How safe is the proposed Tehri dam to earthquakes

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Tehri dam, the construction of which has been stopped presently at a height of 20 m, has been surrounded by controversies. This article explains the main issues related to seismic analysis and design. Since the valley, at the dam site, is too narrow, three-dimensional effects have to be accounted for in the design. Also, the peak ground acceleration of 0.22 g recommended by the expert committee appointed by Govt. of India needs considerable upward revision.

In the context of the Tehri dam Valdiya[1] recently raised the question 'must we have high dams in the geo-dynamically active Himalayan domain?' Many other individuals[2] and environmental groups have also raised this question, so much so, the issue has become a controversy. INTACH (Indian National Trust for Art and Cultural Heritage) organized an international workshop on 'Earthquake hazard and large dams in the Himalaya' under its 'Science and Public Policy' debate series in New Delhi during 15–16 January 1993. In this connection I have looked into several technical reports containing details about the dynamic analysis of the Tehri dam under artificial and real earthquake excitations. Another useful source of information has been the 14th Annual IGS lecture delivered by Thatte[3] at the Indian Geotechnical Conference in 1991. However not much information is available about the seismic safety analysis and design of Tehri dam in the open literature on earthquake engineering.

Location of the dam

Tehri dam is located at 30° 28′ N and 78° 30′ E, very near the town of Tehri, in the Garhwal region of Uttar Pradesh. The location being in the Himalayas, the site is seismically very active. The tectonic features and seismogenity of the area have been well documented and discussed in several places[1,4].

The structure and its natural frequencies

An earthquake engineer's interest in seismo-tectonics stems from his concern to know how the proposed dam would respond to one or more possible future earth-...akes. Whatever may be the earthquake excitation, ... behaviour of the dam is governed by the laws of ...hanics or more properly structural dynamics. Thus, one writes the equations of motion of the dam, however complicated they may be, to find the free vibration characteristics, namely the first few natural frequencies and mode shapes. This is followed by a forced vibration study of the dam under the postulated earthquake excitation. First let us see the likely natural frequencies of the Tehri dam. These depend on the geometry of the dam and the material properties. With reference to Figure 1, the structure is built across the Bhagirathi river which flows in a deep nearly triangular canyon at the site. The height (H) of the crest of the dam above the foundation is 260 m at the deepest point. The length (L) of the crest across the valley is 574 m. The base width of the dam in the upstream–downstream (US–DS) direction is nearly one kilometer while the crest is 20 m wide. The rock-fill dam is built with an impervious core made up of clayey materials and a shell of graded gravel topped with blasted rock. This description is by no means complete but gives an idea of the massive structure with a complicated geometry that one has to deal with. The dynamic analysis of such a structure is not easy, but certainly possible, nowadays. Conventionally for an earth or rock-fill dam, the one-dimensional shear beam theory has been used to find the natural frequencies, participation factors, etc. For the Tehri dam also, this appears to be what has been done by the designers initially. Thatte[3] quotes the equation for the fundamental period T, in seconds, as

$$T_1 = 2.61\, H \sqrt{\rho/G} \tag{1}$$

H = height of section
ρ = mass density of the material
G = shear modulus

which is the classical result[5] for an infinitely long earth-structure (shear beam) with a symmetric triangular cross section. The Tehri Hydro Development Corporation Ltd (THDC) with headquarters at Roorkee are the designers. They mention in their 1990 report[4] that natural periods for the first six modes have been computed for the river bed section and the right abutment section.

