ISET Journal of Earthquake Technology, Paper No. 387, Vol. 36, No. 1, March 1999, pp. 1-13

FAIL-SAFE LARGE DAMS IN EARTHQUAKE PRONE HIMALAYAN REGION

B.L. Jatana

Former Engineer-in-Chief, Irrigation Department, U.P.

The lofty Himalayas have exercised a unique influence on our existence. As a part of our great Heritage, they have shaped and nurtured our civilisation over the ages, becoming part of our lore, legend and mythology. On material plane, Himalayas have exercised a very powerful and benign influence on our climate. They provide shelter from the cold winds from the North, intercept the moisture-laden winds originating in the Indian Ocean from the South causing precipitation in plains of North India and thus providing water for agriculture, which is the source of livelihood for enormous population in these regions.

Himalayas are the source of large number of streams and mighty rivers, which ensure all-the-year-round availability of water for irrigation, domestic and other needs. These rivers have very large potential for generation of hydropower.

Planned development of Himalayan water resources was started over 150 years ago with the taking up of large canals systems on Ganga and Indus river systems for providing irrigation. In a span of hundred years irrigation facilities were extended to large tracts in Indo-Gangetic plains by construction of new canal networks. These canal systems were based on utilisation of run-of-the-river flows. Since independence, three major multipurpose projects and a number of schemes for hydro power generation have been completed in the region, mostly in the foot hills. More such projects are planned deep in the Himalayas.

The pace of development in Himalayas has, in general, gathered momentum after independence. Because of pressure of population, which has witnessed steep increase, there are increasing demands for creation of necessary infrastructure for human settlement for roads, railways, townships and domestic water supply. Opening up of very remote and inaccessible regions in Himalayas has resulted in increasing urbanisation. Increased levels of human activities have led, in some cases, to deforestation and large scale denudation of vegetation. This has raised concerns about the pollution of environment and damage to Himalayan eco-system. There is organised compaign by environmental groups supported by international organisations, against taking up of large scale developmental projects. As a result, since the last two decades, there is a very perceptible reduction in the pace of water resources development in the region and very few new projects are being taken up.

While the root cause of pressure on the Himalayan eco-system is the sharp increase in population, the ire of the environmentalists is almost solely directed against large water resources projects in Himalayas in general and large dams in particular. Dams and reservoirs, being the biggest man-made structures, have become special targets for their criticism and opposition. Proposals for new major projects in Himalayan terrain are haunted by questions of damage to environment, ecology on account of seismicity, geology, flora and fauna etc.

One of the main grounds for opposition to construction of large dams in Himalayas is high seismicity of the region. Environmentalists' view is that safety of such dams, in event of occurrence of large earthquake, cannot be ensured. To stress their point and to raise public scare, doomsday scenarios are being projected of dam failures during earthquakes. As individuals, as earthquake engineering experts and as dam designers, we know that such concerns are exaggerated and that with modern technology, it is possible to build safe structure in seismically active regions. However, a clear-cut appreciation of true facts in this regard seems to be lacking at policy making levels in the government. In context of building, we have to take an 'in-depth' look at the validity of concerns expressed against building large dams in Himalayas. For this, basically two issues have to be answered:

- Can we afford not to build large storage dams in Himalayas?
- Can 'Fail-safe' dam structures be designed to resist very severe earthquakes of large magnitude.

I propose to discuss these two issues in this lecture.

HIMALAYAS – TECTONIC SETTING AND SEISMICITY

As is well known, origin and evolution of Himalayas is explained as a result of collision of Asian and Indian continents. Northward drifting of Indian plate has caused successive breaking up of its northern front by deep faults and uplift of deformed rocks. These faults – Main Central Thrust (MCT), Main Boundary Fault (MBF) and Himalayan Frontal Fault (HFF) – running all along its length, constitute landmark tectonic features of Himalayas. Continued movement along the faults is stated to have caused wrenching and tearing of Lesser Himalayan terrain by a number of transverse tear faults. Frequent shakings by earthquakes are manifestations of continued movements along faults and ceaseless tectonic activity in the region.

