Guidelines for Seismic Analysis of Concrete Dams: Experimental Evaluation

by

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ABSTRACT

The analysis and evaluation of the seismic response of a concrete dam constitutes a complex problem in which the accurate representation of the material behavior is one of the most important issues. In case of severe ground motions, substantial cracking is likely to develop across significant regions of the dam, and its consequences must be taken into account for a rigorous seismic evaluation. Accurate modeling of the tensile behavior of mass concrete requires some form of nonlinear representation. However, valuable and insightful information is still gained through analysis procedures that are based on the assumption of linear elastic behavior. In spite of their inherent limitations, these procedures can be used to provide not only information about the dynamic response characteristics but also qualitative estimates of the expected level of damage. This paper focuses on the set of guidelines recently prepared by the U.S. Army Corps of Engineers (USACE) for the evaluation of the seismic performance of concrete hydraulic structures. These guidelines establish a systematic methodology for qualitative damage estimation using standard results from linear time-history analyses. The guidelines propose a systematic interpretation of these results in terms of local and global performance indices. Several performance criteria are defined for different structural types and they form the basis for a qualitative estimate of the probable level of damage. A preliminary evaluation of the USACE guidelines is carried out using the results from a recent series of shake table experiments performed on a 1/20-scale model of Koyna Dam.

KEYWORDS: Concrete gravity dams, seismic performance evaluation, damage estimation.

1. INTRODUCTION

The analysis of the seismic response of a concrete dam constitutes a complex problem in which the accurate representation of the material 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 of the dam can only be determined by performing the corresponding nonlinear dynamic analysis. There are several computer programs currently available for this type of nonlinear time-history 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 still lack extensive validation and often they must be used with great care and engineering judgment (Darbre, 1998).

Linear time-history analyses, on the other hand, are based on the basic assumption of elastic material behavior. These proven procedures 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

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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.

In a linear time-history analysis, the dynamic response of the system is computed based on the elastic stiffness characteristics of the component materials. The corresponding results are obtained in the form of time histories of the relevant response quantities. A common approach is to present these results as contour plots that depict the spatial distribution of the peak values reached by selected response quantities 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 the integration points of the finite element discretization, represent values that are not simultaneous and they only characterize the peak response at each point. 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 (Hatami, 1998) 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 (Hall et al., 1999).

The application of these types of performance measures can be extended to not only 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 could be carried out according to empirical rules of thumb or some other practical criteria based on previous experiences. Unfortunately, relatively little effort has been expended on the validation of this type of approach. An interesting contribution in a related area is the experimental work by Slowick and co-workers (Slowick et al., 1996) that focused on the study of the fracture response of concrete under low-cycle fatigue. A series of wedge-splitting tests were carried out to investigate the dynamic strength of cracks under variable amplitude loading. The emphasis of this experimental work was on the calibration of a quantitative measure of the damage induced by the cyclic excitation, and a fracture-mechanics based empirical law was proposed to predict crack growth.

This paper focuses on a set of guidelines recently prepared by the U.S. Army Corps of Engineers (USACE) for the evaluation of the seismic performance of concrete hydraulic structures using linear time-history analysis (HQUSACE, 2000). One of the objectives of these guidelines was the development of a systematic methodology for qualitative estimation of the expected level of damage, based on the work by Ghanaat (Ghanaat, 2000). A primary motivation for such a methodology is that it can be used to establish a practical range of validity for the linear elastic analysis of a structure. In this framework, the results from a linear time-history analysis are not automatically invalidated by the fact that some of the local stress responses reach values beyond the tensile strength. The response time histories can be used to formulate an approximate judgment about the expected level of damage. This provides a standard criterion to justify whether a more sophisticated analysis is needed. In the context of this methodology, a qualitative conclusion predicting "severe damage" does not necessarily mean that the dam will experience global failure. It means instead that the actual dynamic response could be significantly different from the one computed through linear elastic analysis. This does not automatically imply that the dam will suffer catastrophic consequences, because stress redistributions or changes in the natural vibration characteristics may take place and limit the propagation of damage. These effects can only be appropriately evaluated by the corresponding nonlinear time-history analysis.