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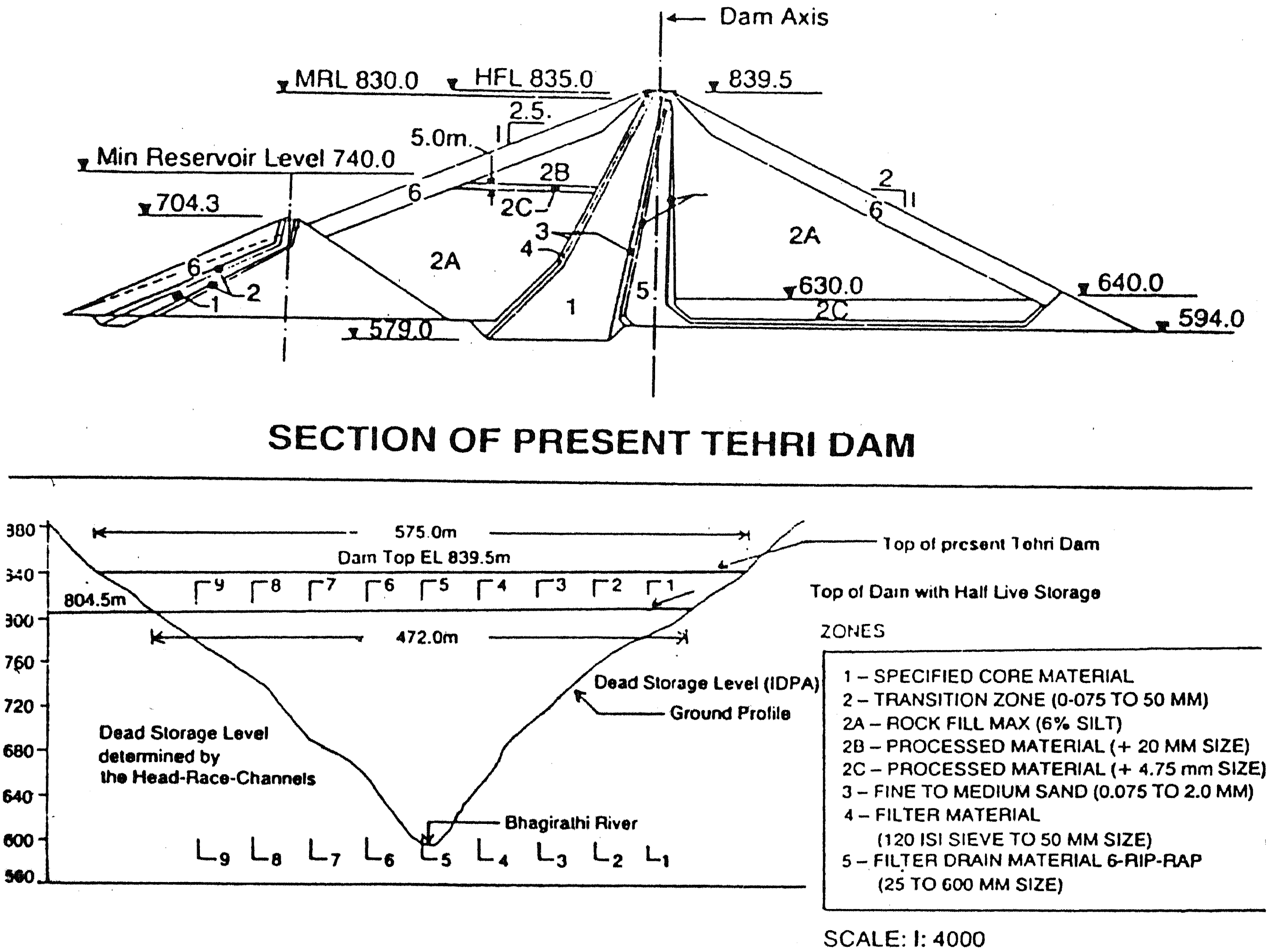
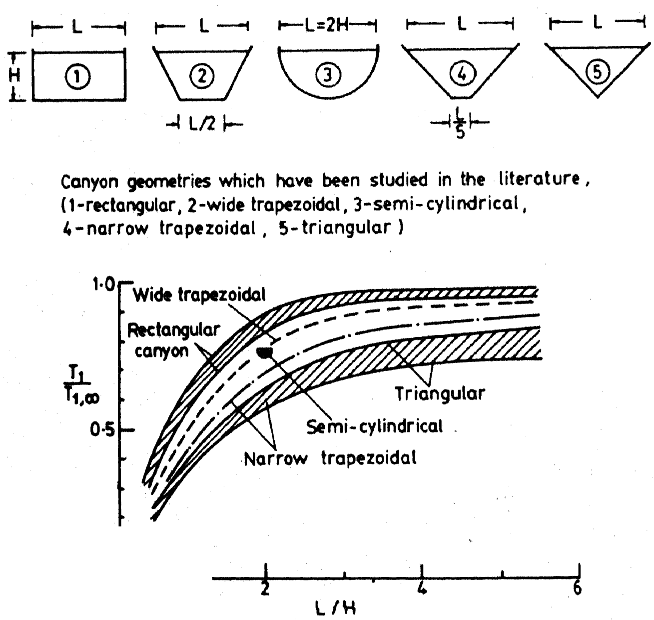


Figure 1. Cross section of valley at Tehri dam site.

