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SEISMIC PERFORMANCE EVALUATION OF CONCRETE GRAVITY DAMS

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SUMMARY

The rigorous evaluation of the performance of typical concrete gravity dams subjected to strong earthquake excitation requires accurate modeling of the nonlinear characteristics associated with the tensile behavior of mass concrete. Under severe ground motions, tensile cracking may develop in several regions and this has the potential to significantly change the dynamic response characteristics and compromise the integrity of the structural system. Under these conditions, a seismic performance evaluation should include nonlinear time-history analyses to directly estimate the severity and extension of the damage that could be expected. Of course, the use of nonlinear models increases the complexity of the seismic evaluation procedure with added difficulties associated with the appropriate definition of material parameters and augmented sensitivity to the characteristics of the input ground motions.

Ideally, the entire seismic evaluation process should be performed according to a systematic approach consisting of different phases carried out in order of increasing complexity. The application of nonlinear models should be preceded by the corresponding linear analyses, which can always render valuable information about the main characteristics of the seismic response of the dam. This paper, jointly prepared by dam engineers from Japan and the United States, discusses the role of nonlinear dynamic analyses in seismic evaluation problems in these two countries. In addition, this paper examines the application of linear analyses to provide qualitative estimates of potential level of damage under moderately severe excitations. A two-dimensional section of a concrete gravity dam is evaluated using various linear and nonlinear procedures and it serves as case study for the discussion.

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INTRODUCTION

Engineers in Japan must pay special and careful attention to the problem of earthquake loading in the design and evaluation of almost all permanent civil engineering structures. Naturally, critical structures such as dams need to be designed and constructed so that the possibility of catastrophic damage induced by earthquake motions is not likely. Dams must be completely safe and stable because of their immense impact in case of collapse. The total number of large dams (height over 15m) in the Japan inventory is more than 2,600. Additionally, there are more than 400 dams currently in final design or construction stages. Of the total number of structures in service, earth fill and gravity dams constitute the two most common types of dams in Japan. They represent 57% and 31%, respectively, of the total inventory, followed by rock fill dams (8%) and arch dams (2%). A large part of the inventory (1,397 dams) is comprised of earth fill dams with heights between 15 and 30m. It is interesting to note that if only those dams that exceed 30m in height are considered, their total number reaches 931, and 60% of them are concrete gravity dams. The first part of Table 1 lists some of the highest dams in Japan.

The significant effects caused by earthquakes on dams are not only those directly related to the seismic motions but also those directly associated with the ground displacement along the fault line. Concerning the effects of seismic motions, dams in Japan are designed using the seismic coefficient method in accordance with the present design criteria. Based upon the recent history of seismic activities, all of Japan is categorized into three seismic zones (strong, intermediate, and moderate), and the seismic coefficient according to dam type is selected for each seismic zone. If verification of the expected earthquake performance is necessary for an existing structure, this is usually done by the modified seismic coefficient method and/or dynamic analysis procedures.

The conservative nature of this design practice has been verified by the fact that no serious damage on dams has been observed during large earthquakes, including the Hyogoken-Nambu (Kobe) January 17, 1995 earthquake. About 50 dams were located within 50km of the epicenter of this severe earthquake and they were subjected to significant shaking. For example, the accelerations reported at Hitokura Dam during this earthquake were among the largest ever reported for a dam site, but in general none of the dams suffered damage serious enough to compromise their safety as indicated by Uesaka [1]. Very significant accelerations were also reported at Kasho Dam during the Western Tottori-Prefecture October 6, 2000 earthquake. Despite the large accelerations, this concrete gravity dam (Figure 1) survived the earthquake with no damage to the dam body and only minor damage, such as concrete cracking, on the side-wall of an elevator shaft. However, as the dam was located just above the seismic fault, permanent ground displacements were observed for the entire dam site as reported by Ohmachi [2].

While the earthquake-resistant design process can effectively deal with the problem of imposed seismic motions, the standard design framework cannot directly address the ground displacement problem. After the Kobe earthquake, determination and assessment of active faults became a major topic of discussion even for the design and construction of ordinary civil engineering structures in Japan. When carrying out the site selection process for dams, in addition to the conventional studies of past seismic activities, an active fault survey currently constitutes a very important component of any preliminary investigations. In general, great progress has been made in determining the location and history of large-scale active faults, and detailed information about active faults near major cities has been obtained. However, investigations of active faults in mountainous areas, where many dams are planned, have not yet been comprehensively conducted. No effective method has been established for investigating and evaluating active faults in such areas as little is known about the base topographies. This is clearly an area where more research is needed.