A preliminary evaluation of the USACE guidelines is carried out using the results from a recent shake table experiment performed on a 1/20-scale model of Koyna Dam. This experiment was formulated as an effective way to provide realistic data for validation of numerical procedures modeling the seismic performance of concrete gravity dams. The model was tested under several sinusoidal base motions with increasing amplitude, and its dynamic behavior was well documented. This study employs those strain time histories recorded near the critical zone (i.e., where damage initiated) to investigate the applicability of the evaluation criteria proposed in the aforementioned guidelines.

2. USACE GUIDELINES FOR TIME-HISTORY ANALYSIS

The USACE guidance document entitled “Time-History Dynamic Analysis of Concrete Hydraulic Structures,” currently designated as Engineer Circular 1110-2-6051, is undergoing the final stages of review before final publication as an Engineer Manual (HQUSACE, 2000). These guidelines describe procedures for the linear-elastic time-history dynamic analysis of concrete hydraulic structures. These structures present distinctive response characteristics when compared to other civil engineering structures, and the evaluation of their dynamic response is usually complicated by structure-foundation and structure-water interaction phenomena. The first chapter of this manual provides an overview of the seismic performance evaluation process for concrete hydraulic structures. Chapter 2 discusses the general methodology for time-history dynamic analysis, including general descriptions of structural types, modeling aspects, water and foundation-rock interaction, energy absorption effects, and the ground acceleration time-histories required for each structural type. Chapter 3 focuses on the computational aspects regarding the solution of the equations of motion in both time and frequency domains. A general methodology for performance evaluation and qualitative estimation of the probable level of seismically induced damage is presented in Chapter 4, whereas Chapter 5 describes the procedures for development of earthquake input acceleration time-histories. The final chapter provides practical examples of time-history evaluation for major concrete hydraulic structures including a gravity dam, a concrete arch dam, an inclined intake tower, and a W-frame lock structure (HQUSACE, 2000).

A main objective behind the USACE guidelines was the development of a methodology for performance evaluation and qualitative damage estimation using standard results from linear time-history analyses. As mentioned before, these topics are addressed in Chapter 4 of the guidelines. Based on the methodology proposed by Ghanaat (Ghanaat, 2000), a systematic interpretation of linear time-history results is presented in terms of local and global performance indices: demand-capacity ratio, cumulative inelastic duration, and spatial extent of overstressed regions. Several 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 an appropriate nonlinear model. The USACE guidelines provide the analyst with a set of standard criteria that, along with the proper engineering judgment, allow him/her to ascertain whether a nonlinear dynamic analysis is needed to complete the seismic evaluation.

This paper focuses only on those sections of Chapter 4 that apply to concrete gravity dams. These sections represent a substantial contribution that complements and expands previous technical specifications for dynamic stress analysis contained in the USACE Gravity Dam Design Manual (HQUSACE, 1995). The performance indices proposed to evaluate the time-history response of gravity dams and the corresponding performance criteria are discussed next.

Demand-capacity ratio (DCR): This parameter represents a dimensionless stress level that, in the case of gravity dams, is defined as the ratio between the maximum principal stress and the tensile strength of concrete. The tensile strength used in this definition is the static strength characterized by the splitting tension test. Although the tensile strength of concrete is strain-rate sensitive, this effect is neglected and the demand-capacity ratio parameter is intentionally defined in terms of the static strength in order to provide some degree of conservatism in the qualitative estimation of damage.

Cumulative duration (CD): The response parameter is defined as the total duration of the stress excursions that exceed a certain level of demand-capacity ratio. This parameter 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.