The reported natural periods in seconds are 2.272, 1.672, 1.476, 1.256, 1.087 and 1.104 for the central section. The corresponding figures for the abutment section are 1.504, 1.025, 0.952, 0.854, 0.753 and 0.640 seconds. These are presumably obtained by a finite element analysis of the section and are generally referred to as the two-dimensional values. The shear wave velocity $V_s=(G/\rho)^{1/2}$ for the dam material has been estimated to be 300–320 m/s. This gives from eq. (1) the first natural frequency at the central section to be $f_{1D}=0.51$ hz ($T_1=1.96$ sec). This frequency is understandably higher than the two-dimensional value of $f_{2D}=0.44$ hz, since in the latter case, not only the US–DS flexibility but also the vertical flexibility of the dam is included. However, neither of the theories is applicable at Tehri. The dam being constructed in a triangular valley with L/H nearly equal to 2, there will be severe stiffening due to the canyon walls, which calls for a three-dimensional analysis. The two-dimensional analysis can be justified only in the 'plane strain' case of the classical Theory of Elasticity. For this to happen, the (L/H) value should be more than six. The canyon effect and the implications of it to seismic analysis are well known. The results are available in the open literature on earthquake engineering. There are two classical papers on this problem by Makdisi *et al.*[6] and Mejia and Seed[7]. In the first paper[6], the effect of a triangular canyon on the response of an earth dam has been studied in detail. It is shown that for a dam in a triangular canyon for L/H=2, the three-dimensional fundamental frequency is 1.8 times the two-dimensional value. In a companion paper[7] the seismic response of the Oroville dam, USA has been studied by two-dimensional and three-dimensional theories. This dam is in a triangular canyon with L/H=7. The height of the dam is 235 m. The fundamental period of the dam is reported to be 0.78 seconds. To study the effect of a steeper canyon the same dam section but with L/H=2 has also been studied. The three-dimensional fundamental frequency is found to be 50% higher than the two-dimensional value. Further their conclusion is 'for dams in steeper canyons than that of Oroville dam, the results seem to indicate that plane strain analyses of the maximum section and the quarter section of the dam cannot simulate correctly the behaviour of the embankment, and that it is necessary in those cases to perform three-dimensional analysis to obtain satisfactory results for design purposes'. Dakoulas and Gazetas[8] in their work on semi-cylindrical valleys published in 1986, compiled the known stiffening effects of canyons of five shapes (Figure 2). For any (L/H) value the triangular canyon has the highest stiffening. At (L/H) = 2 the actual fundamental frequency is about 1.8 times the 2-D frequency. It is convincingly shown by Gazetas[9] that this stiffening effect results in considerably higher displacements and accelerations (Figure 3) in the body of the dam during seismic excitation. However, the shear strains may not be very sensitive to the shape of the canyon. An important offshoot of the three-dimensional effect is the possibility of longitudinal vibration of the dam. Abdel-ghaffar and Scott[10], Abdel-ghaffar and Koh[11] have analysed the measured response of Santa Felicia dam in Southern California under the San Fernando earthquake of February 9, 1971 and the Southern California earthquake of April 8, 1976. Interestingly, the dam is a rockfill dam 83.3 m in height with a crest length of 390 m. The canyon is roughly trapezoidal in shape. The 1971 earthquake caused a transverse crack attributed to longitudinal dynamic strains. The records parallel to the dam axis show in their spectrum, several strong peaks (corresponding to the longitudinal natural frequencies) with almost equal amounts of participation.

From the above considerations it appears that the Tehri dam (3-D) first natural frequency would be nearly equal to 0.8 hz (= 1.8/2.27). Furthermore, the section of the dam is not a neat triangle. At the mid section, the downstream arm is unusually short[4]. Also, the river bed



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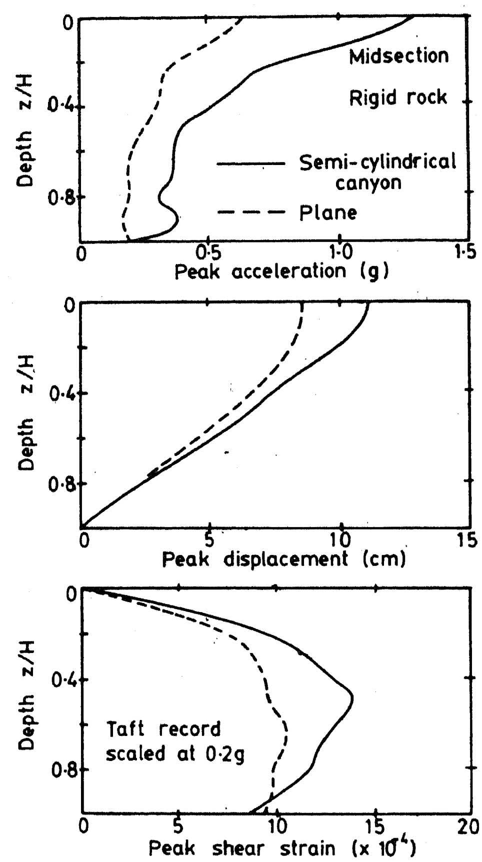

Figure 3. Plane versus three-dimensional analysis distribution with depth of peak response variables (dam: H = 120 m; V_s = 280 m/s, β = 0.1) (Gazetas[9]).

section and the abutment sections are geometrically dissimilar. Thus, the actual fundamental period of the dam is likely to be 1–1.25 seconds, which is roughly half the current reported value. The frequency spectrum of other modes which will contribute under an earthquake, are likely to extend at least up to about 0.3–0.5 seconds (2–3 hz). Thus, the view held by some engineers that the dam is very flexible and hence will not respond severely to the Himalayan earthquakes which have their energy concentrated in the high frequency end of the design seismic acceleration response spectrum, is not justified. The Soviet report[12] on the behaviour of the Tehri dam under the Gazli accelerogram does mention about the canyon effect but is obscured by the fact that only a 2-D analysis has been done that too on a section which differs from the one exhibited as the river bed section in the THDC report[4]. In any case only one component of the horizontal accelerogram has been used indicating that no longitudinal response studies were done, for understanding possible development of transverse cracks.