Himalayas constitute, generally, a very active seismic domain. Four Great earthquakes have occurred in the region in the last hundred years at Shillong, Kangra, Bihar-Nepal and Assam. While good deal of knowledge about tectonic processes in Himalayas has been built-up in the last few decades, there is very little recorded data about earthquakes and about Himalayan seismicity in general. There is no consensus amongst the seismologists about the level of seismicity along various segments of Himalayan arc, origins of some past earthquakes, concentrations of seismic activity and likely locale of future earthquakes. The seismicity of the region is generally explained on the basis of various models and hypotheses, which are not universally accepted. As a result, quantification of seismic hazard in Himalayan region is still a matter of individual judgement and at times, prone to overestimation due to fear psychosis.

WATER RESOURCES OF HIMALAYAS

Himalayan rivers account for about 50 % of total utilisable surface water resources of our country. These rivers have enormous potential for generation of hydro power.

1. Utilizable Surface Water Resources

Total available surface water resources of India are assessed around 180 Million hactare meter (Mha.m) which is about 7 % of total water resources of the world. Due to limitation of topography, climate and soil conditions, it is assessed that only about 70 Mha.m can be utilised. Bulk of the utilisable water resources, 104 Mha.m, are from river flows from the great river systems originating from Himalayas-Indus, Ganga and Brahmputra. Currently about 50 % of river flow in Indus and Ganga basins stands utilised. Utilisation of Brahmaputra basin, which is water surplus, is low at about 5 % of utilisable resources (see Table 1).

Table 1: Surface Water Resource of Himalayas in Mha.m

S. No.	River System	Average Annual Flow	Utilizable Flow
1.	Indus Basin (India's share)	7.7	4.6
2.	Ganga Basin (Himalayan rivers only)	42.5	21.9
3.	Brahmaputra Basin including Barak	54.0	2.4
	Total	**104.2**	**28.9**

2. Hydro-Electric Power Potential

As per latest assessment carried out by the Central Electricity Authority during 1980s, the hydro-power potential of India has been assessed at 84,000 MW at 60 % load factor. A total of 845 hydro-electric schemes have been identified in various river basins and annual energy contribution from these schemes is expected to be about 600 Terra Watt hour (TWh). Total hydro-power potential of Himalayan rivers is assessed as 64,653 MW (Table 2), which is 73 % of total assessed hydro-power potential of India. Presently only 7,044 MW of hydro-power potential of Himalayan rivers has been developed/is under development and the balance potential, 57,609 MW, which is 63 % of total assessed potential for the country (Table 3) still remains to be developed.

Table 2: Hydro-Electric Power Potential of Himalayan Rivers

S. No.	River System/Basin	No. of Schemes identified			Potential @ 60 % Load Factor in MW
		Run-of the-River Type	Storage	Total	
1.	**INDUS BASIN:**				
	Indus			47	1205
	Jhelum			22	1632
	Chenab			37	5932
	Ravi			20	1577
	Beas			34	1981
	Sutluj			30	7661
	Sub Total	**167**	**23**	**190**	**19988**
2.	**GANGA BASIN:**				
	Upper Ganga			50	5249
	Upper Yamuna			32	1331
	Lower Yamuna			-	-
	Gomti-Sarda-Ghagra			24	3041
	Gandak-Kosi-Mahananda			3	57
	Lower Ganga			2	67
	Sub Total	**96**	**15**	**111**	**9745**
3.	**BRAHMAPUTRA BASIN:**				
	Dihang-Dibang			20	13615
	Lohit			11	4152
	Subansiri			25	6893
	Upper Brahmaputra			19	789
	Kameng			34	1982
	Kalang (Kopili)			16	510
	Teesta			30	3021
	Lower Brahmaputra			3	50
	Barak & Other Neighbouring Rivers			60	3908
	Sub Total	**150**	**76**	**226**	**34920**
	Grand-Total	**413**	**114**	**527**	**64653**

Table 3: Status of Development of Hydro-Electric Power Potential of Himalayas

S. No.	Basin/River	Total Assessed Power Potential in MW (at 60 % Load Factor)	Power Potential in MW (at 60 % Load Factor)			
			Developed	Under Development	Total	Balance
1.	Indus	19988	2762	1224	3986	16002
2.	Ganga (Rivers Originating from Himalayas)	9745	1310	926	2236	7509
3.	Brahmaputra	34920	399	423	822	34098
	Total	**64653**	**4471**	**2573**	**7044**	**57609**