The enormous damage caused by the Kobe earthquake motivated many comprehensive research activities in several earthquake engineering disciplines, and dam engineers in Japan have focused their attention on advanced dynamic analysis methods. As indicated before, the application of the seismic coefficient method for the seismic design of concrete gravity dams in Japan has been traditionally considered a safe approach since no significant earthquake damage has been ever reported. However, because of the natural limitations of this approach, vigorous studies are taking place at universities and public/private research institutions in order to establish more rational earthquake resistance design and evaluation methods, as noted by Sakamoto [3]. Several evaluation studies have been recently conducted on many gravity dams using linear time-history analyses, in some cases taking full advantage of any available response acceleration measurements. However, it is clear that if the goal of the analysis is to determine the extent of cracking and ultimate behavior of dams subject to very severe earthquake motions, then the use of nonlinear models becomes necessary, as indicated by Kanenawa et al. [4]. The Ministry of Land, Infrastructure, and Transport, Government of Japan, has recently completed a thorough evaluation of the state of practice regarding stability evaluation techniques for dams subject to seismic motions associated with a Level 2 Earthquake (which corresponds to Maximum Credible Earthquake or Maximum Design Earthquake levels in the United States). Based on this study, a new set of seismic evaluation guidelines is expected to be released in the near future. These recommendations will likely address the application of nonlinear dynamic analyses as an effective approach to evaluate potential seismic damage on concrete dams.

The problem of seismic evaluation of dams has also been the focus of extensive research in the United States, with more than 6,700 large dams (height over 15m) owned by federal, state, local, public utility, or private entities. The second part of Table 1 lists some of the highest dams in the United States. In particular, the U.S. Army Corps of Engineers (USACE) owns more than 600 dams across the country, many of them constructed between 1940 and 1980. Of the total number of dams under USACE responsibility, 259 dams exceed 30m in height. Some of these dams are located in seismically-active areas where consideration of the effects of the potential earthquake ground motions constitutes a critical problem for design and evaluation purposes. Figure 2 depicts Dworshak Dam, which is the highest dam in the USACE inventory.

The seismic design and evaluation of dams under USACE responsibility must be performed in accordance with the technical policy established for civil work projects in Engineer Regulation No. 1110-2-1806 [5], which provides general criteria for seismic design of new projects and seismic evaluation of existing projects. This regulation also addresses the sequence of analysis procedures to be followed during the design and evaluation process. It recommends that the overall analysis should be performed in various phases in order of increasing complexity. The recommended analysis progression for each particular case depends on the seismic hazard at the site and the controlling loading condition for design or evaluation.

The seismic coefficient method, although it fails to account for the true dynamic characteristics of the dam-foundation-reservoir system, constitutes a convenient initial step for estimating the structural global stability of concrete gravity dams, and it has been often used as a tool to decide if more rigorous dynamic analyses should be undertaken. Estimation of dynamic stress responses is typically done using a simplified response spectrum approach as developed by Chopra [6], and Fenves and Chopra [7]. In those cases where it is necessary to obtain a more specific assessment of the expected seismic performance, this initial approach is typically followed by linear time-history analyses. The quantification of the time-varying characteristics of the relevant response quantities provides very important information regarding the expected behavior under seismic loadings. Recommendations for seismic evaluation using time-history procedures are provided in the USACE Engineer Manual 1110-2-6051, “Time-History Dynamic Analysis of Concrete Hydraulic Structures,” HQUSACE [8]. This manual recommends a systematic interpretation of linear time-history results and it provides performance criteria for qualitative estimation of the level of damage. As a final step in the analysis progression, and for those cases where it is absolutely necessary to quantify the magnitude and spatial distribution of the resulting damage, the determination of the actual response of the dam must be carried out using nonlinear time-history analysis.