The seismic response spectrum

Even if the dam were to be modelled in the best manner possible for structural analysis, the design engineer faces the unenviable task of forseeing, to what kind of earth shaking the dam may be subjected to in the years to come. This clearly puts ethical and moral responsibilities also on the shoulders of the earthquake engineer, which has not been realized by the society at large, particularly in this country. Predicting any natural phenomenon under the best of circumstances can only be statistical, even if a long data base is available. In the absence of past data any prognosis will be speculative, coloured with personal beliefs and preconceived notions. Earthquake engineering research in the last 30–40 years has been grappling with this uncertainty. Two schools of thought are visible. The first is the deterministic school wherein the uncertainty is either overlooked under the guise of 'expert judgement' or accounted in a manner by introducing multipliers (e.g. factors of safety, three sigma levels, importance factors). This is by and large the approach of building codes for routine constructions in large numbers. However, for isolated sensitive structures like nuclear power plants wherever they may be and for high dams in seismically active areas the only rational approach is probabilistic, wherein the uncertainties are accounted and audited at every stage till one or more earthquake accelerogram time histories are generated as the most severe plausible future excitations. In this exercise the involvement of experts in geology, geophysics, seismology and soil mechanics is important. In the context of the Tehri dam, the engineers seem to have resisted if not opposed, from the beginning the considered views of the geophysicists. The sequence of events appear to be that first[13] a 7-magnitude earthquake with peak ground acceleration (PGA) of 0.5 g was postulated. Further based on a comparison with the El Centro earthquake of 1940 and an estimated natural period of 3.1 seconds for the dam, the equivalent static seismic coefficient of 0.15 has been recommended. In the second stage a dynamic analysis has been proposed with a notional PGA value of 0.446 g but lowered through the assumption of effective peak ground acceleration[4] (EPGA) to 0.25 g. In the final stage the effort has been to argue that the dam is anyway immune to even higher PGA values, because of its long period modes which are not sensitive to the high frequencies in ground shaking. We have already seen that the last argument is not tenable since at present the precise 3-D frequency range of the dam structure including the canyon effect is not available. The natural periods which matter, instead of getting so closely packed in 1.8–2.2 seconds as reported, are likely to be spread out in 0.3–1.25 seconds. To understand why PGA enters into picture we have to see how the seismic threat perceptions are converted into tangible dynamic effects on a structure. It is here the concept of response spectrum occupies the central place in aseismic design. Response spectrum is a frequency domain description of an earthquake accelerogram, which also incorporates the effects of the earthquake on a standard engineering structure in a way accepted and understood by the engineering community universally. At the purely mathematical end it is the supremum of the absolute response of a linear system (underdamped simple harmonic oscillator). However at the application end it represents a philosophy of design.

It is through the response spectrum that the owners of a dam or a power plant are expected to fix up the seismic performance criterion for their structure. In this respect the response spectrum is similar to the shock spectrum which is widely used in defence practice to design, qualify and accept equipments and sea going vessels which have to perform safely under percieved threats. The relative displacement of a single degree-of-freedom oscillator under a ground acceleration $\ddot{x}_g(t)$ is governed by the simple second order differential equation

$$\ddot{x}+2\,\eta\,\omega\,\dot{x}+\omega^2 x=\ddot{x}_g(t). \tag{2}$$

This is also the first level representation of how a one-storeyed building or an elevated water tank or a tower vibrates under the earthquake excitation. The parameter η is the damping coefficient ($\eta<1$) in the system which mainly depends on the material of construction (e.g. concrete: $\eta=0.05$, soil: $\eta=0.1$). ω is the natural frequency in radians per second, which provides the engineer with a strength *versus* weight perspective of the structure. For a large number of real strong motion earthquakes, eq. (2) has been solved by several workers in the past. It is clear that the response $x(t)$ of a given system (i.e. η, ω are fixed) depends crucially on the amplitude and frequency distribution of the input $\ddot{x}_g$. But the system essentially acts like a filter and allows through mainly its own natural frequency $f=\omega/2\pi$ hz. The most important design information from this exercise is the absolute maximum (highest peak) displacement $S_d(\eta,f)=\sup|x|_m$ during the earthquake. Equivalently the acceleration spectrum is $S_a(\eta,\ T)=\omega^2 S_d$. A plot of S_a vs. T for any sample accelerogram will show a highly erratic picture, but an interesting fact is that in the limit $f\to\infty$ or the natural period $T=1/f\to 0$, $S_a\to\sup|\ddot{x}_g|$, which is the peak ground acceleration. This is true for all η and hence PGA is an anchor point in the otherwise random function $S_a(T)$. This also provides a good datum for scaling, so that the overall amplification pattern of earthquakes in relation to structural frequency can be established. Several past earthquake spectra are averaged after dividing by the PGA to arrive at standard mean level spectra. Invariably there will be considerable scatter and hence one has to recognize percentile level spectra also. What level spectrum one uses for a particular project is a judgement based on the risk one is willing to take. The costs involved in meeting the demands of a higher percentile spectrum are more but with it the risk of failure under the threat of an earthquake also decreases. In any case assurance of 100% safety against all future earthquakes is an impossibility. In recognition of this fact engineers talk of a maximum credible earthquake (MCE) for the region under which some damage which can be tolerated, may occur. Without going into the detailed definitions and interpretations of the MCE, it could be again a percentile level spectra multiplied by the corresponding level PGA value accepted as credible. With this in the background let us look at the Tehri dam seismic parameters.