NEED FOR DEVELOPMENT OF WATER RESOURCES AND CREATON OF STORAGE RESERVOIRS IN HIMALAYAS

1. Future Water Needs

With our population growing annually at a rate of around 2.2 %, it is obvious that demand for water for various purposes would go up. As per estimates made by Shah in 1987, the projected water utilisation in the years, 2000 and 2025, for meeting the needs would be as follows:

Water Use	**Total Projected Water Utilization- All India (Mha.m)**		
	1985	**2000**	**2025**
Irrigation	47.0	63.0	77.0
Domestic & Municipal Supply	1.7	3.0	5.3
Industrial Requirement	1.0	3.0	10.0
Thermal Power Generation	0.3	0.7	1.5
Pisciculture (Fisheries)	--	--	2.8
Forestry	--	--	2.2
Livestock	0.5	0.7	1.2
Miscellaneous	3.5	7.5	10.0
Total	**54.0**	**78.0**	**110.0**

With total surface water resources (utilisable) being 70 Mha.m and another 40 Mha.m from ground water sources (total utilisable ground water resources are assessed as 42 M.ha-m), it means that we would need to utilise practically all utilisable water resources in the country. These estimates are based on projected population of about 1345 million by 2025 A.D. The food grain requirement of this population will be about 365 million tons against the present production of around 190-195 million tons based on annual nutrition requirement of 270 kg/person. The major increase in food production will have to come from irrigated areas. Here the assessment is that irrigated area will have to increase from about 80 Mha.m at present to 110 Mha.m by 2025 A.D.

2. Accelerated Development of Hydro-Power

Despite impressive increase of power-generation capacity during various five year plans, there is over 10 % shortage in power supply in the country. The corresponding shortage in peak power is around 18 %. The total installed generation capacity in India is 85,019 MW (as on 31.3.97) of which about 21,645 MW is from hydro schemes. The bulk of power generation is by thermal power plants; the ratio of thermal-hydro power mix being 75:25 as against desirable optimal mix of 60:40. Additional hydro-power generation is required to be created to correct this imbalance.

Future expansion of thermal power generation capacity has to deal with the problems of pollution due to fly ash, on account of very high ash content of Indian coals in general and economics of hauling coal to distant locations from coal fields in eastern and central India. Also, our meagre foreign exchange earnings would prohibit import of high-grade coal and fossil fuels for energy production. For meeting the peak power needs and to conserve our limited fossil fuel resources and further to avoid unnecessary strain on the transport infrastructure, accelerated development of hydel power has to be accorded the highest priority. Exploitation of huge hydro-power potential available in Himalayas, would, therefore, become inevitable in the coming decades.

3. Need for Storage Dams

It is well known that rainfall in the Indo-Gangetic plains is limited to 32-38 days in the year, almost entirely during the rainy (monsoon) season. Given this situation of the rainfall and consequent pattern of river flows, it is obvious that most of the water cannot be utilised unless a substantial part of it is stored during the monsoon period. This can only be done by construction of storage dams.

Unfortunately, because of topographical limitations, adequate number of storage sites are not available on our rivers. It is estimated that ultimate storage capacity that can be created on our rivers could be of the order of 30 Mha.m, i.e., about 17 % of available surface water resources. In comparison, U.S.A., which has the same water potential as India, has already a storage capacity of 70 Mha.m which is 2.3 times the ultimate storage capacity that can be created in India.

The ultimate storage capacity of reservoirs which can be constructed on rivers originating from Himalayas is about 12 Mha.m. At present, only 1.76 Mha.m of storage capacity has been created on these river systems and storages totaling 0.61 Mha.m capacity are under construction (see Table 4).

Table 4: Live Capacity Storage on Himalayan Rivers in Mm^3 Unit

River System	Ultimate Assessed Storage	Storage Capacity Created	Storages Under Construction	Balance Storage Yet to be Created
Indus	25,615	13,755	2,340	9,520
Ganga (Himalayan rivers only)	21,030	3,105	3,252	14,673
Brahmaputra	74,200	738	485	7,2977
Total	120,845 or 12.08 Mha.m	17,598 or 1.76 Mha.m	6,077 or 0.61 Mha.m	97,170 or 9.72 Mha.m

Major storages created so far are Bhakra and Pont in Indus basin and Ramganga in Ganga basin. Large storage projects under construction are Thein dam (Indus basin) and Tehri & Lakhwar (Ganga basin). No major storage project has been taken up so far in Brahmaputra basin.

