Earthquakes, Dam Design
And
Tehri Project*

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DAMS AND THEIR DESIGN PHILOSOPHY

ROLE PLAYED BY DAMS AND RESERVOIRS

Dams have been built across rivers by mankind right from the dawn of civilisation for storing the river flow during rainy season and releasing it during the remaining part of year for either domestic use or for irrigation. Flood control has been another important function of these dams. While releasing water from the storages, hydroelectric energy is also generated. With the growth of population all these functions of dams and storages have assumed great significance and hence every civilisation has tried to keep pace with the needs of the society for food, energy, fibre and well being through this activity of water resources development.

INPUTS FOR SAFE DESIGN

Dams constitute perhaps the largest and the most complex of structures being built by civil engineers. Basic input of water is dependent on nature, so also the river course, its history, its underlying strata and its stability. Assessment of the variability of these natural phenomena and providing for it in the design of a dam, has been an important challenge for the dam builders. The dams are built to last from 100 to 300 years depending upon merits of each case. During their service life, they are designed to withstand all the possible destabilising forces with a certain factor of safety which has been an indicator of a factor of ignorance or lack of knowledge of various response processes of materials used in construction, the stresses caused, the strains experienced and finally the failure mechanism.

DESIGN CONSTANTS

The destabilising forces themselves are associated with a significant natural variability. Assessment of the range of these forces likely to affect a dam stability during its lifetime and then ascribing a design value for such forces has been and will continue to be a matter of study and concern for the designers. Every design or construction engineer cannot study these processes for every dam and hence standards or codes of design and construction practice are laid down and updated as information and knowledge grows. Assistance of Scientists working in fields such as Hydrometeorology, Geoloy, Geophysics, Geomorphology, Seismology in assessing the likely parameters of these forces is taken, the information collected is processed as per standards and design constants worked out.

Large dams store very large volumes of water. Design of such dams, therefore, has to be extra safe so that there is a minimum probability of their failure and consequent rapid or sudden release of storage which can cause disproportionate flooding and losses to the human habitats in the downstream. Very stringent codes are laid down for this purpose. In case of inflow into a reservoir, for instance, a conceptual probable Maximum flood (PMF) is determined by following special analytical procedures. If the reservoir and the spillway caters to a properly determined out flow on the basis of such inflow, the dam would be hydrologically safe. In similar manner, geotechnical properties of foundation material or construction material can be determined and design constants worked out so that structural design based on them yields a safe structural construction. Statistically speaking, the design constants should cover the probability of occurrence of forces expected during the lifetime of the structure under design.

DESIGN PHILOSOPHY

The codes of practice invariably lag the state of knowledge or state of Research & Development (R & D). In fact codification follows verification of generated knowledge and its global acceptance. Codes, therefore, tend to remain conservative and normally incorporate a higher factor of safety and hence perhaps yield structures with larger dimension and/or with higher costs. There is yet another aspect of design philosophy which is not very explicitly understood nor adequately explained. It pertains to the various stages of design for complex structures like dams viz. Conceptualisation, prefeasibility, feasibility, detailed project report (DPR), pre-construction, early construction and advanced construction stages.

REFINE THE DESIGN AS YOU BUILD

A designer starts with broad concept of design parameters in the beginning and goes on refining his data base and hence the designs, as he proceeds through the various stages. He assumes for the sake of his inadequate data base, simplifications or generalisations which obviously incorporate a large factor of safety in initial stages. As the project passes through successive stages, his data base improves, better and more accurate data base emerges; the range of design constants narrows down and factor of safety reduces.

Generally, the outer dimensions of a structure do not necessarily get modified; but components, zones or internal arrangements of a structure do undergo modifications. The structures's response to the destabilizing forces is worked out with greater detail and is refined while moving from one stage to the next stage. Engineers call this a process which is loosely described as 'Design as you build' or 'Refine the design as you build' mode. It certainly does not mean inadequacy of design or does not reflect on ignorance or incompetence of project or design engineers. However an inadequate understanding of this very philosophy is one major factor responsible for much public criticism of many of our water resources projects.

The paper attempts to bring out the salient aspects of earthquakes in general, their impact on structures and structures' response to the shaking caused by them. Engineering aspects of these processes are touched upon with Tehri Dam as a case in point.

EARTHQUAKES, FAULTS AND THEIR INTER-RELATIONSHIP

THE EARTH AND EARTHQUAKES

The planet Earth born about 4800 million years ago is slightly sub-spherical in shape with a diameter of about 12,740 km. At the centre of the earth is a core of 3470 km radius. The core has a covering mantle of about 2,750 km thick, which is followed by a crust of about 150 km in thickness. Properties of these constituents are indicated in Table. 1

TABLE 1

PROPERTIES OF 'EARTH' MATERIAL

	Density (T/m³)	Temperature °c	State	Radius(r)/Thickness(t) (Km)
Inner core	13.6	2500	Solid	3470 (r)
Outer Core	10.0	2300	Molten	
Lower mantle	5.5	1700	Solid	2750 (t)
Upper mantle	4.3	1400	Probably molten	
Sima Crust	2.9	1100	Solid	150 (t)
Sial Crust	2.8	500	Solid	

Since its birth the Earth is cooling, the surface being the coolest, the core the hottest. The density and temperature differentials set in motion a sort of convection current in the Earth's mass. The cooling process also causes cracking in the crust which has rigidity and is designated as Lithosphere. It does not possess uniform composition and hence cracking takes place in comparatively weak zones, but with accumulated strains. When strain is accumulated beyond the mechanical strength, it is released through crustal segments called plates on which continents and life rides and engineers build structures as large as Tehri Dam. When such energy is released, the earth's crust shakes and causes Earthquakes (of Tectonic origin). Earthquakes of volcanic origin

are rare and India is free of them. A major Tectonic Earthquake is preceded by foreshocks and or followed by after-shocks which represent small ruptures or plastic deformations. The capacity for stress accumlation in a rock mass perhaps is a function of its depth of location below the earth surface. Larger build ups take place at greater depths, where large magnitude earthquakes can occur.

FAULTS

The strain energy released in damaging earthquakes is of the order of 10^{25} ergs. It is futile and meaningless to compare it with any man-made energy releases like atom bombs, simply because they are not comparable but may serve the purpose of scare-mongering only! Earthquakes are caused on plate collision boundaries, subduction boundaries or on boundaries of closely moving plates. When two plates collide, one with higher density sinks below the other with lower density. The phenomenon is known as under-thrusting or subduction.

It is not only at the plate boundaries that earthquakes occur but they do so within a plate area too, on finite sized ruptured surfaces like a discontinuity in a seemingly continuous rock mass and are known as 'faults'. For a petroleum, mineral or ground water prospector a fault means an opportunity; for an engineer, however, it means a problem in foundation of his structure. A quiescent fault is one which has not been activated for about 10,000 years and it really does not matter; an active one matters a lot because an earthquake could occur nearby. If one looks at any world map showing locations of past earthquakes and another showing faults, one would notice similarity in the two patterns because most earthquakes are caused near faults where release of accumulated energy is easy. Major plate boundaries of the earth's crust are near these locations. Major tectonic earthquakes of the world occur in the circumpacific belt comprising west coast of America, Japan, South East Asia, New zealand, Himalayas, Burma, Tibet, China, Central and Western Asia. The movement starts at a location, spreads over an area in all or in specific direction and stops when residual strain cannot cause a further tear, all in a matter of tens of seconds.

An existing tear or fault provides a line of least resistance for movement and dissipation of accumulated thermal stress/strain. Location, size and recentness of activity along a fault, therefore, are ascertained to predict location and size of further earthquakes. Size of a fault is mostly described by length of a fault which is delineated with the help of geomorphic evidences, aerial mapping or remote sensing supported by ground truthing. Movement along a fault is mostly a stick-slip behaviour which excludes a regular continuous rate of movement. In fact, movement may not occur at all for a century at a stretch while rockmass gets strained & keeps accumulating it, but may occur abruptly, releasing the accumulated energy with an earthquake of a large magnitude. In most earthquakes actual movement of surface is not seen. It lies deep inside near the focus.

LOCATION AND MAGNITUDE

The Focus of an earthquake is an instrumentally determined area below the earth's surface where slipping or fracture begins. Although the word focus indicates a point source, it represents as area of rupture due to release of accumulated energy. The depth of the focus below the earth's surface is called the focal depth. The location on earth surface directly above the focal area is called Epicentre. The distance of any location on the earth's surface from the epicentre is called the epicentral distance and that from the focus or hypocentre is called hypocentral distance. The energy released by the fault rupture reduces by damping and dissipation as it travels by wave motion towards earth's surface. The waves are classified as (i) compressional, longitudinal or primary (p); (ii) shear, transverse or secondary (S) and (iii) Raleigh or Love-waves. Of the above, most of the energy is transmitted to the ground through the short period waves (0 to 0.5 sec) only. The first group waves are fastest, the last slowest. The differential in arrival of waves at recording stations is utilised in determining Focus. The energy released at the focal area is quantified as Magnitude (M) on a logrithmic open ended scale which was originally developed by Charles F Richter. Magnitude of earthquake is associated with an area or length of rupture on an existing fault. It is obtained by recording amplitude of ground motion on a Wood Anderson type torsion seismograph at a number of places and after averaging, the results are expressed in ordinary integers with fraction upto one place beyond decimal. Although open ended, Magnitude has not exceeded NINE anywhere in the world. Earthquakes with M greater then EIGHT are devastating and rare. Magnitude is defined as a logarithm to the base 10 of the amplitude of ground motion recorded in millimetres at a distance of 100 km from the epicentre. As amplitude at 100 km distance exactly, is not available, distance correction is applied to determine M. One unilt increase in magnitude corresponds to about 30 fold increase in energy release. Richter has indicated the relationship between the two as log E = 11.4+1.5 M.

Where

E = Energy Release in Ergs

M = Richter Magnitude of Earthquake

INTENSITY

Earthquake intensity is an arbitrary measure of its effect. The Modified Marcalli (MM) intensity scale is commonly used in this regard. As one moves up in the intensity scale, more damaging effect is indicated. Magnitude of an earthquake per se does not indicate its damaging effect. As larger magnitude earthquakes can occur only at greater depth, their damaging effects are attenuated because of larger thickness of rockmass through which the energy waves have to travel.

After a particular earthquake event, intensity observed at various locations around the area is surveyed and plotted on a map. Lines connecting points showing identical intensity are called isoseismic lines or isoseismals. These are normally in the form of some-what elongated concentric lines of equal intensity, the elongation largely depending upon the rupture length. Obviously this exercise is highly subjective and the results are qualitative.

RELATIONSHIP AND ENERGY RELEASE

In table 2, an idealized relationship between Magnitude and the length of the fault which undergoes rupture is indicated.

