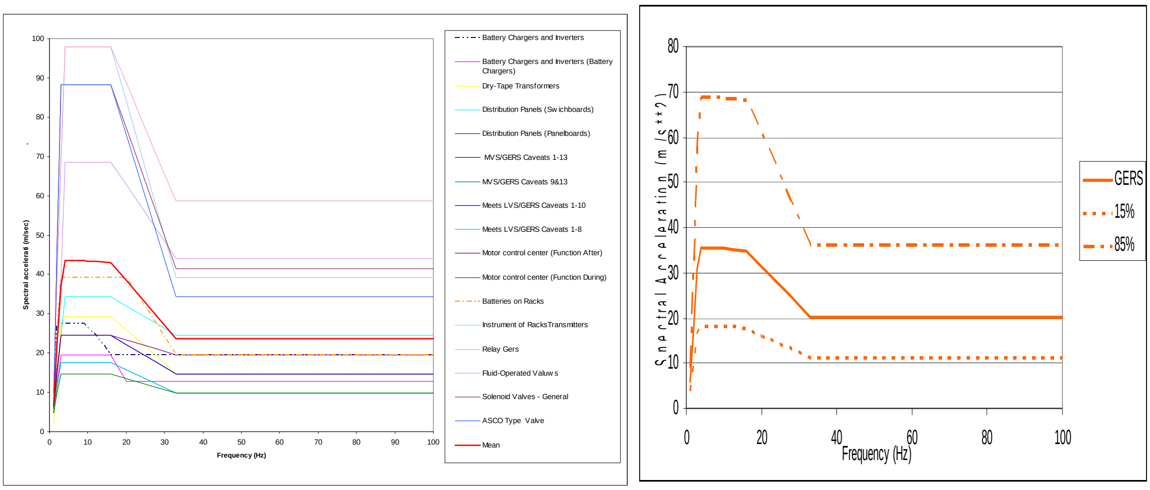

Figure 5 Equipment capacity spectra, statistics

EVALUATION PROCEDURE

Nuclear Facilities

The procedure for estimating OBE exceedance US NRC RG 1.166 (March 1997) is based on DIP. It is considered that if all the requirements of the procedure are met the installations have no damage. The criteria are simple: if at frequencies between 2(1) and 10(2) Hz any of the three component ground motion response spectra exceeds the corresponding OBE response spectra or the limit value of 0.2g (0.152m/s) , whichever is greater, and if any of the three component CAV values exceed 0.16 g*sec, then OBE is exceeded. This procedure is using criteria for evaluation of the acceleration response spectra, velocity response spectra and CAV. Additionally, there are limitations for the frequency content of the response spectra that could be considered as criteria as well. All plant specific ground motion records that are subject to evaluation in the OBE exceedance procedure are on free field.

Based on the example of OBE exceedance procedure and also considering the statistics of the European Strong Motion Data Base and the equipment capacity as described by DOE, an extended procedure is proposed that may not only be used for assessment of the operability of the plant but partially also for safety assessment in case the plant is subjected to an external dynamic impact (earthquake, blast, airplane crash, etc). It is a multi-step approach that includes evaluation of CAV and I_{JMA} intensity, assessment of Sa, assessment of Sv and Sd, and finally also may include detailed (traditional) analysis. The procedure requires development of spatial in-structure response, including in-structure response spectra, in-structure CAV and I_{JMA} intensity. The thresholds are best estimate values, based on strong motions causing effects of EMS intensity 8 (operational state) and intensity 9 (safe state). As it was shown earlier, according to EMS, structural damages in safety related buildings are not expected if they are subjected to excitations corresponding to intensity 9.

Step one in the evaluation is in-structure response estimation in terms of CAV and I_{JMA}. This requires a three dimensional response evaluation of the structure under impact. For each location where there is a critical structure, system or equipment CAV and I_{JMA} are evaluated. If each component of $CAV<0.16g*s$ or $I_{JMA}<4.5$, then no damage is expected and operation should not be affected. Further, if each component of $CAV<0.3g*s$ or $I_{JMA}<5$, safety is not going to be affected, i.e. structures and equipment are in a safe state. For all structures and equipment for which the conditions are not fulfilled, Step two of the evaluation is required.

In Step two the in-structure acceleration response spectra are examined. In case each component of $Sa<2m/s^2$, we should expect no damage and operation is not affected, if $Sa<4.5m/s^2$, then safety will not be affected. Again if those conditions are not fulfilled, we should proceed with Step three and compare the velocity response spectra and the displacement response spectra (drifts). An alternative comparison could be performed within Step two in case there is sufficient information regarding the design response spectra for the respective equipment. In such a case, the design spectra could be increased (multiplied) by a series of safety factors and transferred to a capacity spectrum. The safety factors could be developed in a similar way, as in the case of fragility analyses, by scaling. In this case the comparison is made between demand spectrum and capacity spectrum and positive outcome is when the demand is less than the capacity.