For harnessing Himalayan water resources, it is imperative that all feasible storage sites are exploited by construction of dams, large and small, to meet water needs for increased agriculture production, drinking water, industry and for power generation. If we succumb to exaggerated fears about dam building in Himalayas and cap this activity, the scenarios of frequent water scarcity in the region, droughts, inadequate food grain production to feed our population, starvation and even famines have to be reckoned with in not-too-distant future. Given these stakes, building of large dams in Himalayan terrain is a dire necessity.

FUTURE DAM PROJECTS IN HIMALAYAS

Presently, the highest dam in Himalayas, 260 m high Tehri Dam, is under construction. Unfortunately, being the first high dam venture in Himalayas, it has become a point of controversy for the last two decades due to opposition by environmental groups. For tapping water potential, still bigger projects have been identified in India, Nepal and Bhutan, all along the length of Himalayas. Storage dam projects in Nepal and Bhutan for power generation are going to be of direct interest to India, since bulk of power from such projects would be available to India, there being not much demand for electricity within these countries. Table 5 gives details of major dam projects planned in Himalayas.

As per present indications, some of these dam projects in Himachal Pradesh and Uttar Pradesh are likely to be taken up within the next 10-15 years, including Pancheshwar (jointly with Nepal). The four mega projects planned on Brahmaputra (Dibang, Dihang, Subansiri and Lohit), on completion would enable exploitation of 25 % of the huge hydro-power potential of Brahmaputra.

ASSESSMENT OF SEISMIC HAZARD

Major ground of opposition to dams in Himalayan terrain is their perceived inability to withstand large earthquakes. Quantitative assessment of seismic hazard at Himalayan project sites has become a key issue, in context of ongoing controversy about Tehri dam. This needs to be examined in depth.

It is well recognised that Himalayas are seismically very active and have been the locale of four Great earthquakes in a span of last hundred years. There is, however, no consensus among the seismologists regarding assessment of seismicity levels in various segments of Himalayan arc. The occurrence of earthquakes in the past or prediction about likely locale of future earthquakes is based on various tectonic models and hypotheses, about which there is no agreement among seismologists. For instance, prediction of future big earthquake in central region of Himalayas is made by some seismologists based on what is called the hypothesis of 'seismic gap'. According to them, accumulated strain on tectonic features in this region (lying between epicentres of Kangra and Nepal-Bihar earthquakes) is likely to be released with an earthquake of magnitude 8+ within the next hundred years or so. The other point of view is that accumulated strain is getting released through creep and cluster of smaller magnitude seismic episodes which have occurred in the region and that it is not necessary to invoke the prospect of an M 8+ earthquake for the release of the accumulated strain. Many models regarding occurrence of earthquake in Himalayas are based on interrelationship between main Himalayan tectonic features and transverse faults oriented across or obliquely to the Himalayan arc. There are different views about the sources of Shillong and Assam earthquakes.

Table 5: Future Major Storage Dam Projects in Himalayas

Name of Project	Height (m)	Type	Proposed Hydro-Power capacity (MW)	Live Storage Volume (Mm^3)
INDIA				
Jammu & Kashmir				
Hanzel (Marusudar)	252	Rockfill	N.A.	617
Himachal Pradesh				
Kol	163	Embankment	800	210
Uttar Pradesh				
Lakhwar	204	Concrete	300	333
Kishau	253	Concrete	350	1,230
Uttyasu	236	Embankment	1,000	3,200
Kotli Bhel	210	Embankment	1,875	2,600
Pancheshwar (jointly with Nepal)	290	Embankment	6,000	6,640
Arunachal Pradesh, Sikkim & Manipur				
Dibang	270	Embankment	2,350	5,046
Dihang (Passighat)	296	Embankment	20,000	35,500
Subansiri	257	Embankment	4,800	10,015
Lohit (Demwe)	269	Embankment	3,765	4,545
Tipaimukh	163	Embankment	1,500	2,590
Teesta High Dam	250	Rockfill	2,500	7,300
NEPAL				
Kamali (Chisapani)	270	Embankment	10,800	16,200
Kosi High Dam	200	Rockfill	3,300	N.A.
BHUTAN				
Sankosh	265	Rockfill	4,000	6,525