TABLE 2

MANITUDE, RUPTURE LENGTH & ENERGY RELEASE

MAGNITUDE	LENGTH OF RUPTURE (Kms)	ENERGY RELEASE (ergs)	MM INTENSITY APPROXIMATE
3.0	0.5		III
4.0	.1.3	6.3×10^{17}	V
4.5	2.0	3.6×10^{18}	
5.0	3.3	2.0×10^{19}	VI
5.5	5.4	1.1×10^{20}	VII
6.0	8.0	6.3×10^{20}	VII
6.5	15.0	3.6×10^{21}	VIII
7.0	40.0	2.0×10^{22}	IX
7.5	112.0	1.1×10^{23}	X
8.0	304.0	6.3×10^{23}	XI
8.5	850.0	3.6×10^{24}	XII

It also shows the relationship between Magnitude and energy release for various levels and brings out a very broadly generalised indicative association between magnitude and intensity. This association is not used in scientific work because no ideal mathematical relationship exists, nor is possible; parameters/factors like properties of earth material, focal depth and duration of shaking really matter, which modify the intensity considerably for the same Magnitude. Table 3 indicates a general description to identify the MM intensity values. Various relationships have been advocated by researchers between energy released at source, mode of travel of the waves through earth's crust and effect of quality of rock medium on their attenuation and finally the ground movement and acceleration caused by the energy release.

TABLE. 3
MODIFIED MERCALLI SCALE FOR ASCERTAINING INTENSITY OF AN EARTHOUAKE

1. Very slight , felt only instruments.
2. Felt by resting people.
3. Feels like passing traffic.
4. Furniture and windows rattle.
5. Can be felt outdoors; clocks stop; doors swing.
6. Furniture moves about; cracks appear in walls.
7. People knocked over, Masonry cracks and falls.
8. Chimneys and monuments fall.
9. Heavy damage to buildings.
10. Most buildings destroyed; landslide occurs; water thrown out of canals and lakes.
11. Railway lines badly bent.
12. No building left standing.

GROUND MOVEMENT

ACCELERATIONS

The effect of an earthquake on any structure is like shaking it at ground level with an arbitrary varying severity for a short duration of time. The shaking starts slowly, quickly increassing to a maximum degree and then reduces rather slowly. The period of a shaking episode is normally less than a minute. It possibly is a function of Magnitude.

Shaking due to an earthquake is thus distinctly different than vibrations caused by a machine which starts and completes vibration in similar manner but imparts sustained vibration almost at same frequency and amplitude over a long period extending into hours.

The shaking can be idealised as movement of particles on ground resolved in longitudinal, transverse or vertical direction. A seismograph records weak motions. It is a very sensitive instrument largely used by seismologists. Seismographic rocord is usually suplemented by that of an accelerograph. A strong motion accelerograph records accelerations in all three axes beyond a threshold value of say 0.03 g. The speed of its recorder is about 20 mm/sec which is higher than a seismograph, to enable better resoultion for engineering purposes. The movement is about a stable position and hence is better described by velocity or acceleration around it. Gravity acceleration (g) being a universally accepted standard value, the ground accelation during each cycle of vibration can be described as its fraction say 0.05g, 0.15g etc. meaning that the accleration force of the cycle was 5% or 15% of the gravity acceleration values respectively.

The acceleration in vertical direction is normally less than that in horizontal direction, except in near source record, and is of the order of about 50 to 75%. For design of a structure the vertical acceleration and the higher of the two values in horizontal plane are of significance.

PEAK GROUND ACCELERATION (PGA)

An accelerogram is a graph of an earthquake shaking showing accelerations caused to the instrument recorder through every cycle of vibration. Peak value of the event is known as Peak Ground Acceleration (PGA). Energy content of an event which affects a structure is best given by integrated effect of each cycle of vibration. The PGA alone does not determine it. Other parameters required for the purpose comprise frequency of each cycle, duration of the event and speed with which decay of the peak acceleration value takes place.

The PGA despite its recognised shortcomings remains the most used element to characterise the seismic evaluation parameters for dam stability analysis. The shortcomings in utilising PGA are due mainly to lack of predictability of PGA in near field or its occurance at high frequency which is of little engineering significance.

EFFECTIVE PEAK GROUND ACCELERATION (EPGA)

Accelerogram records made at various sites around the world show that the largest peaks of acceleration on the record may occur in the form of few spikes only. They are not representative estimates of the acceleration which was being experienced through the strongest ground shaking. It is thus a common practice to adopt mean-plus-one-standard deviation of the peak values as Effective Peak Ground Acceleration, for dam design purposes.

DURATION AND VIBRATION FREQUENCY

The duration of shaking is perhaps the most important seismic parameter as it is directly related to damage especially in the case of embankment dams. Of significance to engineers is the bracketed duration, measured between the first and the last occurrence of acceleration pulses greater than 0.50g at frequencies about 2 Hz which is related to the total amount of energy contained in a specific record.

INERTIA, FUNDAMENTAL PERIOD AND DAMPING

Inertia is the property of a body by virtue of which it offers resistance to any change in its state of motion. Inertia force unlike a contact or gravitational force can still be quantified as mass of the body times its acceleration. Thus greater the mass of a body, more would be its inertia.

When the ground shakes during an earthquake, a structure tries to retain its original position due to inertia. For the same degree of shaking, a body shall offer resistance in proportion to its inertia. Thus a rockfill dam with fill material of unit weight close to that of stone/concrete and with much flatter slopes than a concrete or masonry dam of the same height, would, by virtue of its enormous mass, exert significantly high resistance to shaking as compared to a gravity dam.

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The fundamental period of a structure is the measure of its vulnerability to any vibration loading. If the period of the structure and that of the vibrations are in close proximity, resonance may take place which is obviously an undesirabale situation for any structure. The fundamental period of a rockfill dam is given as :

$$T = 2.61 \; Ht \; \sqrt{\rho/G}$$

Where   T = Time period

       ρ = Mass density

       G = Shear modulus

       Ht = Height of the dam

As may be seen, the fundamental period is directly related to the height (Ht) of the dam indicating for a given material, a higher time period corresponding to a higher earth and rockfill dam. The following table indicates the values of T for different dam heights and two shear modulus values :

TABLE 4'

DAM HEIGHT AND FUNDAMENTAL PERIOD

H	T-Sec	
(m)	G=133.3 kg/cm²	G=66.7kg/cm²
15	0.45	0.64
30	0.50	1.27
60	1.80	2.54
90	2.70	3.81
120	3.60	5.08

Gravity dams with higher values of 'G' tend to have lesser time period.

As has been brought out earlier, most of the earthquake energy is transmitted to the ground surface through waves of very short period range viz. 0 to 0.5 sec. only. The fundamental period of High Earth and Rockfill dams, being much higher, the resonant amplitudes do not develop. On the contrary, dams of moderate height with lower time period are more likely to develop high amplitudes due to resonance. This factor of time period making high rockfill dams inherently more quake resistant than even low rockfill dams fails to register upon a layman's mind.

Another factor which increases the quake resistance of rockfill dam is the higher damping property of the fill material. Damping indicates resistance which reduces or opposes vibration by energy absorption. Different materials used in the body of the dam will have different damping characteristics. The least amount of the damping which will prevent free oscillation for a system with one-degree-of-freedom is known as critical damping. The damping ratio for earth dams is of the order of 10 to 30% as compared to 3 to 10% for concrete dams. Thus a rockfill dam is inherently more resilient to vibrations than a concrete gravity dam.

DEGREES OF FREEDOM

When a mass is vibrating, its position in space with respect to its equilibrium position, can be described by six co-ordinates, three translational, say, along the co-ordinate axes x,y, and z and three rotational about the same axes. However, a mass may have freedom to move only in certain directions and constrained in other directions. The numbers of co-ordinates required to describe the position of a vibrating mass are termed as degrees of freedom of that mass. For a multi mass discrete system, the total degrees of freedom of the system would be sum of degrees of freedom of individual masses If a system is described by a single mass and it is constrained such that its motion is described by a single co-ordinate, it is termed as single-degree-of-freedom system.

In systems where there are a number of masses connected with each other, even if each mass is constrained to have one degree of freedom, the system as a whole has as many degrees of freedom as there are masses. In general the number of degrees of freedom of a system will be equal to the sum of the degrees of freedom of each discrete mass into which the system has been discretized or lumped. If a dam is considered as an assemblage of small elements of single or more degrees of freedom the dam constitutes a multiple degree-

of-freedom system.

RESPONSE SPECTRUM

A response spectrum is a plot of maximum values of the acceleration, velocity and displacement responses of an infinite series of single-degree-of-freedom system subject to time dependent dynamic excitation. The maximum response values are expressed as function of undamped natural period for a given damping and tend to increase with damping.

The results are arranged in order of increasing flexibility designated by natural period of a cycle of vibration. The information is plotted in a graphical form of acceleration on y axis and the natural period on x asis; the graph known as response spectrum. Using statistical theories, it is then possible to generate an earthquake record or synthetic accelerogram which is used to ascertain likely deformation in a structure.

If we see any typical Response Spectrum Curve for a specific excitation and for a range of damping values, it is evident that the magnitude of response relates inversely to the time period as well as to damping. Infact in the period range of high rockfill dams spectral ordinates remain almost insensitive to the variations of the degree of excitation. This is how the variations in the values of PGA of the Design accelerogram make little difference in the response/design of these structures(Fig.1).

DESIGN OF DAMS FOR EARTHQUAKE FORCES

STATIC-DYNAMIC EFFECTS

A destabilising force gets distributed in the body of the structure according to the density of various constituent materials. One approach to analyse the effect of this essentially dynamic force comprises, its coversion into an equivalent static force, and its application in the direction of other destabilising forces and lastly calculating the factor of safety against movement or overturning. This approach is known as pseudo-Static Analysis and has been used because of its simplicity, consistency and adequate factor of safety. The name perhaps has been a little misleading. It is really meant to convey that the analytical procedure involved takes care of the dynamic forces which are converted (deceptively perhaps-hence the word pseudo) into static equivalents

FIGURE 1

NATURAL PERIOD OF VIBRATION IN SECONDS

RESPONSE SPECTRA
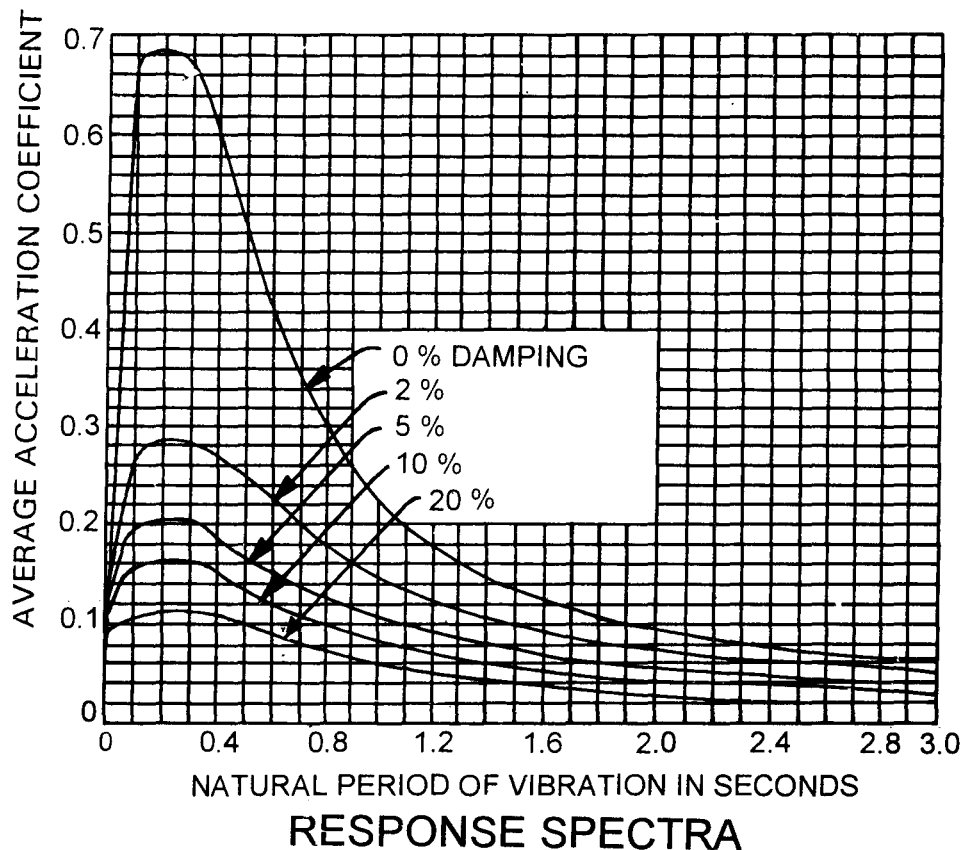
(almost truly) with adequate margin of safety introduced for parameters defying conversion or simulation.