MCE and DBE spectra

The THDC report[4] and the IGS lecture[3] are unclear about the concept of maximum credible earthquake (MCE) and design basis earthquake (DBE). In fact the latter takes them to be one and the same (p. 26 of ref. 3). However, the University of Roorkee report[14] EQ83–4, defines the two concepts in a fashion which is accepted widely. MCE is the most severe earthquake that may occur once in the life time of the structure. Under the MCE some local repairable distress is permissible, but overall survival of the structure is a must. The non-linear behaviour of the dam should also be analysed under the MCE for ensuring its structural integrity. These and other recommendations of the above University of Roorkee report are well reasoned out. The report also presents a discussion on the seismotectonic set up of the Tehri site. However, the major weakness of the report is in its advocacy of the effective peak ground acceleration (EPGA) concept. Another questionable step taken is the enveloping of individual site spectra in the frequency domain to arrive at the MCE spectral shape.

PGA versus EPGA

A typical strong earthquake accelerogram record is shown in Figure 4. A high isolated peak (PGA$\simeq$0.5 g) is clearly visible. The proponents of the EPGA concept will say that the effective PGA is however less than this value. Their main argument is to show that the response spectrum of the accelerogram would be relatively insensitive in the frequency range of interest, to variations in the isolated PGA value. This of course is a verifiable fact, but this is no proof that observed PGA values should be disbelieved. It is a reflection of the strong filtering property of the underdamped oscillator, which is not much affected by the PGA which sits as a high frequency kink. This cannot be the basis for wishfully reducing a crucial seismic parameter such as PGA. If we have to follow the scientific approach of observation, analysis and inference, the instrumental recordings have to be believed and retained for whatever they are worth. The PGA as explained previously is a bench-mark with which the spectral shape will get multiplied to arrive at the MCE spectrum. Since EPGA is always less than PGA, acceptance of this concept could be construed as *erring on the unsafe side*. For small amplitude earthquakes, when the structural response will be linear, curtailing a high peak may not matter. But the same is not true with nonlinear systems. A rockfill dam like Tehri is highly nonlinear when the slope failure modes are analysed. Even though we do hear the concept of EPGA floated by some individuals now and then at conferences and meetings, it is not a universally accepted philosophy of design in earthquake engineering. The THDC report (p. 5) mentions about the PGA of 0.56 g recommended by NGRI and the EPGA of 0.25 g recommended by the DEE (Department of Earthquake Engineering, University of Roorkee). Further, in a valiant effort to justify the EPGA, the report says, 'For proper understanding of the difference between PGA and EPGA knowledge of dynamic analysis for dams is essential'. A typical case of putting-the-cart-before-the-horse syndrome! Further, the THDC report disappoints, to put it mildly, in telling, 'In a real accelerogram, the value of peak ground acceleration may be reduced without effecting its damage potential as the latter is not dependent upon single peak'. If the damage potential is not affected by the single high peak, as made out, why not allow it to be there, at least in public interest?

Enveloping site response spectra

The report EQ83–4 identifies four potential threats and four corresponding spectra. The envelope of these is recommended as the MCE spectra. The desire behind enveloping is to arrive at something which is worse than the individual spectra. This of course is certainly an acceptable principle. However, the possibility exists that simple minded enveloping and smoothening in the frequency domain may distort the energy concentration bands which in turn mask the quasi-resonance effects in the response. In the case of stiff structures like nuclear containments[15] enveloping spectra at the ground level is not justifiable. Fortunately, in the context of the Tehri dam, this is not a serious limitation. The maximum amplification possible in the MCE spectrum has been kept at 2 and is supposed to occur in the interval 0.1–0.4 sec. These are *ad hoc*, but in the absence of past site data, these may be as good as any other numbers. But there is difficulty in interpreting the