SEISMIC EVALUATION OF CONCRETE DAMS

The analysis of the seismic response of a concrete dam is a complex problem in which the accurate representation of the material's behavior requires some form of nonlinear model, especially if the concrete material is subjected to significant tensile stress demands. In case of severe ground motions, considerable cracking is likely to develop across extensive regions of the dam, particularly at the dam heel and in the vicinity of abrupt changes in geometry. Therefore, the proper consideration of this nonlinear phenomenon and its consequences on the dynamic response of the system become critically important for a rigorous seismic evaluation. The actual post-cracking behavior and the ultimate capacity of existing concrete dams can only be determined by performing the corresponding nonlinear dynamic analyses. Some efficient numerical procedures have been successfully developed to model the material's nonlinear response and other nonlinear phenomena such as interaction of monolith vertical joints and behavior of horizontal lift joints. There are several computer programs currently available for this type of analysis, and they provide the analyst with alternative material modeling schemes and different solution strategies. It is important to mention, however, that some of the numerical models currently available still lack extensive validation. Because of their complexity and the difficulties involved in the determination of their input parameters they must be used with great care and engineering judgment.

On the other hand, linear time-history analyses provide the analyst with valuable insight and information and they should be considered a necessary step in the analysis progression. In spite of the fact that their range of validity is obviously limited to those cases in which the behavior of the material is essentially linear, they represent a very useful tool that not only can provide significant information regarding the main characteristics of the dynamic response of the dam but also can be used to yield qualitative damage estimates. Results from response history analyses are typically presented in the form of time histories of selected response quantities and by means of contour plots depicting the spatial distribution of the peak values reached over the duration of the analysis. Typically, the peak values of principal stresses are used as local indicators of the system's seismic performance. These types of local performance indices, which are usually computed at discrete points of the finite element discretization, represent values that are not simultaneous and they only characterize the local peak response. However, an overall evaluation of the seismic performance must take into account not only the magnitude of the stress responses but also their time-varying characteristics. Different ground motions can induce similar values of peak stresses in the dam section but the potential consequences of these input motions could be very different regarding crack initiation and propagation. Therefore, solely examining the peak stress responses does not provide sufficient information to judge the comparative severity of different ground motions.

Hatami [9] proposed a local index that incorporated the time variation of the stress response by integrating the positive side of the maximum principal stress time history. Using these local indices computed at the finite element sampling points, a global performance index was defined based on their average value weighted by the corresponding areas of influence. Several alternative performance indices have been proposed in the literature as additional analysis tools that allow a more systematic comparison of the effects of different ground motions as indicated by Hall et al. [10]. The application of these types of performance measures can be extended not only to rationally compare the effects of different earthquakes, but also to render qualitative damage estimates by linking them to some predetermined performance criteria. This qualitative estimation can be carried out according to empirical rules of thumb or some other practical criteria based on previous experiences but unfortunately relatively little effort has been expended on the validation of this type of approach. An example of this type of approach can be found in the

USACE guidelines for evaluation of the seismic performance of concrete hydraulic structures mentioned in the previous section, which propose a systematic interpretation of linear time-history results in terms of local and global performance indices. Empirical performance criteria are defined in terms of these indices and they form the basis for the qualitative estimation of the level of damage. If the predicted performance falls within the specified limits, the seismically induced damage is expected to be minor or negligible and the results of the linear time-history analysis will be sufficient to characterize the performance. Otherwise, the level of structural damage is expected to be severe, and the accurate estimation of its actual extent and consequences should be carried out using nonlinear models. Therefore, these guidelines provide a set of standard criteria that, along with the proper engineering judgment, allow the analyst to ascertain whether a nonlinear dynamic analysis is needed to complete the seismic evaluation.

The following section discusses a particular case study that, in spite of its very simple formulation, still provides some interesting discussion elements for a comparison between the different approaches for seismic evaluation of concrete gravity dams currently employed in Japan and the United States.

CASE STUDY

A simple case consisting of a numerical model of a non-overflow monolith of Koyna Dam subject to earthquake motion is considered for this study. The historic performance of this dam and the special characteristics of its original cross-section have made this structure a classical example for experimental studies and for the validation of numerical procedures modeling the seismic response of concrete gravity dams. The same basic geometry was considered for a series of finite-element dynamic analyses conducted using the programs EAGD-SLIDE, developed by Chanvez and Fenves [11], FRAC-DAM, developed by Bhattacharjee and Leger [12], and DIANA [13]. The finite-element models consisted of quadrilateral elements with a finer discretization in those areas were high stresses were expected. A refined mesh consisting of triangular elements with uniform size was considered for the DIANA analyses. For the analyses with FRAC-DAM and DIANA, the nonlinear fracture behavior of concrete was modeled using the smeared crack constitutive model available in both programs.