Pseudo-static analysis against dynamic earthquake forces involves computation of minimum factor of safety against sliding when a static horizontal force is included in analysis to simulate the dynamic force. The analysis is treated as a static problem, and the horizontal force is taken as the product of (the seismic coefficient) and the weight W of the potential sliding mass. The basic assumption involved is that the portion of the dam above the rupture surface is rigid. IS 7894-1875 titled "The Code of Practice for Stability Analysis of Earth Dams" provides for the minimum factor of safety required during such analysis as one.

DYNAMIC BEHAVIOUR

The pseudo-static analysis is, however, being gradually replaced for important structures by advanced methods of analysis which recognize the fluctuating and reversing nature of forces caused by earthquakes and take into account characteristics of construction materials viz. damping, natural period, elasticity, plasticity, granulometry, particle binder properties, etc.

All structures including dams are largely elastic. As a force is applied to a structure while it undergoes deformation, it also generates internal forces which oppose the applied force and neutralise it. The degree of deformation, however, depends upon elastic properties of construction materials and binders, considered collectively. When the external force is removed, the shape is regained in case of a completely elastic body. Partial deformation remains to the extent the body is not elastic.

In the event of rapid shaking as experienced in case of earthquake, by the time the body responds to the force in one direction, the direction of application is reversed. Thus, the structure undergoes oscillation about its stable position. The oscillation cycle generally lags behind reversal cycle of shaking force. The rapid deformation and reformation create some permanent microscopic adjustment amongst constituent particles of the construction material. This process also absorbs part of the applied energy. The structure, therefore, does not vibrate or oscillate as vigorously as the applied force and the stresses and strains generated in the dam therefore get moderated. This phenomenon is known as damping.

DAMPING RESPONSE

Like all structures, an earth dam is composed of billions of particles but they are held together by inter granular friction and or cohesion. Though not apparent, the grains have considerable freedom to adjust or move in relation to each other locally without triggering a movement over a larger area which can lead to major movement right across a structure and cause failure. Earth and rockfill dams, therefore, have considerably high damping characteristics than other structures. Behaviour of granular material has been studied since 18th century and reliable methods of analysis are available for the designers to design embankment dams to take care of local adjustments and or movements.

APPLICABLE FREQUENCY RANGE

An alternating horizontal force caused by an earthquake applied to a body can be compared with a block resting on a table being pushed in both directions alternately. The block moves only when the applied force exceeds the resistance generated by friction between the surfaces of the table and the block. Since the earthquake force varies with time, the block moves during the shaking period only when the force exceeds the frictional force. Thus, there is only a certain limited period during which the block can move on the inclined plane. A base of a structure does not move easily in relation to the foundation surface. The internal adjustment or movement of constituent materials, however, takes place in this limited period of the shaking episode. To find out total residual deformation of a structure at the end of an earthquake an accelerogram is used, discretizing the record to suitable time steps is done for better results and this is around 0.01 sec in respects of fill dams and much less for concrete dams. For each such interval, the permanent displacement likely due to excedence of limiting force is computed. The permanent displacement during each interval is integrated for the entire accelerogram. The work involves extensive computations; these are facilitated with the advent of high speed digital computer and appropriate software that can be an effective numerical model.

FINITE ELEMENT METHOD

Alternatively, the dam is conceptualised as an assembly of large numbers of blocks connected with each other at specified points along the periphery of individual blocks. Each block is assigned parameters of behaviour depending upon its location in a cross section and to simulate the constituent material it comprises. Time dependent forces simulating an earthquake are than applied to these blocks. It involves millions of computations

which are speedily and accurately performed by using a computer.

DYNAMIC ANALYSIS

Basically it is a numerical solution process by which the effect of seismic forces is studied in detail for various components of a structure which is discretized into small finite elements. For dynamic analysis, the full time history of the earthquake motion in terms of acceleration versus time and its compatible response spectrum is needed. A step by step procedure or a procedure called mode super position is followed to study the effect of dynamic loading. The essence of the dynamic analysis is to study the deformation of the dam. The methods also yield a picture of the final state of an earth dam after an earthquake.

DESIGN BASIS EARTHQUAKES

With each seismogenic source viz. a fault system, a notional Maximum Credible Earthquake (MCE) is associated which is the largest reasonably conceivable earthquake that can happen near the source within the probabilitically geographically defined tectonic province and frame work. The MCE is also defined as an upper bound of expected magnitude. The Maximum Design Earthquake (MDE) will normally be characterized by a level of motion equal to that expected at the dam site; from the occurrence of deterministically or/evaluated MCE. The Operating Basis Earthquake (OBE) represents the level of ground motion at the dam site at which minor damage to the structure is acceptable. The OBE is determined by probalistic methods. A critical MCE, however, is worked out to envelope MCE from different identified seismogenic sources and is called a design basis earthquake (DBE).

SEISMIC PARAMETERS DETERMINATION

The important requirements to be ascertained before arriving at seismic design parameters in respect of large dams relate to :

i)   the seismic hazard rating;

ii)   the risk rating of the dam site; and

iii)   type of dam and possible mode of failure.

Risk factor is classified as extreme, high, moderate or low on the basis of likely risk quantified with each of the attribute viz. capacity of reservoir, height of dam, evacuation requirement and potential downstream damage. International dam design practices recommend detailed dynamic analysis for all dams with high & extreme risk rating.
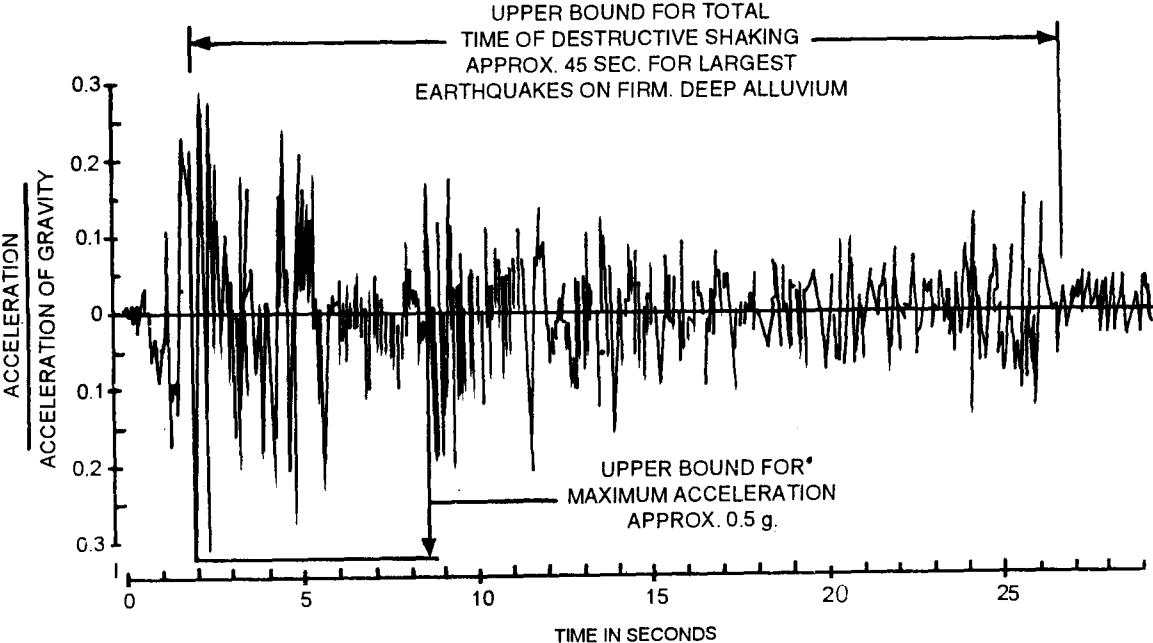
ACCELERATION TIME HISTORIES

The definition of seismic parameters by peak values and spectral characteristics is generally sufficient for dam design application. Evaluation of critical dams by non-linear analysis however requires specification of earthquake motion as acceleration time history records. It is recommended that several acceleration time histories be used to represent either of the MDE, or OBE, as certain time histories have a lower energy content at some frequencies and their use may result in an unconservative analysis. Acceleration time histories may be specified for horizontal and/or vertical motion and should preferably be represented by real accelerograms obtained for site conditions similar to those present at the dam site under consideration (Fig. 2).

Since available strong ground motion data do not cover the whole range of possible conditions, such records must often be enriched by artificially generated or synthetic motions representing specified earthquake parameters and seismotectonic environment. Synthetic record is developed by superposition methds, by stochastic processes, or by mathematical simulations of fault rupture and is invariably rich in all frrequencies and in energy content. A design based on artificial accelerogram is, therefore, more conservative than the one generated from an actually observed accelerogram (Fig 3).

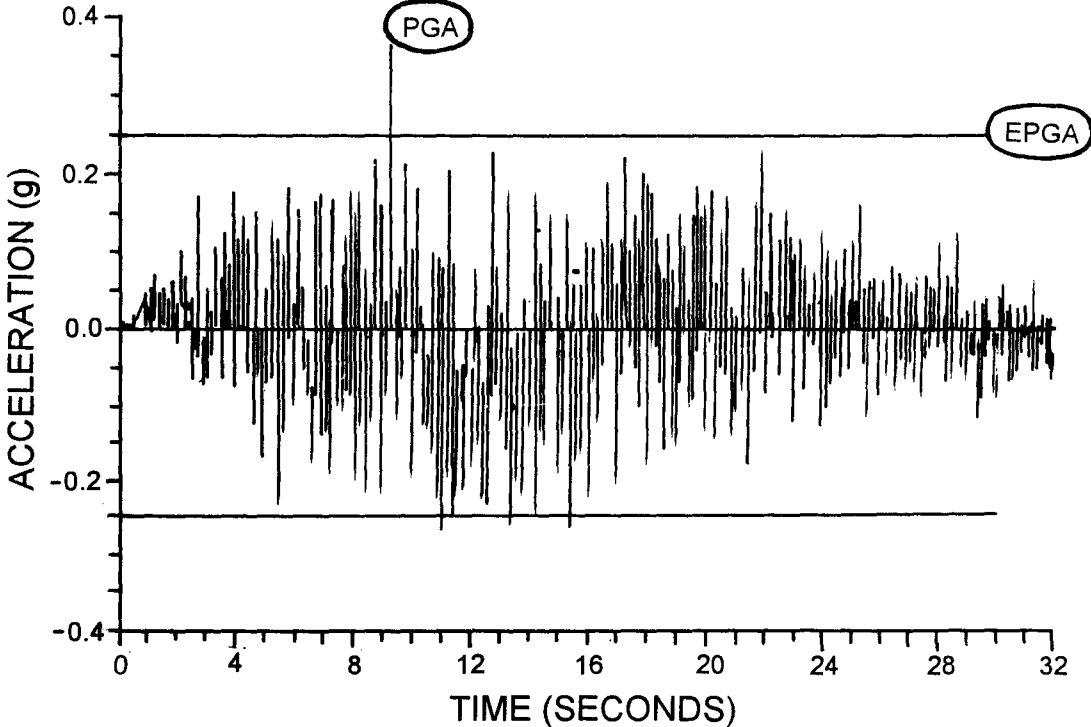To recapitulate the foregoing, it is seen that :

(i)   when an earthquake occurs, accumulated strain energy is released at a depth which increases with the magnitude;

(ii)   existing fault gets ruptured, the area of rupture increasing significantly with the magnitude;

(iii)   as a result, large areas on earth's surface shake releasing acceleration forces which affect man-made structures and natural geomorphic features alike;

(iv)   the response of each such structure depends on its own properties; and

FIGURE 2

UPPER BOUND FOR TOTAL
TIME OF DESTRUCTIVE SHAKING
APPROX. 45 SEC. FOR LARGEST
EARTHQUAKES ON FIRM. DEEP ALLUVIUM

UPPER BOUND FOR
MAXIMUM ACCELERATION
APPROX. 0.5 g.