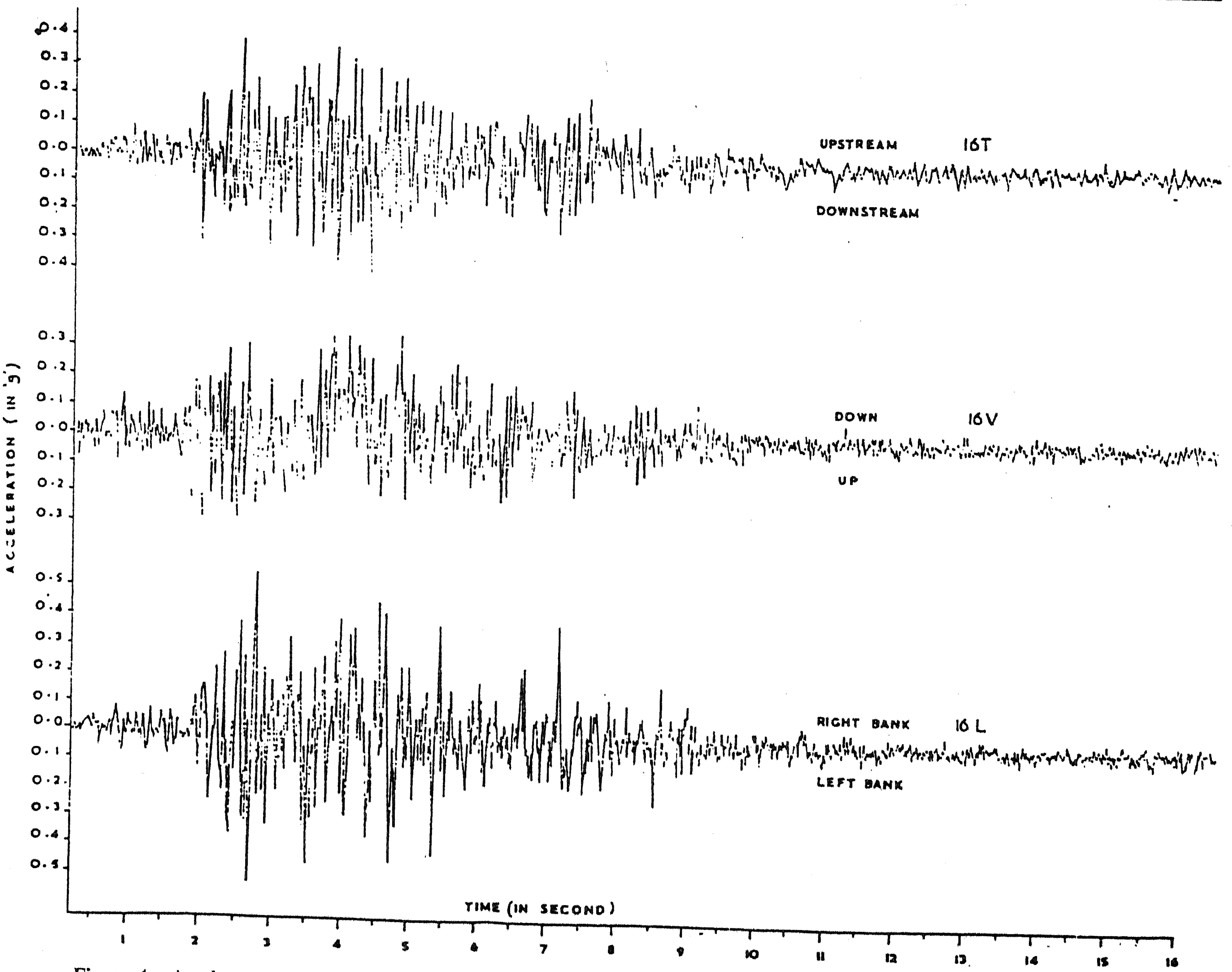

Figure 4. Accelerogram recorded at Koyna dam (1 a gallery) for earthquake of 11 December 1967 (time of origin $t_0 = 04:21:17$ IST).

normalized MCE spectrum at 10% damping since the level of risk involved, or probability of exceedance with respect to the past data base, is not known. In the THDC report[4] an attempt is made to compare the severity of the adopted spectra with other spectra (exhibit 5 of ref. 4). The damping level is not mentioned and furthermore the Tehri spectra is shown to have an amplification of more than 2 which is not the same as the EQ.83–4 recommendation. The exhibit-2 of the THDC report shows a spectrum with amplification 2 but shows a well defined peak which is not the one recommended in the EQ-83.4 report. There seems to be some difficulty in reporting the spectra clearly. Since the adopted spectra have been justified in comparison with other standard mean level spectra, we have to conclude that the THDC is setting its MCE spectrum at slightly lower than 50% level of exceedance. In other words, there seems to be still about 45% risk to the dam from future earthquakes exceeding the selected seismic specification.

Artificial accelerogram

The fixing of the MCE spectrum describes in broad-brush the design philosophy and risk levels. This is usually made into a practical methodology in three ways, viz. (i) modal summation procedures (SRSS or CQC) which use the spectrum directly to arrive at approximate response values, (ii) inverting the response spectrum to arrive at one or more accelerograms in the time domain (spectrum compatible accelerogram or SCA generation), for further dynamic analyses, (iii) finding the spectrum compatible power spectral density function as a description of the earthquake for further use in a random vibration study of the structure.