Performance criteria: The evaluation of the seismic performance is accomplished based on the previous performance indices, which are computed using linear time-history analysis results. If the computed stress demand-capacity ratios 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 tensile cracking is expected to occur and therefore the results from the linear analysis contain all the relevant information regarding the dynamic response of the dam. If some demand-capacity ratios 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 surface area and the cumulative duration of stress excursions beyond the tensile strength of the concrete falls below the performance curve shown in Figure 1. Note that the maximum admissible value of demand-capacity ratio is equal to 2.0, which is the value that corresponds to zero cumulative duration. Under the specified conditions, 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. In this case, a nonlinear time-history analysis would be required to determine the dynamic response and to quantify the magnitude and spatial distribution of the resulting damage.

It is interesting to compare these criteria with the technical specifications in the USACE Gravity Dam Design Manual (HQUSACE, 1995). As indicated in Section 3.1.e.3 of this manual, “when the tensile stress in existing dams exceeds 150% of the modulus of rupture, nonlinear analyses will be required to evaluate the extent of cracking.” In this case, strain-rate effects are taken into consideration and the value of strength represented by the modulus of rupture is increased 1.5 times to account for the rapid loading rate induced by the typical seismic excitation. The static tensile strength determined through a splitting tension is typically about 3/4 of the value determined by the corresponding modulus of rupture test, and therefore this criterion specifies that the evaluation of damage using a nonlinear analysis should be performed if the tensile stress exceeds twice the value of the static strength given by the splitting tension test. Since this limit condition corresponds to a demand-capacity ratio of 2.0, both USACE guidance documents are consistent with respect to the peak value of tensile stress excursions that can be locally allowed in a linear time-history analysis. Of course, a criterion like this is only based on the maximum values of the local stress histories, and it does not take into consideration the cyclic nature of the tensile excursions or the spatial extent of the areas with high tensile demand. The new guidelines incorporate these elements in the seismic performance evaluation for those cases that exhibit demand-capacity ratio values between 1.0 and 2.0.

3. SHAKE TABLE EXPERIMENTS

A series of shake table experiments were performed on a 1/20-scale model of the tallest nonoverflow monolith of Koyna Dam (Wilcoski et al., 2000). This 103m high concrete gravity dam is one of the few concrete dams to have experienced significant damage induced by seismic ground motions. The 1967 Koyna earthquake caused significant structural damage in the form of horizontal cracks on the upstream and downstream faces of several nonoverflow monoliths. The historic performance of Koyna Dam and the special characteristics of its 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 main objectives of this experimental program were the determination of the dynamic characteristics of the model and the measurement of its forced response when subjected to base accelerations acting along the in-plane direction. Two different types of base motions were used during these tests. The first input motion considered was a scaled version of the transverse component of the 1967 Koyna earthquake. The peak acceleration corresponding to the original record was about 0.38g. To avoid inducing any damage to the model, the peak amplitude of the acceleration record was scaled down to a conservative value of 0.027g. The second type of the base motion imposed was a sinusoidal excitation with a frequency slightly higher (14 Hz) than the first in-plane natural frequency of the model. This simple type of sinusoidal input was used to ensure that the model response would be dominated by the first in-plane mode of vibration. Several test runs were carried out using this type of input motion, and the peak values of the base accelerations were varied from 0.005 to 0.16g, level at which failure occurred. The dynamic behavior of the model was well documented with acceleration, displacement, and strain measurements. Detailed descriptions regarding model geometry, material properties, and test setup, as well as discussions of results have been presented elsewhere (Wilcoski et al., 2000; Hall et al., 2000; Chowdhury et al., 2001).