TIME IN SECONDS

ACTUAL ACCELEROGRAM

FIGURE 3

PGA

EPGA

TIME (SECONDS)

DESIGN ACCELEROGRAM

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(v) the dimensions and the geometry of the structure can be designed in such a way that likely deformation does not cuase failure.

ASSESSMENT OF DAMAGING EFFECTS OF EARTHQUAKES

DEFORMATION ANALYSIS

One of the detrimental effects of vibration on embankment is compaction of the dam and or foundations, and consequent slump and possible overtopping by stored water. This necessitates deformation analysis for a dam and provision of necessary defensive measures to avoid overtopping or piping.

In the initial stages of desigr.s, plastic displacement analysis based on simplified procedures by Newmark etc. is often sufficient. The approach essentially assumes that displacement would occur when the response acceleration exceeds yield acceleration at which factor of safety would be unity. It can be easily worked out using conventional limit equilibrium appropaches. For a known acceleraion time history, the plot above yield acceleration level when integrated twice gives the resulting displacement of the sliding mass.

For important structures the above analysis needs to be supplemented with a Deformation Analysis using finite element (strain potential) approach.

LIQUEFACTION

Most soils subject to cyclic or fluctuating loads develop continuously increasing pore water pressures and increasing deformation. For clays the changes of pore water pressure and the large increase of deformation occur, only after a very large number of cycles. In typical earthquake conditions, this pressure increase may be insignificant. However, for silts and sands below 75% of relative density very considerable pore water pressure, changes can be recorded in a few cycles. When pore water pressure reaches the level of confining stress, the material exhibits large displacements under cyclic load and a near liquid state is reached. This is so called cyclic mobility distinguished from liquefaction only by the fact that due to dilation at shearing, the effective stress will increase under large strain and the material would retain some ultimate strength.

This occurs due to permanent compaction or densification of the material during alternating stressing, causing an increase of pore pressures and a reduction of effective stress under undrained conditions. Once the water is drained in between successive earthquakes, the material regains its original strength.

In soils for which such effects are important, the simplified analysis is not sufficient. More refined procedure that attempts modelling of the material response is sought.

LIQUEFACTION ANALYSIS OF DAMS

If the soils of either the foundation or the embankment are prone to lose strength under cyclic loading, an evaluation of liquefaction potential and post earthqake stability is carried out. The analysis for the former employs either a simplified method or a rigorous method according to importance of the project.

Semi-empirical methods are based on comparison with performance of other existing dams or rigorously analysed dams, and their past performance. One depends mainly on standard penetration test blow counts. For rigorous analytical procedures, dynamic properties of soil are required with acceleration time history of MDE.

The analysis for embankment consists of performing a dynamic stress analysis based on dynamic strength induced with the strengths evaluated. If the foundation and embankment materials are not susceptible to loss of stiffness and strength, the dynamic analysis will serve the basis to estimate permanent earthquake induced displacements. If they lose stiffness or strength, dynamic analysis is used for estimating the number and amplitude of induced stress cycles to determine whether the earthquake induced stresses are sufficient to trigger loss of strength and if so, to what level.

THE TEHRI PROJECT

SALIENT FEATURES

Tehri multi-purpose project (Lat. 30° 28' N and Long 78° 30' E) is being constructed in head reaches of Ganga basin in Uttar Pradesh State, to generate 2000 MW of hydropower to provide additional irrigation to an area of about 2.70 lakh hectares and to provide drinking water of about 10 m³/s or 86 ha m every day for about 4 million souls residing in metropolis of Delhi. The project comprises construction of two dams (a) the upper dam 260 m in height downstream of Tehri township after confluence of Alaknada and Bhagirathi; and (b) the Koteshwar
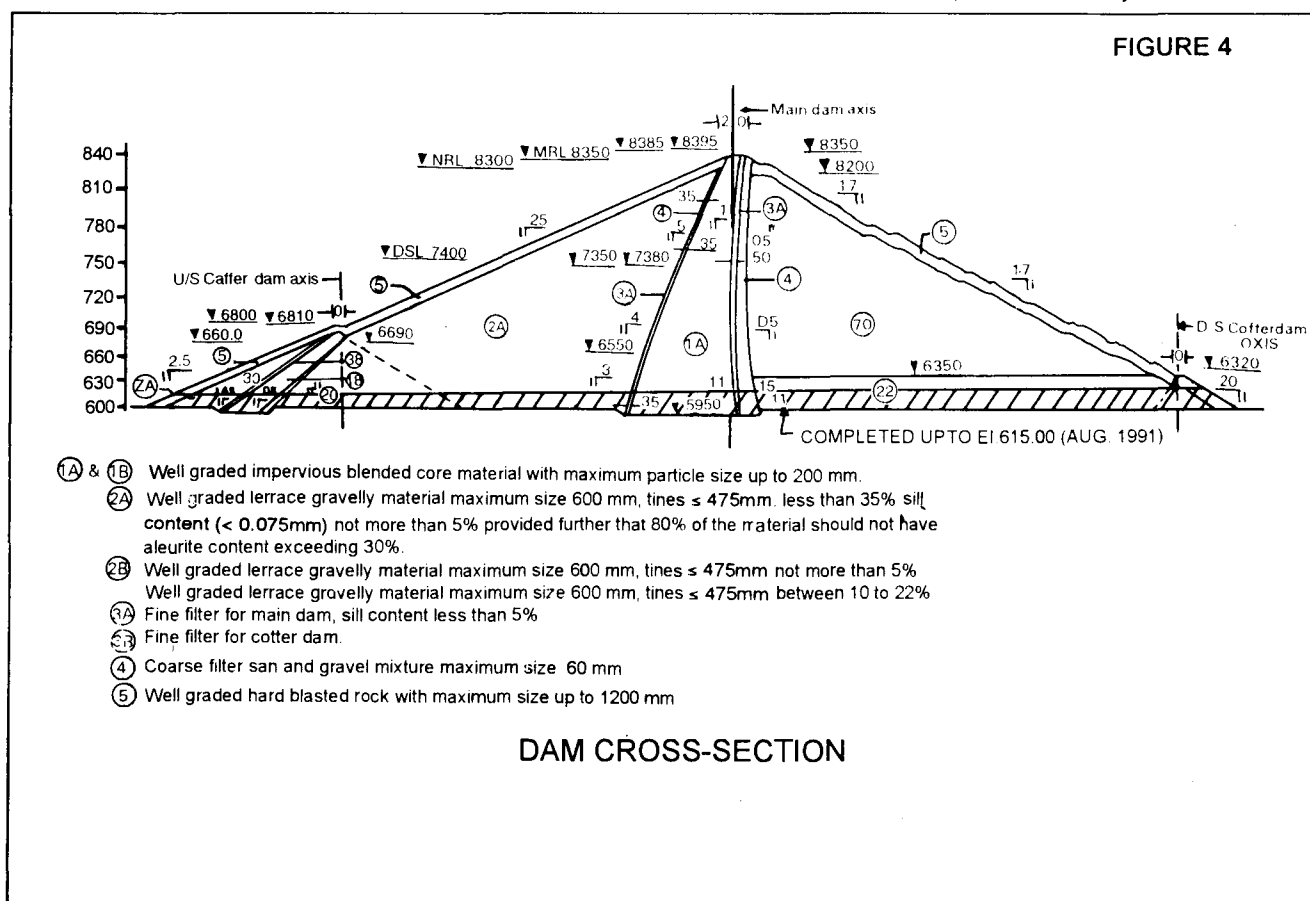
dam 103.5 m in height and 22 km downstream of Tehri Dam. Catchment area at Tehri dam is 7511 sq. km. and the spillway is planned to take care of inflow Probable Maximum Flood (PMF) of 5380 m³/s. The upstream dam is to be constructed in rockfill, the downstream is planned as a straight Gravity concrete dam. The power houses are planned to be constucted at the toe of both the dams. On upstream a diversion dam Maneri Bhali (Stage-1) 45 m in height, has been built about 70 km above Tehri Dam-Site for generating hydropower with an installed capacity of 90 MW, about two decades back.

PRESENT STAGE OF CONSTRUCTION

The Stage-1 Tehri Main Dam and hydropower plant 1000 (4 x 250) MW at Tehri are estimated to cost (in 1991) almost Rs. 1974.00 Crores. The project has been technoeconomically cleared in 1972. The clearance from environment and forest angle had also been given by appropriate agencies in 1986 subject to certain conditions. Pending final investment clearance, allocations have been made and utilized in 6th and 7th Plans. An amount of about Rs. 640 Crores has already been utilized (by the end of June, 1991) for preliminary works, diversion tunnels, and power tunnels including payments for compensation, resettlement and rehabilitation for which the project has got a liberal and progressive package offer. For the main Tehri dam. river bed was cleared, cut off trench excavated, foundation treated and backfilled in 1989-90. The upstream coffer dam is planned to be accommodated in dam section. The embankment of the coffer dam and main dam has been built during 1990-91 in one stretch upto elevation + 615m which is +20m above the river bed level at cut off location. The embankment so constructed was protected to pass the monsoon flow of 1991 over it without causing any washout. As the year was relatively dry, river flow was accommodated through the diversion tunnels and hence no over flow occurred. During the field season 1991-92, it is proposed to raise the upstream coffer dam to its full height.

DAM SECTION ZONING

The dam cross section has been originally designed by Uttar Pradesh Irrigation Department (UPID) and it has been refined by Design Organisation of Tehri Hydro Development Corporation Ltd. (THDC) with the help of their design consultants viz. Department of Earthquake Engineering of University or Roorkee (DEE, UOR). The crest width is 20 m. Upstream and downstream slopes are 2.5 : 1 and 2 : 1 respectively. The core is centrally located and protected by requisite filter and transition zones on both sides. (Fig. 4) The zoned fill has been designed for stability in face of likely deformation or liquefaction when subjected to static and/or dynamic forces as per standard codes of practice. The State of Art design process has been completed recently. After a protocol

FIGURE 4

① & ① Well graded impervious blended core material with maximum particle size up to 200 mm.