For the Tehri dam the recommendation has been to use the second option. An acceleration time history of about 38 sec duration with a highest peak value of 0.25 g has been reported in several reports[3,4,14]. It is supposed to be compatible with the MCE spectrum. However, none of the above reports indicate how well the target spectrum matches with the realized spectrum. It is known[16] that results of the inversion are nonunique and hence one can arrive at an ensemble of records all of which can match with the target spectrum well. There are well documented acceptance standards for artificially generated accelerograms. Since no information is provided on how the accelerogram has been generated, it is not possible to evaluate it in relation to what it is claimed to represent. The THDC report strains itself to show that the artificial accelerogram is severe than a real recording like the Dharmashala trace of 1986. Invitation for such visual comparison only side tracks the main issues of technical importance. An artificial accelerogram is tailored to the needs and requirements of an intelligent designer or to the demands of a manager or a policy maker. The important question a discerning user should be asking is how well the high frequency end of the MCE spectrum is matched by the artificial record. Traditional wisdom in this type of work prescribes that all the structural natural frequencies in the range of (0–33) hz should be made sample points. In addition, many more frequencies are required to be included to demonstrate the richness of the frequencies. With only six natural frequencies being listed, it is doubtful that the user organization has demanded these requirements. Instead, THDC in support of its acceptance of the accelerogram simply quotes from the product supplier's report: 'However the artificially generated accelerogram would be more intense as various frequency components of ground motion are well represented compared to an actual record which may well have gaps'. In the absence of a transparent acceptance specification this statement is unconvincing.

Expert committee report

An expert committee was set up by the Government of India to look into various aspects concerned with the Tehri dam. The committee took 0.446 g as the expected PGA but accepted 0.223 g as the effective PGA for further analysis. The committee does not appear to have had any feeling to handling uncertain quantities. Without worrying about the implications of chopping off a random process, the committee declares 'The effective peak acceleration may be conservatively taken as 50% of the PGA'. I fail to understand what conservatism is involved in reducing a forcing parameter. I wish the committee had first pondered about what is meant by damage potential of an earthquake for yielding, sliding and rocking systems. Not stopping at the level of a misunderstanding the committee also certifies that the EPGA of 0.22 g is for the worst case earthquake for the Tehri dam from the structural damage point of view! The PGA value which appears as the highest peak in the artificial accelerogram is what the specialists should accept as credible for the MCE magnitude of 8–8.5. Presently, neither the specialists nor the lay people find the PGA of 0.22 g even credible, let alone the worst case value. Under the caption 'dynamic analysis' the committee simply mentions about a linear 2-D dynamic analysis. There has been no concern about either the low L/H value of the dam or about the steep canyon.

'EPA' paper by Bolt and Abrahamson[17]

The irony of the situation is that all the claims about EPGA are supposed to emanate from a research paper by Bolt and Abrahamson[17]. The THDC report[4] at least does not cite these authors. But the expert committee has no qualms about this. The committee report on p. 10, para 2.19 says that 'Bolt and Abrahamson (1982)... recommend that if the higher 10% of the acceleration peaks are omitted, the largest acceleration out of the remaining values on record can be considered as the EPA *from the point of view of the damage potential of the ground motion*'. (The emphasis here is mine.) I want to point out that the paper of Bolt and Abrahamson entitled 'New attenuation relations for peak and expected accelerations of strong ground motion' appeared in the *Bulletin of the Seismological Society of America* in 1982. The paper does not claim to study the connection between EPA and damage potential. I quote from the abstract first: '..., a robust and easily computed parameter is defined for significant peak acceleration that meets many engineering requirements. This "effective" peak acceleration is obtained by developing histograms for the number of peaks and troughs on the observed record and by choosing the acceleration value at about the 90 percentile level. This truncation excludes scattered outliers of high amplitude peaks not representative of the general distribution of the ground motion amplitudes. Corresponding values for "EPA" are tabulated for part of the basic data set, and it is demonstrated that the scatter about the attenuation regression line is reduced using the proposed parameter.'

In the body of the paper an interesting statistical analysis has been presented. It is quite common in regression studies to omit the so-called outliers. Whether such an approach is correct or not is not the present issue. What the above authors claim is clear in their own conclusions, which I quote now:

'Difficulties in using the maximum peak acceleration (the supremum) as a dominant measure of strong-motion amplitude can be reduced by use of a statistically based definition of peak acceleration. A suggested measure is the 90 percentile level of histograms that plot the frequency of the amplitudes for selected durations of motion. This definition has the advantages that it is simple to compute, and it is based on the statistical properties of the wave amplitudes over time and, thus, serves many engineering requirements more adequately. Also, it provides a more robust measure of the maximum amplitudes in a similar way to that provided by the mode, rather than the mean, as a measure of central tendency. Our calculations indicate that the new measure reduces the scatter of observations both for a single earthquake and for a collection of earthquakes. For damage assessment purposes, more study is needed to assess appropriate window cut-offs for the significant (effective) peak acceleration. For some types of structures, an abnormal supremum acceleration may indeed control failure.'

The authors have nowhere even used the phrase 'damage potential'. In fact for relating EPA to damage assessment they called for more work. Also they cautioned that the highest PGA may indeed control failure in some types of structures! To interpret that Bolt and Abrahamson opine that the largest few spiked peaks are not representative estimates of acceleration which will influence the *safety* of structures, is an unscientific extrapolation. One of the members of the expert committee after the submission of its report in April 1990, withdrew his support to the acceleration value (see Thatte's talk, ref. 3). At least he had the courage of conviction to put scientific temper before adhocism. Brune, a well-known seismologist, to whom the matter got referred, no wonder ignored the EPGA business and succinctly remarked that he and his several colleagues in USA consider 0.22 g as too low a design acceleration for Tehri dam.