For Step three the requirement is each component of the in-structure velocity spectra to be $Sv<0,15m/s$, then no damage is expected and if $Sv<0,50m/s$, safety is not affected. Correspondingly, for the displacement spectra the requirement is $Sd<0,017m$ (no damage) or $Sd<0,06m$ (safety not affected). It is recommendable to use drift assessment instead of displacement spectra. Using the spectral displacement in the equipment predominant frequency, an equivalent "centre of mass" drift, due to the impact vibration loading, is estimated. The drift is compared, with a threshold value, e.g. 0.1% for active equipment and 1% for passive equipment. If the corresponding drift in each direction of excitation is less than the threshold, then safety is not affected. Equipment specific ultimate drifts (equipment qualification information) could be used instead the prescribed thresholds.

In case none of the above comparisons are positively answered, we have to proceed with detailed analyses.

Other evaluation criteria could be included in the procedure if possible, e.g. interaction with non safety equipment (polar crane); in many cases this interaction could be postulated. The effects of large fire on the facility yard have to be considered also, especially in the case of a large airplane impact. For simplification of the procedure some of the equipment (structures) could be considered as failed under obviously severe conditions, e.g. equipment that is attached to an impacted wall is considered as failed without further evaluation.

Finally, the evaluation is considered successful if a minimum set of equipment is available to perform the basic safety function (beyond design base conditions, DEC).

Other critical structures

For other critical structures or scenario based assessment the procedure based on DIP could also be used (Iliev et al. 2012). We have developed and implemented an express assessment system for dam damage state after an earthquake. The procedure consists of seismic motion recording system and quick estimates of the spectral data, CAV, I_{JMA} and maximal response values. We have used similar table of thresholds as that presented above to have quick assessment of damage state. We may evaluate also different confidence levels of the assessments if we consider the variations.

Five Damage Levels (DL) are defined, based on engineering judgment and various engineering guidelines. The DL represents different states of accumulated damages of the dam from initial superficial cracks to total failure. Short description of the Damage Levels is presented below:

DL0 – elastic response; no cracks expected for the structure;

DL1 – superficial cracking to initial structural damages; minor inelastic structural response;

DL2 – initial to moderate structural damages; moderate inelastic structural response; possibility for significant cracks in the structure; damage inspection should be performed;

DL3 – moderate to heavy structural damages; significant inelastic structural response; possibility for cracks passing through the whole dam cross section; decrease of water level and subsequent inspection;

DL4 – heavy structural damages to total failure; heavy inelastic structural response and possibility for loss of structural integrity; evacuation of local communities is necessary and immediate decrease of water level.

The quick and preliminary estimation of the damage state is based on the following procedure:

First step: evaluation of CAV and comparison to threshold values, i.e. DL0 could be expected for CAV less than 0,12g.sec, DL1 for 0,12<CAV<0,17g.sec, DL2 for 0,17<CAV<0,35g.sec and DL3 for CAV>0,35g.sec.

Second step: comparison of maximal acceleration and/or displacement (including structure response values and spectral values) specifically determined for the dam under assessment.

The procedure is adapted also for quick damage state assessments of dam equipment as gates, valves, lifts, etc.

CONCLUSION

The thresholds that are used in this procedure are derived from the data contained in the European Strong Motion Data Base and the equipment capacity data provided in the DOE procedure for qualification of equipment based on experience. Both data bases are compatible. The performed split of the strong motion database in 3 intensity groups is rather arbitrary and based on the intention to simplify application and to distinguish between damaging and not damaging effects. In case we consider the acceleration response spectra that correspond to each intensity group as seismic demand to a nuclear facility, we may conclude that there is in general a significant margin for the seismic safety of the general "equipment", as shown in Fig.6. In each specific case, however, attention is needed to select proper criteria.

There are two significant and powerful DIPs in the described procedure and these are from one side the CAV and I_{JMA}, and the displacement (drift) criteria, on the other side. These two groups of damage indicating parameters differ in general from the "force based" criteria using acceleration and velocity response spectra. We consider these DIPs reliable and very promising for future analyses and development. The existing analyses are showing strong correlation between CAV and I_{JMA} as shown in Fig.7. The use of both quantities simultaneously leads to a higher degree of confidence of the assessments.