For each of the sinusoidal tests, the support motions ramped up to the maximum amplitude level in 1 second, maintained this level for 5 seconds, and then ramped down to zero in 1 second, for a total duration of 7 seconds. As mentioned before, the peak values of the commanded base accelerations were gradually increased for each test run. The response of the model remained essentially linear up through the fifth test run (SINE5), with maximum amplitude of 0.12g. The last test in the series (SINE6), at an excitation level of 0.16g, induced the first nonlinear response and led to the formation of a failure mechanism at the critical section of the model. Careful examination of the data collected during this test led to the conclusion that a primary crack formed at 1.27 seconds, near the left side of the downstream face of the model at the elevation corresponding to the change in slope (Wilcoski et al, 2000). Figure 2 demonstrates the linear characteristics of the system's pre-failure behavior. This figure shows the peak value of the acceleration at the top of the model as a function of the intensity of the commanded base motion, whose peak values varied from 0.05g to 0.16 g. The peak response values shown in this figure were determined as the average magnitude of the positive and negative peaks of the response time history for the time interval [1.0,1.2] seconds. This allows the incorporation of the results corresponding to the SINE6 test, because the model was still undamaged during this time interval.

Strain time histories corresponding to a strain gage (location S15) very close to the critical location are shown in Figures 3 and 4, and they correspond to SINE5 and SINE6, respectively. These figures show the first 2 seconds of the responses recorded at a point located 1 inch (25 mm) above the change of slope on the left side of the downstream face of the model. These time histories will be considered representative of the state of strain in the region where cracking was observed to initiate during the SINE6 test.

4. EVALUATION OF PROPOSED CRITERIA

The local performance criterion proposed in the USACE guidelines (Figure 1) applies only to a full size structure. In order to determine cumulative durations from the measured experimental responses, it is necessary to take into account that at model scale, time is “compressed” by the corresponding scaling factor (λ_t), i.e.

$$t_{model} = t_{prototype} / \lambda_t$$

Based on the scaling scheme selected for these tests, $\lambda_t = \sqrt{\lambda_L}$ where λ_L represents the geometric scale of the model (Chowdhury et al., 2001). According to this, the values of cumulative duration calculated from the model time-history responses must be multiplied by λ_t. On the other hand, one must notice that the demand-capacity ratio parameter is not affected by scaling issues because it is a dimensionless quantity. Therefore

$$\mathrm{CD}_{prototype} = \lambda_t \, \mathrm{CD}_{prototype}$$

$$\mathrm{DCR}_{prototype} = \mathrm{DCR}_{model}$$

Performance curves corresponding to the critical point (location S15) will be determined by examining the results from the last two tests of the series. One of them, SINE5, corresponds to the maximum excitation level applied to the system without inducing any visible damage, whereas the other, SINE6, corresponds to an excitation level that actually caused the failure of the model. Therefore, the experimental evidence indicates that the actual capacity of the system lies somewhere in between these two cases. Of course, this assessment is valid only for the specific type of input motions considered, i.e., sinusoidal signals with a frequency of 14Hz.

To generate the performance curves using the experimental data collected in the form of strain time histories, it is necessary to compute the corresponding stress histories using the local value of the modulus of elasticity. Additionally, the stress-based definition of the DCR parameter requires the specification of the static tensile strength of the material at that point. Considering the uncertainties associated with the local specification of the tensile strength of the model, a different approach will be pursued here.

In a first scenario (case a), the tensile capacity of the material at the critical location is assumed to be as low as the peak value of the response during the SINE5 test, during which no damage was observed. Under this assumption, this test would correspond to the last possible stage of elastic response. Material data from cylindrical cores drilled near the critical location indicated that the actual value of tensile strength must have been close to this peak response value. Figure 5 shows the performance curves that correspond to this assumption, for both SINE5 and SINE6 tests. The curves were computed based on a limited duration of 1.27 seconds, which is the initial interval of time during which the system remained undamaged in the final test. To compute these curves in a manner consistent with the definitions in the USACE guidelines, it was assumed that the strain rate did not affect the local tensile strength of the material. It was also assumed that the apparent tensile strength was 1.33 times the value of the actual static strength. The left curve in the figure was obtained based on the experimental strain data measured during SINE5, and it represents the performance that should be predicted by a linear elastic analysis that generates the same strain time-history. The second curve was obtained using the SINE5 time-history response (representative of elastic behavior), scaled up by the ratio between the SINE6 and SINE5 peak base accelerations. This is the nominal performance that a linear elastic analysis would have predicted for the SINE6 test. Because of the particular waveform used as input motion, the resulting performance curves exhibit a non-typical shape with a sharp negative slope. Both curves extend into the severe damage region.