The thumb rule of taking half the estimated PGA as the effective value for MCE/SSE design response spectrum scaling, artificial accelerogram simulation and further time history studies, is illogical and unscientific. I fervently appeal to my fellow earthquake and structural engineers, particularly those concerned with large dams and nuclear facilities, to bury this myth of EPGA.

Summary

Considerable technical expertise has been brought to bear on the seismic analysis and design of Tehri dam. I have no hesitation in accepting this. However, I have to point out that, the dam with its height of 260 m is dynamically not long, since $L/H \approx 2$. Further, it is confined in a steep triangular canyon. Thus the currently reported plane strain natural frequency values are unacceptable. If and when the dam has to respond to an earthquake, it will behave like a 3-D body and will certainly execute longitudinal motions also. Hence it is imperative that the dam should be analysed for both the upstream–downstream and dam-axis components of the maximum credible earthquake.

An EPGA value, whatever it may be, for the maximum credible earthquake will not be accepted as credible. The accelerograms should be handled and understood first for what they are, namely samples of a stochastic process. Mixing them with vague difficult-to-quantify terms like damage potential can only lead to further confusion. No single descriptor[18] of an accelerogram describes adequately the damage potential. This applies to the PGA, the EPGA and several others. EPGA is also a statistical characterization of the peaks of an accelerogram. There are other widely accepted statistical measures for peaks. Furthermore one should not forget that standard normalized spectra are as a rule obtained after scaling with respect to the single PGA and not with respect to the 90-percentile EPA value. Here it should also be pointed out that the higher level earthquake, called SSE (Safe Shutdown Earthquake, in nuclear parlance) or what has been called MCE in the Tehri context, is generally selected at the 0.841 percentile level or equivalently with 15.9% probability of exceedance or risk. Since spectral amplitudes are nearly lognormally distributed random variables, the 84.1% level is nearly the mean + standard deviation or $(m+\sigma)$ value. Hence to be on the safer side, and also to be consistent in assessing the safety margins, the PGA in the deterministic approach should be set at the $(m+\sigma)$ level. In the present case, the original NGRI mean PGA was 0.56 g according to the THDC report[4]. Hence with about 25% coefficient of variation, the deterministic PGA should have been more like 0.7 g. Logically it follows that the normalized site spectral shape even if a little bit *ad hoc*, should be scaled by this $(m+\sigma)$ PGA value only, for generation of compatible accelerograms. Such accelerograms only should be used in further time history linear and non-linear dynamic analyses. Interestingly enough one of the speakers at the New Delhi workshop, namely K. W. Campbell[19] of USA presented his latest near-source attenuation relationship for hard rock sites. His results show that for a 8-magnitude earthquake at a distance of 15 km from a strike-slip fault the 84th percentile PGA would be nearly 0.5 g. The corresponding value for a reverse fault is found to be 0.7 g.

Conclusion

I have prepared this article in a spirit of offering constructive criticism. Hence I have not highlighted the many positive aspects which are present in the design of the Tehri dam. The current Tehri dam MCE design response spectrum has been selected with 45–50% risk of getting exceeded by future earthquakes. Even then the dam may not fail under a future earthquake; but it does not appear to be sufficiently safe at present. Safety is a concept that all of us understand but find difficult to quantify. The only rational approach through which we can assess this and maintain a communication line with other engineers, scientists and public is with the help of probability and statistics. In this sense aseismic design at present is more a passive insurance, at non-zero risk levels, which will be effective if and when an earthquake occurs. The risk of failure due to earthquakes can be lessened to small levels. But such an exercise will invariably be very expensive. This is not just an engineer's problem. It is for the planners to calmly decide how much the country can spend in relation to how much risk the public can tolerate in the postulated scenario of a seismic failure of the Tehri dam in the culturally important Himalayas. The planners and the public should actively participate in the decision making process.

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Disorder parameter description of phase transitions

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The Yoga posture, Sirshasana, or standing on ones' head, is supposed to stimulate the brain cells. It is similarly stimulating to see how far one can go in inverting conventional viewpoints. Can the picture of a phase transition as an order parameter formation on cooling, be complemented by a picture of a disorder parameter blow-out on warming?

In this article, we consider: 1. Phase transitions and their conventional 'order-parameter' description; 2. Breakdown of these conventional ideas and the introduction of a 'disorder-parameter' description for certain special two-dimensional systems; 3. Extension of the disorder-parameter description to a particular three-dimensional system with a conventional transition; 4. Suggestion of other models that might also be examined within the disorder-parameter description. As reviews exist[1,2] the subject slice is 'vertical' (following a particular model) rather than 'horizontal'.

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Order-parameter description of phase transitions

Phase transitions are all around us — in the boiling of milk, the formation of rain drops, and the onset of spontaneous magnetization when a hot iron slab is cooled. There is a drastic change of matter from one internal arrangement to another, when a control