The assumed material properties are indicated in Table 2. A dynamic magnification factor of 1.2 was used to account for strain-rate effects in the tensile strength and the fracture energy. Considering the objective of investigating different approaches for seismic damage estimation, the complex dynamic interaction effects that are typical of dam-foundation-reservoir systems were not considered. To facilitate the comparison of the results, perfectly rigid foundation conditions were assumed and no energy absorption effects were considered for the foundation and the reservoir bottom. The hydrodynamic effects associated with the reservoir, which are directly incorporated in the EAGD-SLIDE formulation, were modeled using added masses for the FRAC-DAM and DIANA analyses.

Only the horizontal component of the seismic input was considered for these analyses, which were conducted considering three different earthquake records, shown in Figure 3. These records have been modified to match a given target design spectrum, and the corresponding response spectra are shown in Figure 4. Two different levels of peak ground acceleration (PGA) were considered for the input motions: 0.15g and 0.30g.

Qualitative estimation of the probable level of seismic damage induced by these ground motions is carried out according to the USACE guidelines for linear-elastic time-history dynamic analysis of concrete dams. The methodology, which is based on the work by Ghanaat [14], can be effectively used to establish a range of validity for the linear elastic analyses. This methodology is based on the consideration of performance indices such as the stress demand-capacity ratio (DCR), which is defined as the ratio between the maximum principal stress and the tensile strength of concrete (determined as the static strength values obtained by splitting tension tests); and the cumulative duration (CD), which is defined as the total duration of the stress excursions that exceed a certain level of demand-capacity ratio. This duration index provides a better description of the stress time variation than the sole consideration of the number of tensile pulses exceeding a given threshold, and it allows the analyst to physically quantify the severity of the seismic demand over the entire duration of the earthquake.

If the computed DCR values are less than or equal to 1.0, then the response of the system can be safely considered to be within the linear elastic range. For this level of excitation, no significant tensile cracking is expected to occur and the results from the linear analysis contain all the relevant information regarding the dynamic response of the dam. If some DCR values exceed 1.0, then the linear response of the system is considered to be acceptable only if the spatial extent of the overstressed regions does not exceed 15 percent of the dam section area and the corresponding cumulative duration of stress excursions falls below a curve indicating limit performance. In this case, the actual performance of the dam is likely to exhibit some level of cracking but the global consequences of the resulting damage are expected to be minor. In this case, the results from the linear time-history analysis still provide sufficient information to characterize the response of the system and they are considered acceptable. If these conditions are not met, then the level of expected damage should be considered to be severe.

Figures 5-7 show the results from the linear time-history analyses in terms of the DCR values computed using EAGD-SLIDE for the three ground motions scaled to 0.15 and 0.30g. The shaded areas indicate the material regions where the computed DCR values exceeded 1.0. The figures show that this value was exceeded for the three cases with a PGA level of 0.15g, but the areas associated with DCR>1 represented only 3.4, 3.5, and 1.4% of the total section area. The DCR values computed near the change of slope and the heel corner exceed the admissible limit (2.0) although this occurred only within extremely localized areas. Most of the resulting cumulative duration curves were located within the zone of acceptable performance. Based on these results, it can be expected that the actual response of the dam at the 0.15g level will exhibit some tensile cracking but it will not drastically affect the resulting dynamic behavior. On the other hand, the results corresponding to the 0.30g PGA level clearly indicate that significant damage should be expected for the three cases.

Figures 8-10 show the results from the nonlinear analyses conducted using FRAC-DAM. The figures depict the damage predicted for the three ground motions considered in this study. The shaded areas indicate those elements that experienced some level of tensile damage over the duration of the analysis. Two damage zones are clearly identified and they correspond to the areas associated with the maximum tensile demands predicted by the previous linear analyses. For the seismic motions associated with a PGA of 0.15g, some moderate damage is identified but it does not seem to reach a level that could compromise the integrity of the section. On the other hand, the cases associated with a PGA of 0.30g show clear indications of significant strength degradation in the dam, with a cracking pattern that completely extends across the upper section.