② Well graded lerrace gravelly material maximum size 600 mm, tines ≤ 475mm. less than 35% silt content (< 0.075mm) not more than 5% provided further that 80% of the material should not have aleurite content exceeding 30%.

② Well graded lerrace gravelly material maximum size 600 mm, tines ≤ 475mm not more than 5% Well graded lerrace grovelly material maximum size 600 mm, tines ≤ 475mm between 10 to 22%

③ Fine filter for main dam, sill content less than 5%

③ Fine filter for cotter dam.

④ Coarse filter san and gravel mixture maximum size 60 mm

⑤ Well graded hard blasted rock with maximum size up to 1200 mm

DAM CROSS-SECTION

was signed between USSR and India, Soviet Consultants independently carried out investigations for assessing seismic design parameters and completed the design for the dam section. Certain refinements in the zoning and or defensive measures will be possibly considered and incorporated in the final design section, after considering consultant's views.

RESERVATIONS ABOUT SEISMIC SAFETY

Doubts about the seismic safety of the Tehri Dam were first raised in the year 1986. Replies were provided to dispsel the doubts. But the matter has been periodically raised over the last few years. Reasoning has been provided, the seismic hazard potential evaluated and dam design reviewed every time such issues were raised. Certain groups, however, refuse to give up their mis-informed reservations/objections/resistance. It assumed grave proportions in the years 1990, however, with the acceptance in August, 1991 of an Experts' Group Report about seismic safety, one hoped that these misgivings would be completely eliminated. Meanwhile, the design process described earlier is in progress.

An earthquake of magnitude of about 6.1-6.5 on Richter Scale, however, occurred in the early morning of 20th October, 1991 in Garhwal region of UP where Tehri project is located. It took a death toll of around 768 people in the rural area surrounding the epicentre. Although the earthquake has not affected well engineered structures besides several traditional non-engineered structures also, doubts have been expressed once more by the same groups through media, through social workers and this time even through some professionals, politicians and laymen about the seismic safety of Tehri Dam. These concerns have been understandably influenced by emotional response to the scale of loss of life and property.

The following paragraphs explain the effect of seismic forces, how Tehri Dam has been designed to withstand the hazard due to perhaps a worse than'worst case scenario' which it may be subjected to, in an extremely rare case. It has been explained that the earthquake of 20th October, 1991 has not necessitated any design review because the design forces take care of a much worse scenario.

ON HIMALAYAN EARTHQUAKES

Earthquakes in the Himalayas are caused by the collision of tectonic plates and subsequent subduction. The plate containing the Indian Sub-continent is thrusting below the one containing northern Asia called Eurasian Plate. The result is creation of Himalayas which took place about 40 million years ago when the plates came to collide with each other.

Initial covergence of plates between India and Eurasia involved the closing of an ancient sea located between the two land masses. During this stage in the evolution of the Himalayas, the Indus Tsangpo Suture (ITS) acted as the primary locale of plate interaction and Eurasian land masses was completely closed. Shortly following this time, the ITS ceased to be the active plate boundary. One hypothesis is that since the closing of the ITS, the active boundary has jumped 'progressively' southward, first to the main Central Thrust (MCT) and more recently to the main boundary thrust (MBT) and thereafter to Himalayan Frontal Thrust (HFT). The rocks between the ITS and the MCT as well as between MCT and MBT represent successive sectors of the Indian plate that have been subducting below the Eurasian plate (Fig 5).

SEISMIC DESIGN PARAMETERS AT TEHRI DAM SITE

TECTONIC SET UP OF HIMALAYAS AND REGIONAL GEOLOGY

The rocks of Lesser Himalayas, have been classified into two major tectono-stratigraphic units, viz., sedimentary low grade metamorphic rocks overlying the main Boundary Thrust (MBT) in the south, and the parautochthon Garhwal Group (sedimentaries, basic volcanics etc.) limited on the North by the Main Central Thrust (MCT). The near-oldest exposed rocks of the Supra MBT sequence i.e. the Chandpur phyllites, are well exposed in the Bhagirathi valley. These are in direct tectonic contact with the Quartzites etc. of the Garhwal Group. In between these major groups of rocks, a narrow linear structural belt exposes the slates with thin arenaceous laminates, etc. of Simla group in the Bhagirathi valley. In sections where Simla group rocks are not exposed, the Garhwal Group directly comes in tectonic contact with the Chandpur phyllites. This contact is often designated as Srinagar Thrust. These thrusts as also the major formations trend in general WNW-ESE directions, with a number of local attitudinal variations. Local tectonic lineaments identified near the Tehri dam project are Gadolia, Deul tears, Tehri, Marh and Chamba faults. These features have to be considered in evaluating their seismic potential. The major thrusts i.e. MCT and MBT and reverse faults have northeasterly dip at angles between 45° and 60° at the surface.

The rocks of Jaunsar series (Mandhali, Chandpur and Nagthaht Formations) as the oldest exposed assemblages, are overlain successively by Krol Group (Blairi Infra Krol and Krol formations of vendian age and Tal formation of Cambrian age). Overlying the Tals, the rocks of Subathu formation of Eocene age are exposed far off in the WNW- ESE trending Mussoorie Synform to the southwest of the Tehri gorge. The Mussorie Synform is made up to the complete succession of Krol Group, the overlying Subathu and a small klippe of overthrust metasediments/sediments in the frontal range. The Chandpur-Nagthat formations on the Northern side of the synform are highly folded. This Chandpur-Nagthat sequence is seen to extend eastward from the Bhagirathi valley as a part of the Tehri-Chandrabadni synform with clear exposition across the Alaknanda valley. Tight synclines with Nagthat quartizites in the core of Chandpur phyllites are also seen in the vicinity of the project site. The rocks of the Garhwal Group occur in a wide linear folded belt, north of the Chandpur formation of the Bhagirathi valley in the Tehri area. The formations essentially consist of thick sequences of coarse quartzite and basic volcanics, dolomite, subordinate phyllites, arenaceous facies etc. of late Proterozoic age. These rock units are also folded with axial trace trending in the WNW-ESE direction.

GEOLOGICAL SETUP

The Tehri Dam site is located in Chandpur phyllites of varied physcial characteristics because of their alterations of varied proportions of arenaceous and argillaceous materials and varied degrees of tectonisation suffered by them. Based on metamorphic and lithic criteria the rocks exposed in the area have been phyllitic quartizites, which are predominantly arenaceous, massive and well jointed; quartzitic phyllites with rhythmic alternate bands of very thin arenaceous and argillaceous material; foliated phyllite composed mainly of argillaceous material puckered and profusely impregnated by quartz veins; sheeted phyllites and sheared phyllites. These rocks are traversed by a number of shear zones most prominent of which are those which are parallel to the foliation-bedding and the ones which have almost the same strike but dipping at 40° and 65° in opposite direction i.e. towards the upstream. A few transverse shear zones have also been recorded. The former two sets of shear zones have been designated as diagonal (D) shears with dips varying between 40° to 70° in the northerly quadrant and the logitudinal (L) shears almost parallel to bedding and foliation at this site.

STUDIES FOR ASSESSMENT OF SEISMICITY

To make an assessment about maximum credible earthquake which can ever occur in the dam site region, following special detailed studies were carried out.

FIGURE 5
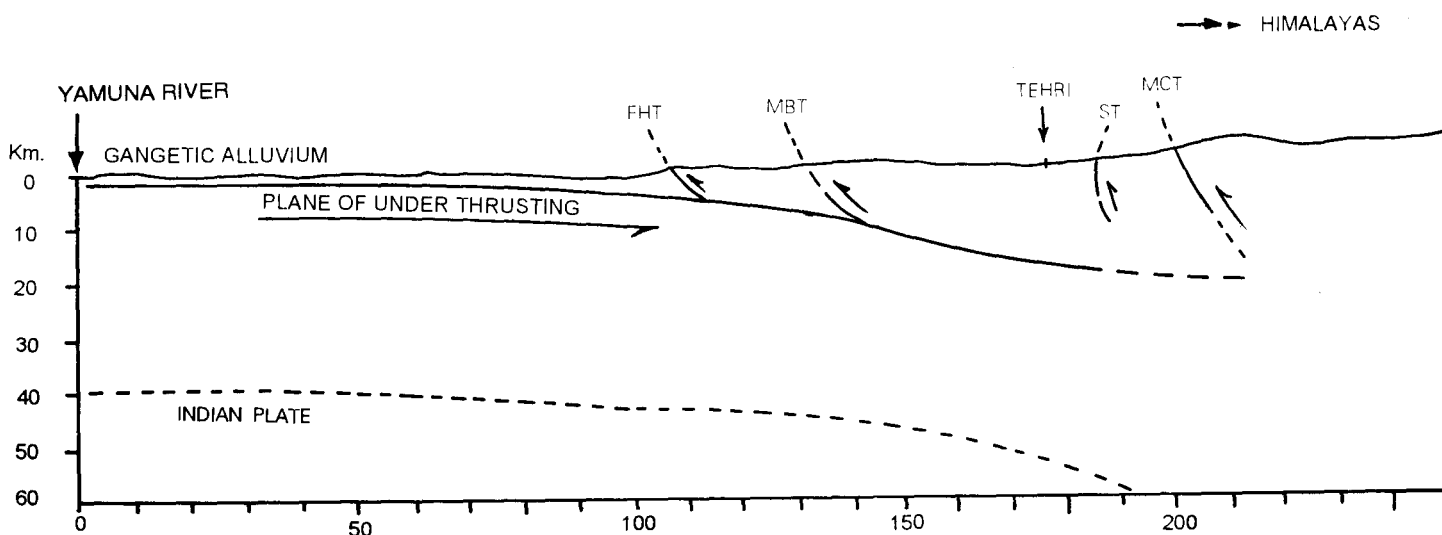
SUBDUCTION MODEL

REVIEW OF PAST EARTHQUAKES

A list of past earthquakes of magnitude greater than 3 with their parameters were compiled from both Indian and foregin sources. Evaluation of the data reveals that epicentres of 77 earthquakes lie within a radial distance of 320 km from dam site, the nearest earthquake being located 35 to 40 km northeast from the dam site. Most of the earthquakes had a magnitude of 5 to 7. During the well-known Kangra earthquake of 1905 the area of Tehri dam project lay between isoseismals VI and VII.

IDENTIFICATION OF TECTONIC FEATURES

There are well-known tectonic features like, Main Central Thrust (MCT), Main Boundary Falut (MBF) and Himalayan Frontal Thrust (HFT) which characterise Himalayan Geology. In addition there are other important tectonic features. Aerial surveys were also carried out to pick up such tectonic features, which were then delineated and proven by ground mapping. Some of the close features around Tehri dam area are Srinagar Thrust, Deuel Tear Fault, Godaulia and Tehri Tear Fault. These lie between 5 km to 10 km from the dam site.

ESTABLISHING SEISMOGENEITY OF TECTONIC FEATURES

Next step was assessing whether there was any possibility of ground movement along these identified tectonic features. To assess and determine the site specific Design Seismic Parameters, Department of Earthquake Engg., University of Roorkee was Commissioned in 1984 as consultants. Inter-alia they carried out a study of micro earthquakes by using special portable instruments and recording earth tremors over a period of weeks at a number of places situated in close vicinity of proposed Tehri reservoir. These investigations indicated that there was very little seismic activity near the Tehri dam and clustering of seismic activity was found near Uttarkashi about 40 km north of Tehri. The magnitude of earthquake which can be associated with each source was assessed as under Table 5, keeping in view the historical maximum observed magnitude of earthquake along each (Fig 6). To be on a safe side focal depth for sources was considered as 20 km.