In a second scenario (case b), the actual tensile capacity at the critical location could not have been any higher than the peak value of the response observed during the SINE6 test. The corresponding excitation level (1.33 higher than the previous one) was severe enough to induce the failure of the model, which was characterized by a cracking pattern that initiated at this particular location. Therefore, it is possible to assume a second case in which the tensile strength is equal to the peak response during SINE6. Figure 6 shows the corresponding performance curves that were obtained following the same procedure as before, that is, based on the SINE5 strain data. The SINE5 curve is completely inside the region for which no significant damage should be expected, whereas the curve corresponding to the SINE6 excitation level partially extends into the severe damage region. It is reasonably to expect that the actual performance curves must lie somewhere in between the two cases depicted in Figures 5 and 6.

This simplified analysis, based on assumptions relating the peak value of the response and the tensile strength, clearly revealed the fact that, for a given structure, the representation of the local performance obtained in terms of CD-DCR curves depends not only on the value of tensile strength but also on the waveform and duration of the input excitation. Because of the sensitivity of the performance curves to the waveform the excitation signal, a comprehensive validation of the proposed guidelines could not be achieved with the experimental data available. Unfortunately, the shake table tests were not designed specifically for this purpose, and the excitation employed as base motion did not represent the typical ground motion that is inherently targeted by the USACE performance criteria. The type of amplitude modulation used for the tests (monotonically increasing amplitude up to peak value) and their relatively long duration (5 seconds at peak value level) introduced severe distortions in the resulting performance curves.

The performance of the model subjected to a scaled version of the 1967 Koyna earthquake is considered next. Figure 7 shows the time history of strain at the critical location and Figure 8 depicts the corresponding performance curves. These curves were obtained based on the conservative value of tensile strength (case a), and they correspond to different amplitude levels of the Koyna record. The three curves shown in the figure are associated to peak accelerations of 0.027, 0.25, and 0.38g, respectively. All three curves were obtained based on the experimental data that was collected at the actual excitation level used in the test (0.027g), which was appropriately reduced to avoid any damage to the model. This strain history was properly scaled to represent the nominal elastic responses corresponding to 0.25 and 0.38g excitation levels. The first case (0.027g) represents the performance of the system during the actual test, and it shows that the corresponding curve is well within the safe region. The last case (0.38g) represents the nominal elastic performance of the model under an excitation level similar to the one that caused significant damage to the dam. The position of the resulting curve is consistent with this observation, since it indicates that a linear analysis would be inadequate to predict the dynamic behavior of the system under these conditions. The intermediate case corresponds to an excitation level (0.25g) that produces a performance curve that is close to the limit established by the guidelines. This case is instructive because it represents the maximum excitation level for which an elastic analysis should be deemed sufficient, according to the USACE guidelines.

5. CONCLUSIONS

Experimental results from shake table experiments performed on a 1/20-scale model of Koyna Dam were used to discuss and evaluate current USACE guidelines for evaluation of the seismic performance of concrete gravity dams. Based on observational evidence, two limit cases were assumed in order to define the local value of tensile strength. Performance curves were obtained using strain data collected during sinusoidal and earthquake excitation tests. It was found that, because of the sensitivity of the performance curves to the general characteristics of the input waveform, it was not possible to perform a complete validation of the proposed performance criteria. The type of input motion used in the experiments to induce the failure of the model (sinusoidal input) was not representative of actual ground motions, and this caused the corresponding performance curves to exhibit a non-typical shape. However, some useful qualitative conclusions can be drawn from this case, and it is clear that the position of the SINE6 performance curve is consistent with the severe damage observed during testing. In the case of the earthquake excitation, the performance curve that was obtained based on the actual experimental results was well within the safe region, as intended. The nominal performance of the system under the Koyna earthquake with a peak acceleration of 0.38g was also investigated and the results are consistent with the severe damage suffered by the dam. The lessons gained through this study will be used to improve the design of future experiments aimed to validate this type of methodologies.