Figures 11-13 depict the results obtained using DIANA for the two levels of semis input, and similar observations apply. Very minor damage should be expected under the 0.15g motions. However, when compared to the results obtained by FRAC-DAM, the DIANA results corresponding to a PGA level of 0.30g show more diffuse damage patterns spreading across wider areas. This could reflect not only the differences in the smeared crack models implemented by these two programs, but also the influence of the finite-element discretization. In general, both sets of nonlinear analyses consistently predicted two different scenarios for the dynamic response of the section that were associated with the two levels of seismic input considered.

CONCLUSIONS AND RECOMMENDATIONS

This paper addressed some of the technical issues related to the current practice for seismic design and evaluation of concrete dams in Japan and the United States. The rigorous seismic evaluation of concrete dams requires an accurate quantification of the damage that can occur under earthquake excitations. Nonlinear analysis procedures can identify the ultimate capacity of existing concrete dams taking into account the most critical nonlinear phenomena controlling the response. However, the complexity of these procedures and the scarcity of appropriate calibration strategies frequently force the analyst to interpret the corresponding results using the best engineering judgment. The influence of the input parameters and ground excitation on the nonlinear dynamic response should be investigated by sensitivity studies that aim to identify the most critical conditions. Methodologies for qualitative damage estimation based on results from linear analyses could be used to develop a systematic assessment tool, and this could provide the analyst with a useful reference framework for the adequate interpretation of results.

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Table 1. Dams in Japan and the U.S.

	HIGHEST DAMS IN JAPAN				
	Dam Name	**Prefecture**	**Owner**	**Height [m]**	**Year**
1	Kurobe	Toyama	Kansai Electric Power Co.	186	1963
2	Takase	Nagano	Tokyo Electric Power Co.	176	1981
3	Naramata	Gunma	Water Resources Development Public Corporation	158	1990
4	Okutadami	Fukushima	E.P.D.C	157	1961
5	Miyagase	Kanagawa	Ministry of Land, Infrastructure and Transport	156	1998
6	Nukui	Hiroshima	Ministry of Land, Infrastructure and Transport	156	2002
7	Urayama	Saitama	Water Resources Development Public Corporation	156	1999
8	Sakuma	Shizuoka	E.P.D.C.	155	1956
9	Nagawado	Nagano	Tokyo Electric Power Co.	155	1969
10	Tedorigawa	Ishikawa	E.P.D.C.	153	1979

Source: Japan Dam Engineering Center

	HIGHEST DAMS IN THE UNITED STATES				
	Dam Name	**State**	**Owner**	**Height [m]**	**Year**
1	Oroville	California	California DWR	235	1968
2	Hoover	Nevada	Bureau of Reclamation	223	1936
3	Dworshak	Idaho	Corps of Engineers	219	1973
4	Glen Canyon	Arizona	Bureau of Reclamation	216	1964
5	New Bullards Bar	California	Yuba County Water Agency	197	1969
6	Seven Oaks	California	Corps of Engineers	193	1999
7	New Melones	California	Bureau of Reclamation	191	1979
8	Mossyrock	Washington	City of Tacoma	185	1968
9	Shasta	California	Bureau of Reclamation	183	1945
10	Don Pedro	California	Turlock and Modesto Irrigation Districts	178	1971

Source: USSD Register of Dams

Table 2. Material properties assumed for linear and nonlinear dynamic analyses.

PARAMETER	VALUE
Elastic modulus, KPa	3.10E+07
Poisson ratio	0.20
Compressive strength, KPa	1.50E+04
Static tensile strength, KPa	1.50E+03
Static fracture energy, N/m	150.00
Unit weight, KN/m^3	25.92

Figure 1. Kasho Dam (Tottori Prefecture, Japan)

Figure 2. Dworshak Dam (Idaho, United States)