TABLE 5

SEISMOGENIC SOURCES NEAR TEHRI (UOR)

Seismic source	Earthquake (Magnitude Richter)	Hypocentral distance (km)	EPGA
Shrinagar Thrust	6.5	26	0.19
MCT	7.0	37	0.20
MBF	7.0	27	0.25
HFT	7.25	48	0.19

SEISMIC INSTRUMENTATION

The seismic networks are an important part of investigations for any important project. The primary objectives of the network are:

-- to monitor the seismicity of the region and

-- to study whether reservoir induced seismicity (RIS) developes after the filling of the reservoir starts.
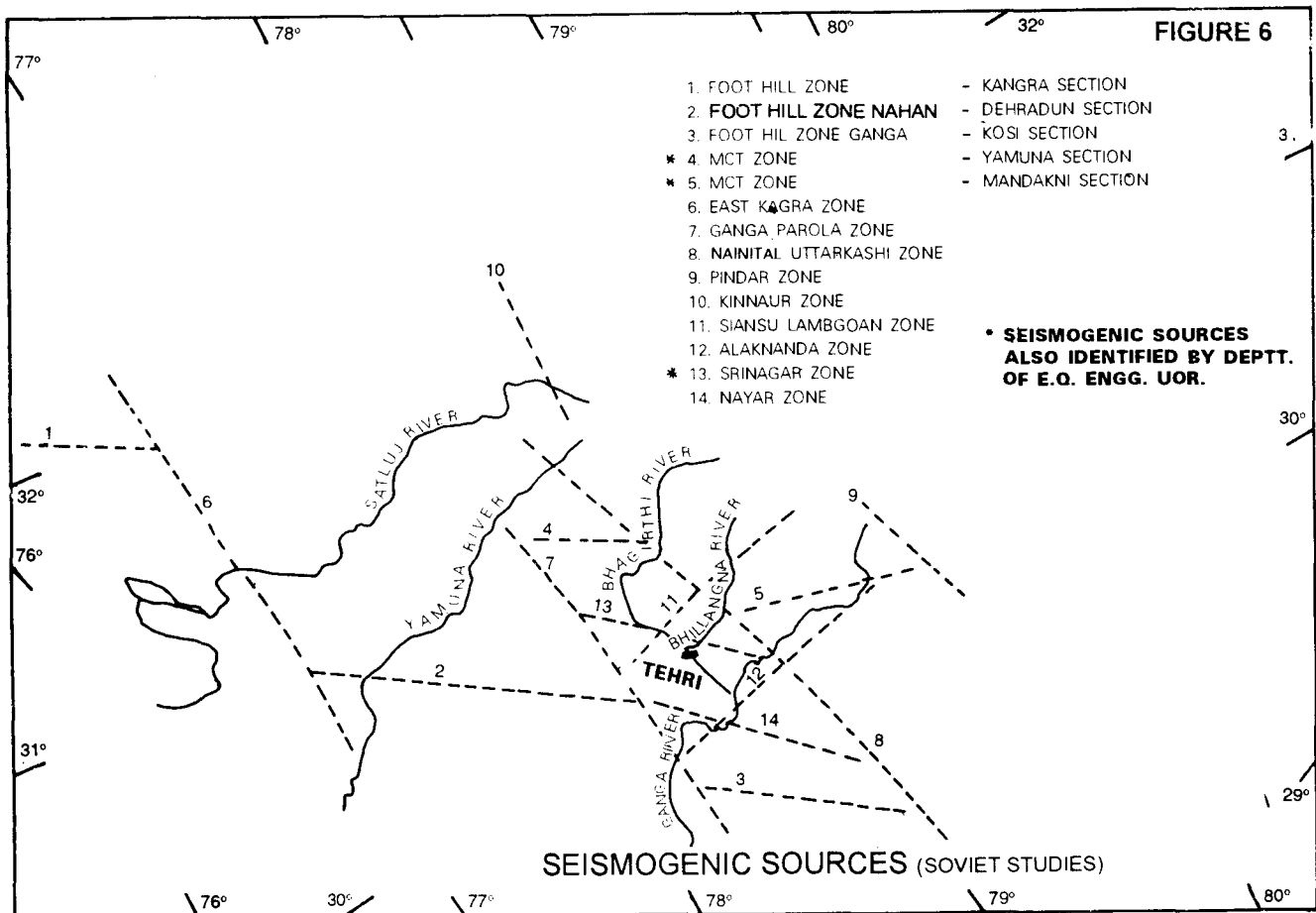
A few site specific microseismic arrays have been operated within the similar tectonic setting. A brief account and finding of two of these, one to the north west of the site (Beas Network) and other around the site (Tehri Network) is as follows :

a)   BEAS NETWORK

Srivastava, Dube and Choudhary (1985) studied earthquake occurrences for the year 1965-1975 with the help of closely spaced sensitive seismic stations around Beas Dam project. They have surmised that most of the activity in the area is related to Main Boundary Thrust and some along trends transverse to the Himalayas.

b)   TEHRI NETWORK

Epicentres of local earthquakes recorded during 1979-80 and 1984-86 define a definite seismic belt extending over a distance of 140 km from NW of Yamuna river to Alaknanda river. The width of the belt appears to be 30 km to 50 km (Khattri et. al. 1989). The focal depth of these local earthquakes varies between 13-23 km. The focal mechanism studies, conducted for discrete events suggest thrust fault type dislocation mechanism. Some events have indicated strike slip mechanism also.

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FIGURE 6

1. FOOT HILL ZONE — KANGRA SECTION
2. **FOOT HILL ZONE NAHAN** — DEHRADUN SECTION
3. FOOT HIL ZONE GANGA — KOSI SECTION
* 4. MCT ZONE — YAMUNA SECTION
* 5. MCT ZONE — MANDAKNI SECTION
6. EAST KAGRA ZONE
7. GANGA PAROLA ZONE
8. NAINITAL UTTARKASHI ZONE
9. PINDAR ZONE
10. KINNAUR ZONE
11. SIANSU LAMBGOAN ZONE
12. ALAKNANDA ZONE
* 13. SRINAGAR ZONE
14. NAYAR ZONE

• **SEISMOGENIC SOURCES
ALSO IDENTIFIED BY DEPTT.
OF E.Q. ENGG. UOR.**

SEISMOGENIC SOURCES (SOVIET STUDIES)

ESTIMATION OF SEISMIC DESIGN PARAMETERS FOR DAM

The Government of India appointed erstwhile 'Standing Committee for Recommendation of Design Seismic Parameters in River Valley Schemes' during its 19th meeting held on 31st August, 1984 recommended a design seismic coefficient of 0.21g to be adopted for the preliminary Pseudo-Static Analysis of Tehri Dam. The committee also recommended to the project to carry out detailed Dynamic Analysis.

Subsequently when seismic design studies were taken up for Tehri, there was no record of any strong earthquake in India in the vicinity of Tehri. As such the maximum peak acceleration and 'response spectra' for design of Tehri dam were worked out by experts and adopted for design of dam.

On 26th April, 1986, a severe earthquake occurred at Dharamshala in Himachal Pradesh, which was recorded by a strong motion array, set up in the region earlier. Data obtained from this earthquake indicated that 'response spectra' adopted for the design of Tehri dam are much more severe than that obtained at Dharamshala. It means that seismic loading assumed for design is much more stringent than what it would be as per actual data of earthquake recorded at Dharamshala.

An independent assessment of seismicity of Tehri area was undertaken by Soviet Consultants following practices and norms prevalent in the USSR after an agreement was reached in 1989. These are reported in para 10.0 below, alongwith results of analyses.

DYNAMIC PROPERTIES OF MATERIALS

STRESS-STRAIN RELATIONSHIP

Finite Element Method, using sophisticated, computer programmes takes into account the variation in strength properties of the dam materials under different loads, laws governing their behaviour, consolidation of dam due to its construction in stages etc. For carrying out such analysis, the material properties under ordinary i.e. static and earthquake or dynamic conditions is necessary. For this purpose apart from numerous tests carried out in the Laboratory, elaborate tests were performed in the borrow areas for the materials proposed to be used in the dam. These included :

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-- Block vibration tests

-- Wave propagation tests

-- Vertical dynamic plate Load tests.

Core and shell material was tested in borrow area for determination of strain dependent dynamic shear modulus. One test comprised determination of resonant frequency of concerte blocks cast on material to be tested. Free vibration (shear strain (SS) range 10^{-4} to 10^{-5}) and forced vibration ((SS) range 10^{-2} to 10^{-3}) was applied to two sizes of concrete blocks viz. 1.5 x 0.75 x 0.70 m and 3.00 x 1.50 x 0.7 m. Shear modulus (G_0) of the shell and core materials were taken as 600 kg/cm² and 200 kg/cm² respectively based on test results.

The second test comprised determination of Shear Modulus from compressional (P) wave velocity through the material to be tested. For this purpose, time taken for transmission of P wave created by sledge hammer impact on a steel plate fixed on the test material was measured by geophones. The strain range for this test was 10^{-6}

In the third test a 1x1x0. 45 m concrete slab was used as a loading plate on the test material. Settlement was measured at each incremental static load of 10 tonnes when dynamic loading of 50% of static load was applied by means of a mechanical oscillator. The load settlement curve so obtained was used to evaluate dynamic elastic modulus which in turn gave dynamic shear modulus.

From the results of three tests for each test material, a standard relationship between dynamic shear modulus and shear strain was derived for a common confining pressure of 1 kg/cm².

LIQUEFACTION

One of the procedures to ascertain liquefaction potential of dam material comprises testing it under water on a shake table. The material is placed in four layers of 15 cm each at Optimum Moisture Content (OMC) with standard proctor compaction effort and saturated. A sinusoidal motion severer than that of the design earthquake is applied and material tested for requisite number of cycles.

The equivalent sinusoidal motion for estimated MCE accelerogram with PGA of 0.25 g was worked out as 0.1875 g x with 28.5 cycles. The shake table was therefore set to a sinusoidal motion with 0.2g maximum acceleration and 30 cycles were applied with frequencies of 5 to 10 cycles per sec on it. It was found that for both the materials, core as well as shell, there was no development of excess pore water pressure for the designed motion. Even upto 100 cycles of motion, there was no development of excess pore water pressure in core material while pore pressures to the extent of 10 to 15% of overburden pressure were found to develop in shell material. Such range was considered safe.

DYNAMIC STABILITY ANALYSIS

Dynamic stability analysis has been carried out using following approaches :

(i) Plastic Displacement Analysis

(ii) Dynamic Stress Analysis by Finite Element Method

PRELIMINARY STUDIES

The Pseudo-Static analysis was carried out following guidelines listed in relevant Indian Standard viz. IS: 1893-1984 using a seismic coefficient of 0.12 g. The factors of safety obtained for the various cases of loading were much higher than the stipulated values.

PLASTIC DISPLACEMENT ANALYSIS

Using Goodman and Seed's approach, two sets of cases were used to workout the plastic displacement for the dam. Firstly the dam was assumed to behave as a rigid strcuture i.e. it was assumed that acceleration time history at each point in the dam body would be same as that of ground motion. The plastic displacement for upstream and downstream slopes worked out to 48.25 cm and 17.37 cm respectively.