6. ACKNOWLEDGEMENTS

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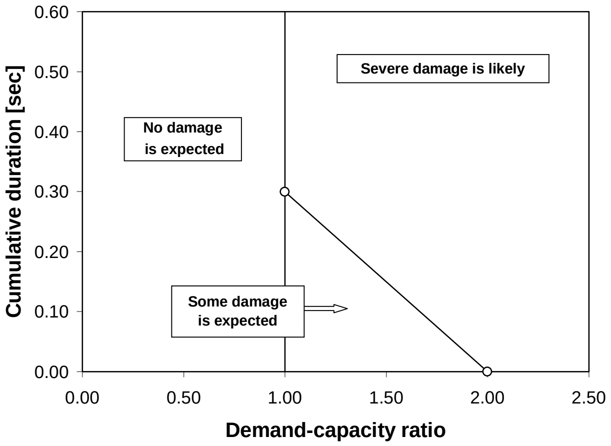

Figure 1. Performance criteria for evaluation of concrete gravity dams

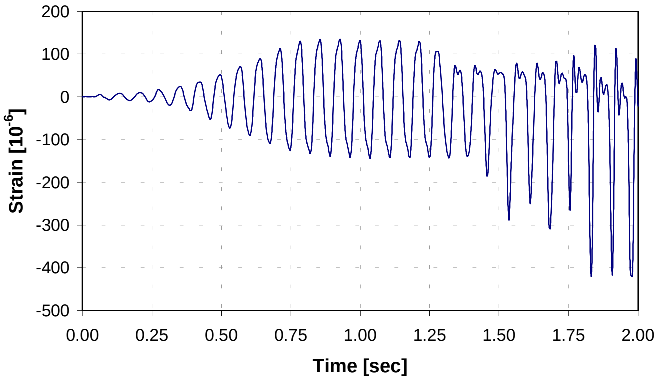

Figure 4. Strain time history at critical location (SINE6)

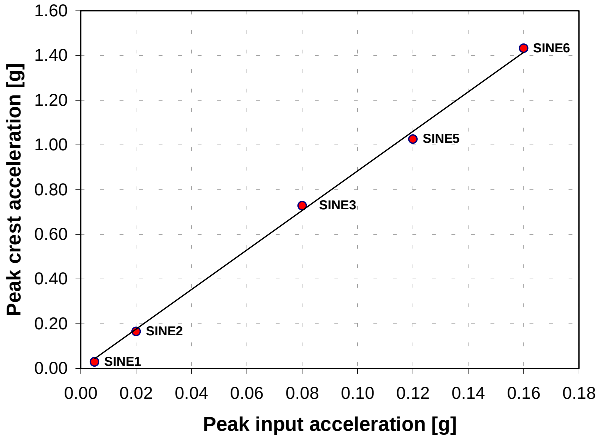

Figure 2. Peak response as a function of the peak input acceleration

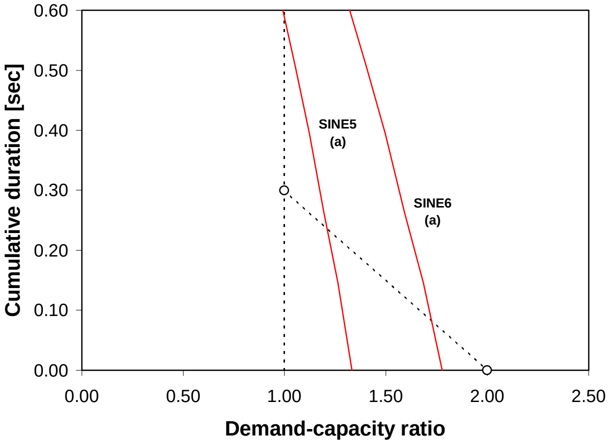

Figure 5. Performance curves - Sinusoidal input (case a)