The drift assessment has to be given preference in comparison to the displacement response spectrum as the drift is individually estimated for equipment (based on the displacement spectra). Finally, the strain and stress in the equipment are due to relative displacements (drift).

The database of DOE and the procedure for qualification, based on experience, is not applicable to all classes of equipment. Most probably DIP evaluations could be applicable and useful for piping and distribution systems. DIP thresholds could be used for post earthquake assessments but also for evaluation of safety significance of induced vibrations due to a crash, blast, impact, etc. These thresholds could be used also in design procedures for prioritizing and limitation of scope of qualifications.

This procedure was originally created for assessment of effects due to a blast near critical facilities. It was further developed and applied for assessment of critical scenarios due to a large commercial aircraft crash on a nuclear installation. Now we apply this procedure for analysis within the "stress tests" of nuclear installations. Further on it was developed and applied for express and preliminary assessment of damage state of large dams after a strong earthquake. It should be emphasized that the application of the DIP based procedures should be considered carefully on a case by case basis. The procedure is especially useful for beyond design base situations. It leads usually to a significant reduction in the detailed analysis.

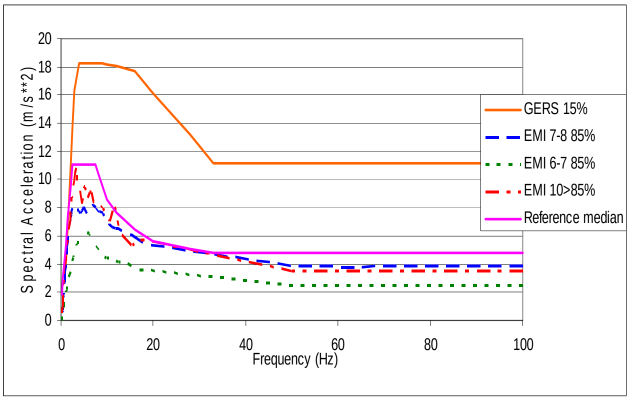

Figure 6. Comparison between generic equipment capacity (15% confidence level) and 85% confidence level seismic demand corresponding to EMS intensities from 7 to 10

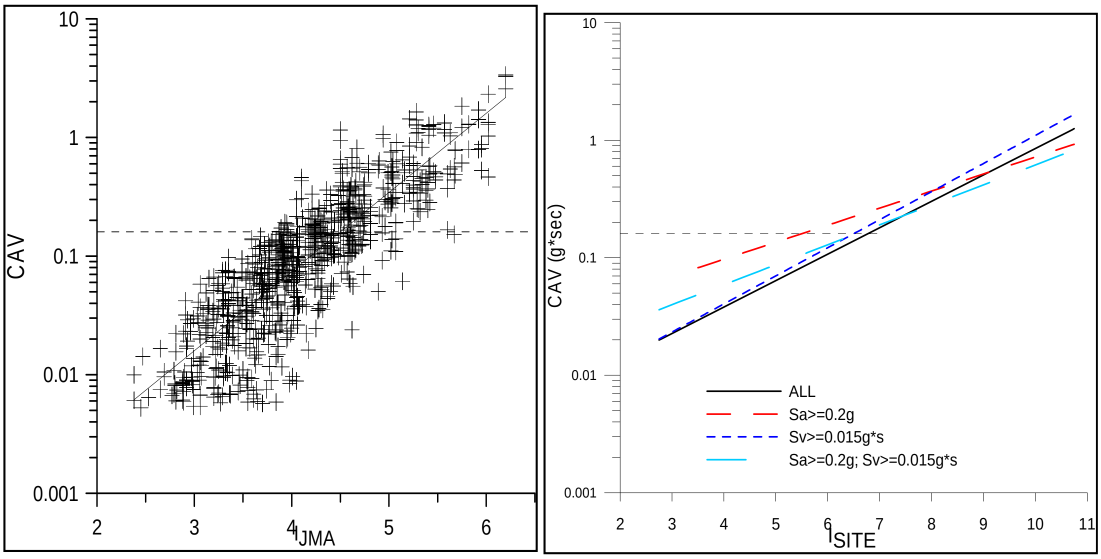

Figure 7. Correlation between CAV and I_{JMA} for the European data base (left) and correlation between CAV and EMS intensity (right)

The main advantage of procedures based on DIP is the control of the high frequency effects, causing large accelerations and apparently high inertia induced forces. This advantage may turn to a significant disadvantage if we do not consider carefully the cases where the high frequency content (acceleration) may be of significance, e.g. I&C equipment. The proposed procedure is successfully tested in several project applications. Nonetheless, there is additional and significant effort needed for further improvement, adjustment, and validation.

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