In the second case the dam was assumed as nonrigid structure through which the ground motion gets amplified depending upon the damping characteristics of the material. In this case the permanent crest settlement was found to be of the order of 52 cm.

DYNAMIC STRESS ANALYSIS

The studies carried out related to two sections of the dam i.e. river bed amd right abutment sections.

Under static loading, maximum tensile stress of 3.3 kg/cm^2 and 2.69 kg/cm^2 and maximum compressive stress of 57.2 kg/cm^2 and 34.9 kg/cm^2 were worked out for river bed and abutment sections respectivley. Under dynamic conditions, the tensile stress increased to 10.5 kg/cm^2 and 7.0 kg/cm^2 while the compressive stress increased to 67.1 kg/cm^2 and 38.4 kg/cm^2 for river bed and abutment sections respectively.

Thus magnitude of tensile stress was permissible. It was caused only in shells and only for very short duration of time intervals. Since shells constitute gravelly or rocky soils, they will not sustain tension and therefore, in actual practice, there would be redistribution in adjacent elements. No tensile stress was obtained in core. The dam was thus found safe from seismic consideration.

Under the static loading, the maximum horizontal deflection of 15.4 cm and a maximum vertical deflection i.e. settlement of 68.4 cm were indicated along the axis of river bed section. A maximum horizontal deflection of 13.3 cm and maximum vertical deflection i.e. settlement of 27.7 cm were indicated in the abutment section.

SEISMIC SAFETY

STATIC AND DYNAMIC STUDIES

The Soviet Consultants indicated that the (i) Tehri structures were located within a single tectonic block. (ii) the peak ground acceleration at the middle level of the canyon which is at about dam crest level will not exceed 0.5g and (iii) the seismological and seismotectonic conditions of the area were suitable for high dam construction.

The Soviets considered 15 seismogenic sources which include those identified by Indian consultants (DEQ-UOR).

A state-of-the-art non-linear, sequential (static as well as dynamic) stress analysis by Finite Difference Method using Elasto-Plastic model was carried out by Scientific Research Centre of Hydro Project Institute, Moscow. The analysis takes into account the stress dependent properties of the material, the schedule of raising of the dam, the schedule of reservoir filling, the consolidation of clay core and development of construction pore pressures, the effect of permeability of various materials in development of pore pressures both during static as well as dynamic loading. It then leads to determination of zone of sustained plastic strains representing likely plastic deformations.

The Soviet Consultants tested the dam section for two accelerograms with worst response spectra- one for a 6.5 M earthquake originating from Srinagar thrust with a ground acceleration of 0.5 g and the other for 8.0 M earthquake originating from MBF with a ground acceleration of 0.4g. These accelerograms were for the mid height of the canyon. The studies revealed that at the bottom of the canyon, their values would be 1.5 times less. But in the actual analysis, accelerograms with PGA of 0.5g and 0.4g were applied at the base of the dam.

In addition to the non-linear dynamic analysis, the Soviets carried out slope stability analysis using accelerations varying with height of dam obtained as response of dam to applied history of ground motion using FEM analysis.

The Soviet studies suggested a modification in the geometry of the dam section with regard to the core. Instead of an inclined core, a fairly vertical core was required to avoid formation of plastic zones under dynamic load while at the same time ensuring that no excess transfer of load from shell to core occurs under static condition

TABLE 6

SLOPE STABILITY-SOVIET STUDY

Sl. No.	Material Characteristics	Applied loading Earthquake M	PGA	Method of response calculation	Minimum factor of safety U/S Slope	D/S Slope
1.	Shell density 2.28 t/m^3 with top 80m of blasted rock	6.5 8.0	0.5 0.4	by response spectra 10% damping	1.15 1.19	1.11 1.16
2.	Shell density 2.38 t/m^3	6.5 8.0	0.5 0.4	by response spectra 10% damping	1.19 1.215	1.23 1.25
3.	Shell density 2.38 t/m^3	6.5 8.0	0.5 0.4	step-by-step Integration, variable stress dependent damping (18-30%)	1.75 1.93	1.54 1.60

which might lead to hydraulic fracture.

STABILITY ANALYSIS OF SLOPES

Stability analysis of slopes using conventional limit equilibrium approach was also carried out by Soviets. The distinguishing feature of this analysis was that strength of materials was defined by a bilinear law. Also earthquake force was represented by acceleration varying with height. This acceleration was worked out by Finite Element Analysis of dam using recommended accelerograms applied at the base of the dam with the amplitudes reduced by a factor of 1.5 and considering stress dependent material properties.

The results are given in Table 6 on previous page.

DEFENSIVE MEASURES

International practice recommends deployment of various defensive measures to provide extra safety in design of high risk dams, as follows

Allow ample freeboard to allow for settlement, slumping or fault movements.

Use wide transition zones of material not vulnerable to cracking.

Use chimney drains near the central portion of embankment.

provide ample drainage zones to allow for possible flow of water through cracks.

Use wide core zones of plastic materials not vulnerable to cracking.

Use a well-graded filter zone upstream of the core to serve as a crack-stopper.

Provide crest details which will prevent erosion in the event of overtopping.

Flare the embankment core at abutment contacts.

Locate the core to minimize the degree of saturation of materials.

Stabilize slopes around the reservoir rim to prevent slides into the reservoir.

Provide special details if danger of fault movement in foundation exists.

This list is not by any means considered as all-inclusive. However, defensive measures, especially the use of wide filters and transition zones, provide a major contribution to earthquake-resistant design and should be the first consideration by the prudent engineer in arriving at a solution to problems posed by the possibility of earthquake effects.

ASEISMIC DESIGN

Both static and dynamic analysis have proven that slopes of the earth & rockfill dam at Tehri will be safe if and when the design ground motion takes place at the foundation. The dam is being founded on rock which cannot liquefy. The material to be used in dam also has not shown potential for liquefaction. Both horizontal and vertical deformations assessed through rigorous analysis due to the design ground motion are small and are taken care of by liberal freeboard provisions. The analysis shows that stresses in the body of the dam are within permissible limits and that local transient plastic deformation will not be problematic.

The design of Tehri dam has proceeded over the years from conceptual stage to the construction stage step-by-step with more and more refined and accurate practices. The design parameters at each stage are different as indicated in Table 7

The figures of accelerations used for analysis different stages of design look bewilderingly different and incongruous for the uninitiated. When it comes to laymen the confusion caused can be well imagined.

All the apex institutions of the country have been involved in providing information to the Standing Committee (now NCSDP) to assess and recommend Seismic Design Parameters. The Indian as well as Soviet consultants both have independetly assessed the seismogenic influences in Tehri area and have carried out designs as per International State of Art taking into account NCSDP recommendations. Both have concluded that the Tehri dam design is safe and takes care of the expected earthquake forces in the region.

No-doubt, refinement in design of the defensive measures will take place as a result of analysis of information generated till the dam is constructed. The parameters of earthquake of 20 October, 1991 are being assessed. The event has been extensively recorded, perhaps for the first time in the country. It will provide to the

TABLE 7

DESIGN PHILOSOPHY AND STAGES IN DAM DESIGN

Stage	Level	General Consideration	Parameters	Remarks
1	2	3	4	5
Feasibility/ Project Report	Preliminary Definition	Pseudo-Static analysis Using seismic Coefficients from IS code (0.12g)	1)Zonation Map 2)Generalised Response Spectra in code 3)Natural period of structure	Seismic forces are taken in terms of fractions of gravitation acceleration 'g'
Pre-tender for specification	Final section	*Site specific 'seismic' parameter *Evolve effective peak ground acceleration (EPGA) and duration (0.25g) *evolve response spectra *evolve accelerogram as applicable	M for each seismogenic zone &PGA. MCE duration	1)Finite Element Method of analysis for (i) stress evaluation & (ii) displacement (Elastic Linear is adequate) 2)Liquefaction analysis
Construction	Further refinements	Rigorous analysis based on additional data, investigations with due revision of assumptions where needed	recorded accelerograms of events, as applicable	Nonlinear Elasto-visco plastic material behaviours are modelled. Sophisticated FEM Softwares used.

Underlying philosophy - Refine the design as you proceed with the project
advantages:
*Validation of data assumed initially by detailed investigation
*economy of cost.

designers a real design accelerogram for the seismogenic source which caused the earthquake. As a result, it will be posible for anybody to see how safe or how conservative the synthetic accelerogram is, in relation to the recorded one in terms of energy, accelerations,frequency, and duration.

STANDARD CODES OF PRACTICE

INDIAN STANDARD

The relevant Indian Standard which provides for the criteria for earthquake resistant design of structures s IS 1893-1984. This code provides for Pseudo-Static analysis of Embankment Dams though recognising the need for a detailed dynamic analysis for important structures.

The seismic coefficient provided in IS 1893-1984 and in its earlier versions has been based on a classification of the country into five zones in which one may reasonably expect earthquake shocks of more or less same intensity in future. Modified Mercalli Intensity broadly associated with the various zones is V or less, VI, VII, VIII and IX and above for zones I, II, III, IV and V respectively. The design value choosen for a particular structure is obtained by multiplying the basic horizontal seismic coefficient for that zone by an appropriate imp rtance factor which is taken as 3 in case of dams.

Since earthquake force experienced by a structure depends on its own dynamic characteristics in addition to those of the ground motion, the code also provides for response spectrum method in working out the horizontal seismic coefficient.

The code provides for a vertical seismic coefficient to be taken as half of the horizontal seismic coefficients as computed above.

The maximum horizontal seismic coefficient computed using the average accleration spectra provided in code for a damping of 10% relates to a value of 0.24g. Corresponding values of seismic coefficients used in USA vary from 0.10 to 0.15 and that in Japan from 0.15 to 0.25.

Ir espect of earth and rockfill dams, the code recommends carrying out dynamic analysis for final design of important dams in order to estimate deformation due to likely future earthquakes. It is however silent on the detailed procedure to be adopted for the purpose, leaving the choice to the designer.

INTERNATIONAL COMMISSION ON LARGE DAMS (ICOLD) PROVISIONS (BULLETIN 52-1986)

The ICOLD provisions on Dynamic Analysis of Embankment Dams consider the conventional pseudo-

static limit type analysis using a uniform acceleration throughout the dam height, as giving good results, for preliminary designs. However as a step forward, it recommends determination of the modal shapes and response of the dam foundation structure using linearized material properties.

This analysis combined with the earthquake response spectra are to be used to evaluate the applicable set of pseudostatic forces for the limit equilibrium analysis. BIS provisions for pseudo-static analysis of embankment dams using response spectrum methods represent similar analysis, though in a generalized manner.

However the above types of analyses are considered applicable for design of dams in which the material strength is not appreciably affected by the cyclic loading occuring during earthquakes viz. materials such as clays, clayey or dense sand etc. In case of existence of saturated material with liquefaction potential (pore pressure build up) more elaborate analysis incorporating pore-pressure effects are recommended.

The procedures recommended for carrying out these refined analyses essentially vary in terms of material modelling. A simplified procedure development by Seed, Lee and Idriss is recommended wherein the analysis is carried out linearizing the problem after adjusting the modulii in accordance with the secant moduli corresponding to the recorded strain range.

Another alternative which is considered more direct is to incorporate the non-linear soil properties in the analysis and solve, using step-by-step computation, for the deformed shape of the dam.