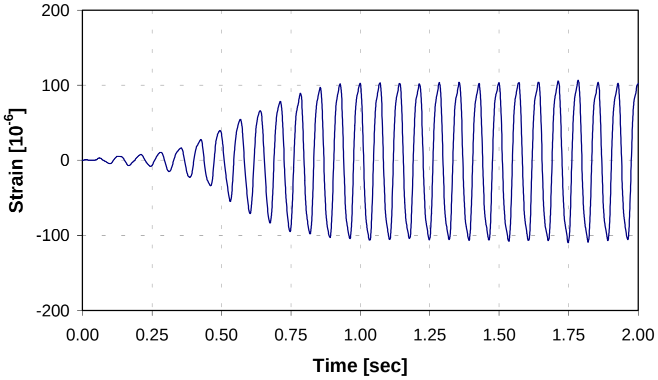

Figure 3. Strain time history at critical location (SINE5)

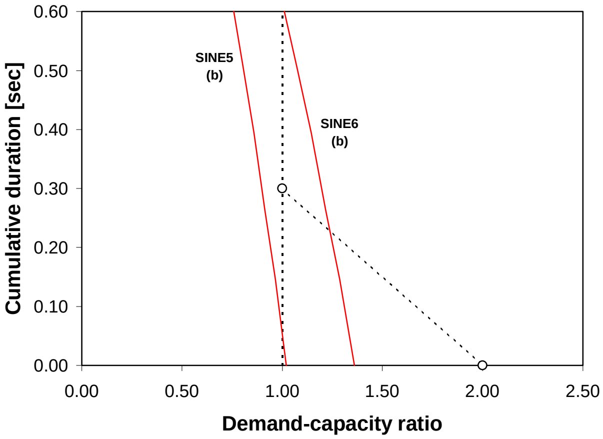

Figure 6. Performance curves - Sinusoidal input (case b)

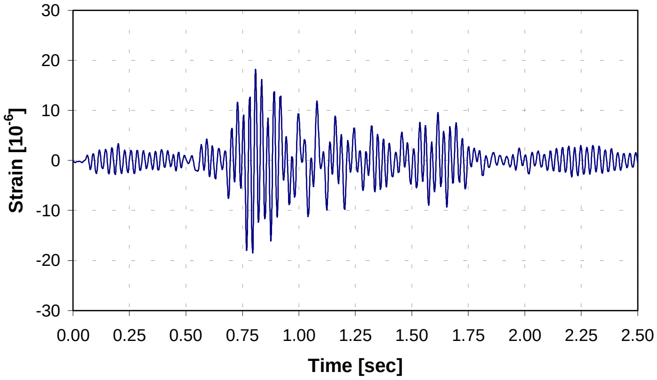

Figure 7. Strain time history at critical location (Koyna earthquake)

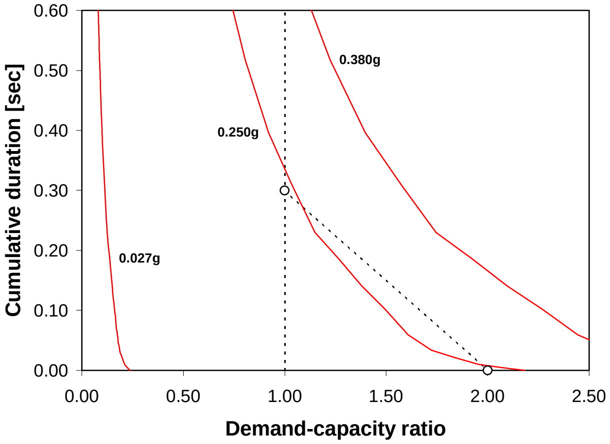

Figure 8. Performance curves - Koyna earthquake (case a)