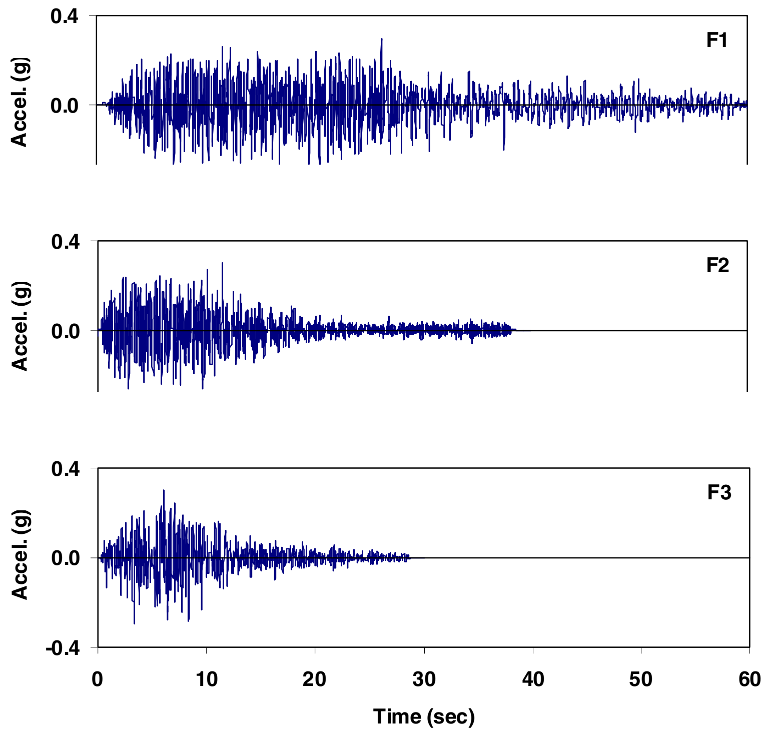

Figure 3. Acceleration time histories F1, F2, and F3 used in study (PGA = 0.30g).

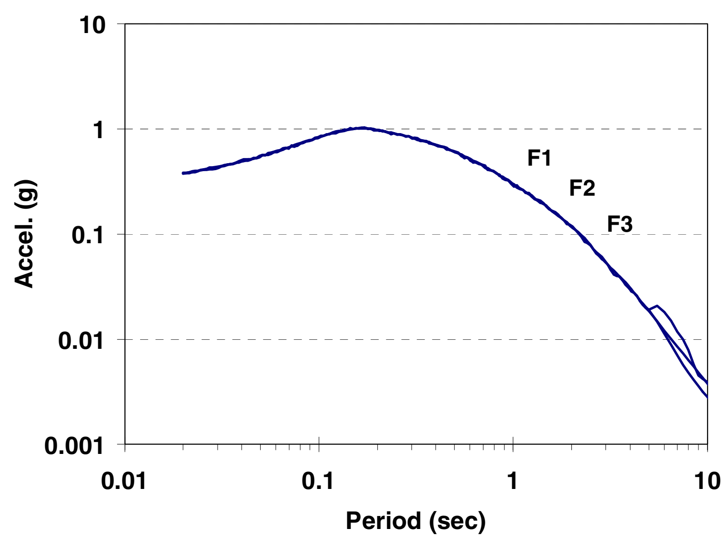

Figure 4. Response spectra for acceleration time histories F1, F2, and F3 (PGA = 0.30g).

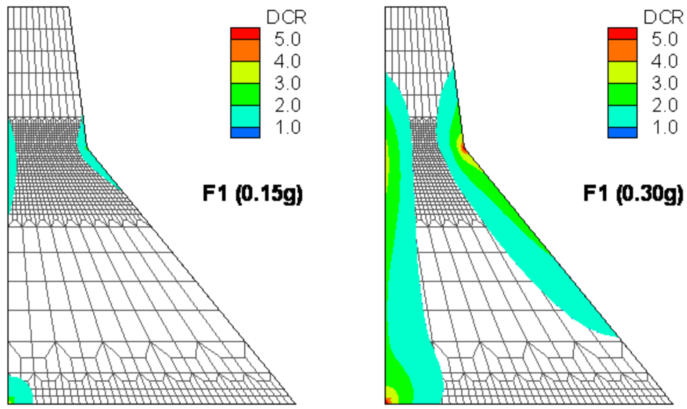

Figure 5. DCR values for two scaling levels of the input motion F1.