SUGGESTED IMPROVEMENTS TO PROVISIONS IN INDIAN STANDARDS

Indian standard for aseismic design of dams viz, the IS 1893-1984, 'Criteria for Earthquake Resistant Design of Structures' recommends detailed Dynamic Analysis for important dams but no guidelines for procedures to be adopted are included. In view of a few important dam projects being under construction active consideration, the need for such guidelines is being increasingly felt by Dam Designers.

In recognition of the need to have such guidelines, River Valley Development Division (RVD -9) of Bureau of Indian Standards has taken up the task of preparing such guidelines. The document is to be brought out in three separate volumes covering the following.

(i)   Recommendations for determination of seismic parameters;

(ii) Aseismic Design of Empankment Dams; and

(iii) Aseismic Design of Gravity Dams.

INSTITUTIONAL SUPPORT, EXPERT GROUPS, TECHNICAL DELIBERATIONS AND CONSENSUS

APEX INSTITUTIONS

The subjects of earthquakes and dam design cover a number of disciplines of science and technology. At the Government of India level, the subject geology is being dealt with by Geological Survey of India (GSI); the seismology is dealt with by Indian Meteorological Department (IMD); the National Geophysical Research Institute (NGRI) deals with geophysical issues. The Wadia Institute of Himalayan Geology; the Central Water & Power Research Station (CWPRS) have been dealing with seismological investigations as related to engineering structures; the Department of Earthquake Engineering (DEE) of University of Roorkee (UOR) is the premier institution looking after assessment of seismic design parameters and aseismic design of structures. In addition, the Department of Science and Technology (DST), the Suvery of India (SOI) and the National Remote Sensing Agency (NRSA) provide support and have some specific R&D Projects. The Central Water Commission (CWC) is the apex organisation in water resources sector and has got a strong Designs and Research (D&R) organisation. It provides guidance to all the state D&R organisations and also provides consultancy for specific jobs. Some Indian Institutes of Technology (IITs) & engineering colleges spread over the country also are engaged in consultancy work regarding aseismic design of structures. The Department of Science & Technology (DST) funds R&D projects in Himalayan Seismology and have got a special working group for the purposee. It will thus be seen that India has got full infrastructural capability to deal with seismic evaluation and aseismic design of dams through these Institutions.

The Ministry of Water Resources set up in 1969 a standing Committee of Experts drawn from various institutions mentioned above to advise dam owners about the seismic design parameters to be adopted for design of dams. The Committee has so far advised owners of atleast 125 dams regarding seismic design parameters. The Committee has been recently reconstituted (November, 1991) and is now called as National Committee for Seismic Design Parameters (NCSDP). The designs are carried out by either the State Design Organisations or CWC as per parameters decided by this committee. As mentioined earlier, the designs are carried out as per relevant Indian standards or International Standards. The Bureau of Indian standards (BIS) through their Civil Engineering Division and now through the River Valley Development Division carries out standardisation, revision, or revalidation work periocically. Revision of existing standards for aseismic design of dams is at present on hand to bring it in line with International State-of-Art.

It is in this context that the work done by various Committees and Expert Groups will be described hereafter.

WORKING GROUP

The Department of Science & Technology (DST) constituted a Working Group on the Tehri project in December,1979 to study the impact of Tehri project on environment. The Working Group comprised representatives of University of Roorkee, Survey of India, Botanical Survey of India, Ministry of Forests and Environment, Zoological Survey of India, Planning Commission, IMD, NGRI, WIHG, JNU, CWC, GSI, DST and others. The group besides examining the Environmental Impact of Tehri Project also concerned itself with the Seismic Safety of Dam. Aseismic design of dams is a highly specialised job which has really nothing to do with environment. The group should not have really concerned itself with it. The matter however was extensively debated and an Interim Report was submitted to the Government in May 1980, which identified number of areas for collection of data as required by the DST. The Committee had protracted discussions over six years and a final Report was prepared by all the members in August, 1986. This Report was not acceptable to the Chairman who prepared his own Report and submitted to Government immediately thereafter. The majority report considered that the Tehri Dam can be designed and constructed to withstand the expected earthquake hazards at the site. All the same, it advised the Govarnement for detailed investigations by way of instrumentation for deciding the seismic potential at Tehri Dam site. The Chairman's Report has not given any specific recommendations but has debated on the seismic safety without indicating acceptability or otherwise of the Tehri Dam safety. The Report also highlights need for detailed investigations for developing an appropriaie tectonic model. The Report does highlight the possibility of a high magnitude earthquake in Tehri Dam area.

REPORT OF ENVIRONMENT APPRAISAL COMMITTEE (EAC) FOR RIVER VALLEY PROJECTS

When the project came up for subject clearance before the Ministry of Environment & Forests (MEF), it was referred to the EAC comprising Chairman and representatives of various institutions. The Terms of Reference (TOF.) required the Commitee (i) to scrutinise environmental impacts and management plans, (ii)to suggest safeguards to mitigate adverse impacts, and (iii)to recommend clearance or otherwise for the project. The members comprised representatives of Wild life Institute, National Malaria Eradication Programme, Centre for Earth Sciences, Indian Institute of Public Administration, Andhra University, Bombay Environmental Action Group, Delhi University-Deartment of Botany, Ministry of Environment and Forests, besides some other experts. Although, the terms of reference (TOR) concerned with environmental impact only, the Committee went into the seismic design parameters and the acceptability of the designs for which obviously none of the members were qualified nor were supposed to be so as per TOR. The composition of the Committee also suggests the scope as indicated in the TOR. Nevertheless, the Committee deliberated on these issues expressed by some and felt that the dam design should take care of earthquake of magnitude 8.5 in the Tehri vicinity. The Committee was told by the project authorities that the design of the dam can take care of any such likely earthquake, although, seemingly one of the parameters of design was Magnitude 7. The Committee was also told about the time history, synthetic accelerogram and responses of dam which determine the design. The arguments were perhaps not well appreciated as none in the Committee was equipped with relevant expertise. All the same, the Committee concluded that as the dam was designed for 7 magnitude, clearance of the project was not recommendable.

While other Environmental issues were sorted out by the project, Government decided to refer the seismic safety to a High Level Team of Experts drawn from apex organisations of the country, obviously because a real panel of expert organisations of the country was the right forum for examination of the issues.

HIGH LEVEL COMMITTEE (HLC)

The Mines Department of Government of India set up the High Level Committee (HLC) of Experts in March, 1990 to examine issues relating to seismic safety of Tehri Dam. The task was assigned to Department of Mines presumably because GSI was under their administrative control. The Committee was chaired by Director General, GSI and comprised Member (D&R), CWC; Director, NGRI; Prof. Gaur and Prof. Srivastava as members. After detailed deliberations, the Committee gave an unanimous report certifying the safety of Tehri Dam as designed for an earthquake of 8 plus magnitude in April, 1990.

After submission of the report, one of the members, however, referred the matter to an expert outside India and raised doubts about the unanimous report. The Department of Mines, therefore, asked the HLC to review their Report again. The issues raised were discussed in detail and a review report was made by the HLC in July, 1990. The HLC reiterated its findings made in report of April, 1990. The member who had raised doubts, however, did not agree with the report and hence dissented.

REVIEW BY INTERNATIONAL EXPERT

Meanwhile some other experts in the world were consulted by Non-Government Organisations (NGOs) and Government was requested to re-examine the safety issues. It was decided by the Government to refer the matter to an internationally reputed expert who was residing in India viz. Prof. Jai Krishna. He examined all the previous reports and gave his report to Government in September, 1990. He concurred with the findings of the HLC in the unanimous report as well as the majority report of July, 1990. When this report came up before the Government for final acceptance, again, pressure was mounted by the NGOs opposing the dam, to have a fresh review.

EXPERT GROUP

The Government, therefore, set up yet another Expert Group to critically examine the seismic safety issues of Tehri Dam. The Report was submitted by the Expert Group in July, 1991, recommending acceptance of the HLC Report including recommendations of Prof. Jai Krishna. A member of this Expert Group did not attend the meeting of the Expert Group but gave a note of dissent. The findings of the HLC and Prof. Jai Krishna were finally accepted by Government of India in September, 1991.

AFTERMATH OF EARTHQUAKE OF 20TH OCTOBER, 1991

The unfortunate loss of life and property associated with the earthquake in Uttarkshi region of 20th October, 1991 was utilised by the opponents of the dam to raise a scare amongst the minds of the public. The Tehri Dam has been constructed to a height of about 20.0 m only, in the river bed. It did not suffer any damage. A 45 m high dam Maneri Bhali-I is within 10 km from Uttarkashi and lies near the epicentre. It also did not suffer any damage due to this earthquake. A large number of buildings in the rural area around Uttarkashi collapsed or suffered damge. One bridge has been damaged. Many more bridges in the area are standing after the earthquake. Most of the damaged structures are non-engineered structures or are built with age-old practices. A survey has proved that well engineered structures withstood the earthquake of 20th October, 1991.

CONCLUSIONS

The paper has attempted to bring out in detail as to how dams are designed to withstand earthquakes of great magnitude. It has been shown that Tehri Dam as designed will be able to withstand the worse than worst earthquake that may occur in the vicinity. The paper attempts to bring out the basic cause-effect relationship and the state-of-the-art technology adopted for taking care of seismic safety of large dams like Tehri.

Response of Media and people at large has been predictably more emotional. The dust is settling down and two outstanding issues remain in the minds of Media and Professionals.

(i)   If the dam design is alright, why not make it public and educate the public including, if necessary, holding a public debate?

(ii)   As doubts have been raised about dam design, why not get it reviewed by International experts?

Replies to these questions are as follows :

(i)   As has been brought out earlier, the seismic design parameters adopted for the Tehri Dam and the dam design itself were under scrutiny by Indian experts so far. The authorities have finally accepted that the dam as designed is safe, only in September, 1991. The earthquake of 20th October, 1991 again caused revival of the controversy about seismic safety of Tehri Dam. It is impossible to talk

rationally when emotions are involved. All the same, efforts have been made through lectures, talks and media briefings over the last two months to bring to the notice of public, the adequacy of the design. It will be appreciated that public debate of design aspects can hardly be held because only specifically trained engineers and those practicing the techniques will be able to appreciate the intricacies of design issues as have been brought out in this paper. The public, of course, have to be assured that the design is considered safe by apex organisations of the country and professional bodies like Indian Geotechnical Society.

(ii) India has got an excellent record of dam building and dam safety. At present there are 3,000 large dams in the country. Not a single dam has so far failed due to earthquakes. Also the dam building activity in the country has been mostly self-reliant. There are hardly any countries in the world today who are building as many dams as India is building every year. It is, therefore, considered that Indian experts are second to none in the world in dam designs.

Secondly, the non-linear dynamic analysis which has been carried out for Tehri Dam has been utilised for very few dams in the world. The USA built most of its dams about three decades earlier mostly on the basis of pseudo-static analysis. USSR is a country which has built recently Nurek and Rogun dams, which are more than 300 m in height. They have adopted the latest technolgy for analysis. When Soviets have independently examined the safety of the Tehri Dam, it can be seen that international expertise has already been utilised for this purpose. The dam design is also vetted by the father figure of earthquake engineering in India, namely, Prof. Jai Krishna. It is, therefore, not at all necessary to get the dam design vetted by any international review team. Such proposals indicate a sort of inferiority complex in the minds of concerned lobby. It not only demoralises our own designers, it shows lack of appreciation of the whole matter of Water Resources Development.

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