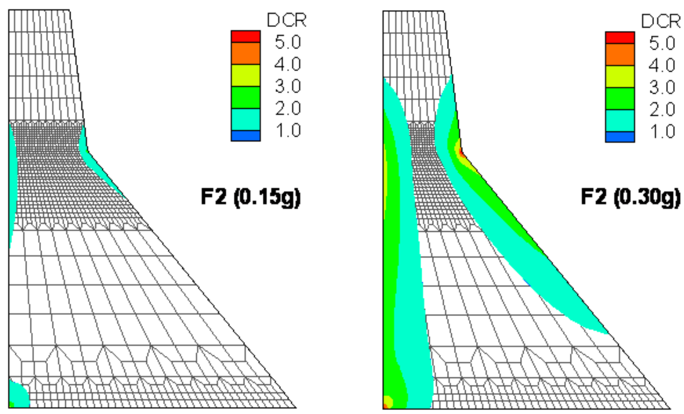

Figure 6. DCR values for two scaling levels of the input motion F2.

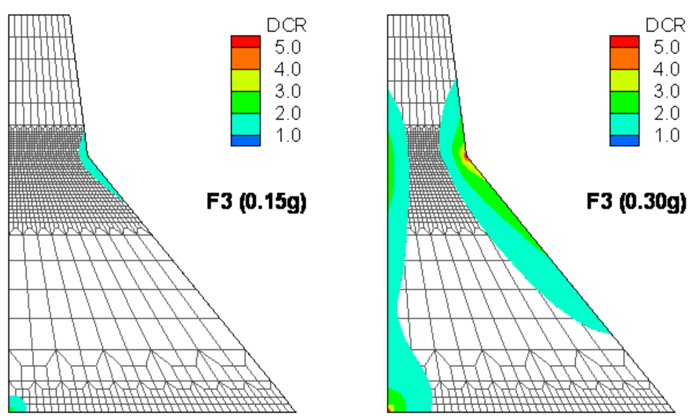

Figure 7. DCR values for two scaling levels of the input motion F3.

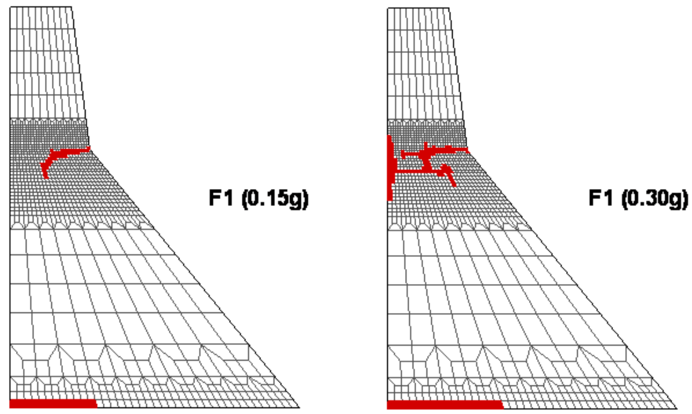

Figure 8. FRAC-DAM damage prediction for two scaling levels of the input motion F1.

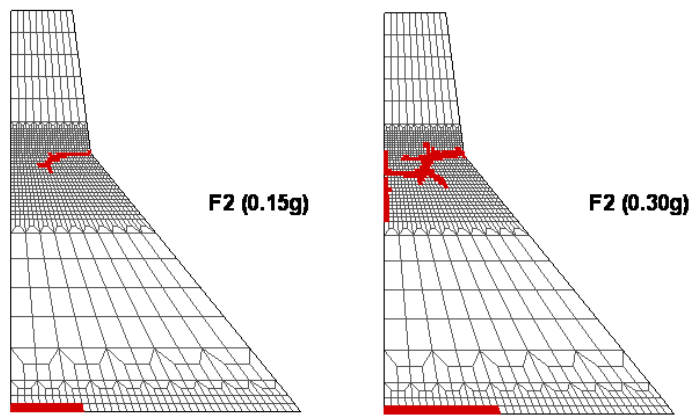

Figure 9. FRAC-DAM damage prediction for two scaling levels of the input motion F2.

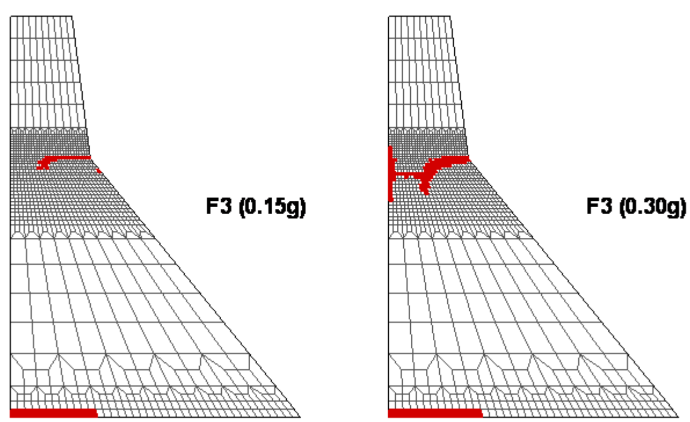

Figure 10. FRAC-DAM damage prediction for two scaling levels of the input motion F3.

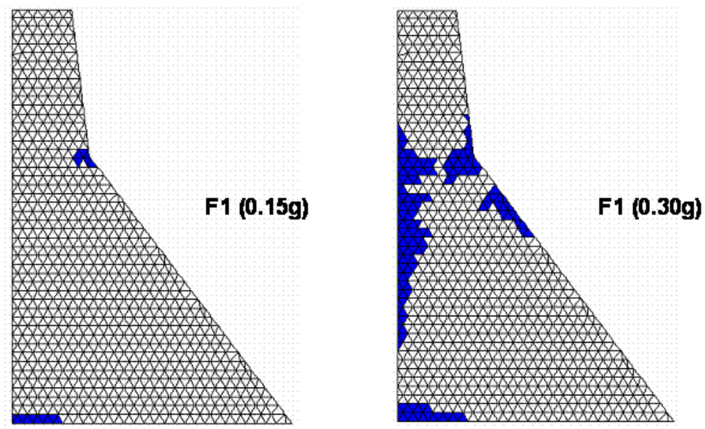

Figure 11. DIANA damage prediction for two scaling levels of the input motion F1.

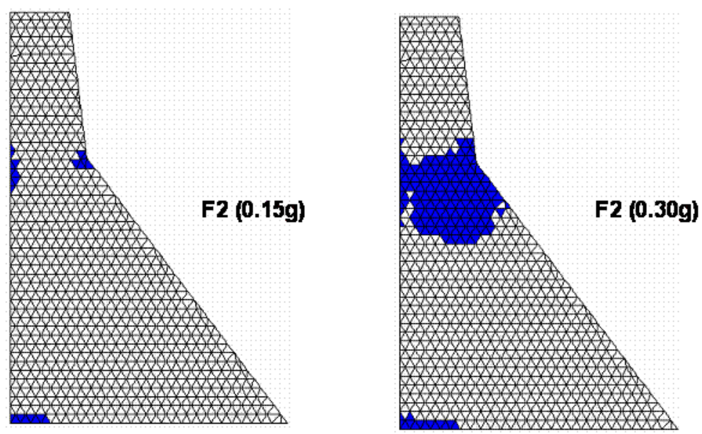

Figure 12. DIANA damage prediction for two scaling levels of the input motion F2.

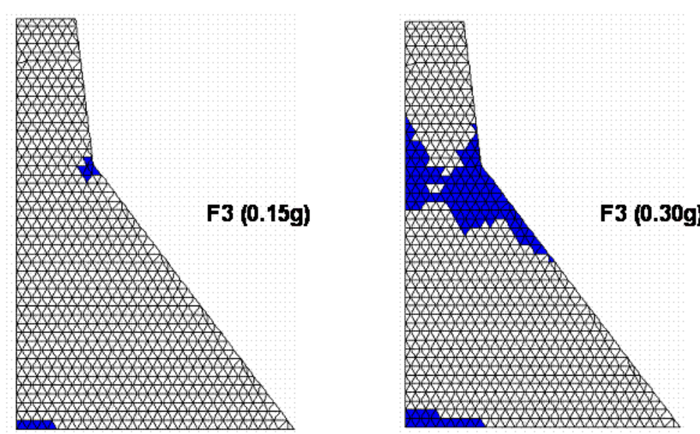

Figure 13. DIANA damage prediction for two scaling levels of the input motion F3.