As per present state-of-the-art, the assessment about seismic hazard at a particular project site is generally done on the basis what is termed as deterministic approach. This consists of

- review of historical occurrences of earthquakes in the region
- identification of tectonic features around project area
- establishing seismogenity of tectonic features through micro-earthquake recordings
- paleo-seismological investigations
- assignment of magnitudes of earthquakes for various tectonic lineaments
- assessment of peak ground acceleration using distance-magnitude-acceleration relation or other techniques
- estimation of synthetic accelerograms and response spectra.

All over the world, seismic parameters for design of structures are assessed on the basis of this methodology.

Recently a group of seismologists opposed to Tehri dam construction, have come up with their estimate of seismic hazard at Tehri. This stipulates a magnitude 8+ earthquake occurring on the detachment plane (of Indian Plate subducting under the Asian Plate) at a depth of 14 km right under the seat of dam. Making subjective assumptions regarding various parameters for simulating the ground motion around the Tehri area, a threatening scenario is sought to be projected for dam safety. If this model for occurrences of earthquakes in Himalayas is accepted, then site-specific assessment of seismicity would become irrelevant and the seismic hazard all along 2,500 km length of Himalayas would be the same. This would imply that all dam projects in Himalayas should be designed to withstand M 8+ earthquakes. This, obviously, would be an unacceptable proposition.

The above discussion is with a view to highlight the need for an unbiased assessment of seismic risk at Himalayan dam sites. Without minimising the challenge posed by seismicity, assessment of seismic hazard in Himalayan projects has to be based on those methods and techniques – using both deterministic as well as probabilistic approaches – that are acceptable to profession at large, as is being done in case of dam projects in seismically active regions all over the world. Here, it needs to be pointed out that certain regions in California (U.S.A.) and Japan are perhaps seismically more active, going by the periodicity of occurrences of big earthquakes there, than the Himalayas. Yet, the assessment of seismic hazard by experts in these countries is not based on any panic, unlike what seems to be the case in our country.

DESIGN OF DAMS – STATE-OF-THE-ART

To allay any genuine fears of the public at large about the dam safety in Himalayas, there is a need to apprise our people about the state-of-the-art for dam building. What is being side-lined in the debate on dams is the fact of availability of modern, proven technology for building fail-safe structures in highly seismic regions. In this context, it is necessary to state some important facts:

- With the availability of computers and development of analytical methods, it is now possible to study and analyse the behaviour of structures with high degree of confidence.
- Use of mathematical models has enabled the designers to have greater assurance of safety. Mathematical simulation is now a standard tool for dam design. With this technique, the effect of changing material properties can be accounted for and stress distribution, deformation and cracking in dams can be studied.
- Great advances have been made in Soil Mechanics and in material testing techniques for testing dynamic properties of materials. Cracking problems in dams can now be studied using physical models (centrifuge etc.).
- Development of large-size construction equipment has improved the economics of dam building, thus ensuring high quality and faster construction.
- Techniques have been evolved to study the behaviour of dam and other structures during earthquakes. Modern dam designs for seismic regions are done on the basis of dynamic analyses based on ground acceleration time histories for the maximum earthquake assessed for a particular location.
- It is now possible to continuously monitor the safety of dam structures by measurement of all important parameters – stresses, deformation, seepage, etc., through instrumentation – during the operation.
- For dams in seismic regions, a number of defensive measures are invariably incorporated in the design, for added assurance of safety during a seismic event.

Two of the world's tallest dam structures that have been successfully built are in highly seismic regions of the world - Nurek (300 m) and Rogun (335 m) in central Asia. Large dam projects have been built, with novel features in some cases, in regions of very high seismicity similar to Himalayas, in central and south America (see Table 6).

The soundness of modern dam building technology is further evident from the fact that many dams in seismic regions have successfully withstood large earthquakes without any substantial damage. Some outstanding examples are 60 m high La-Villita dam and 146 m high El Infiernillo dam in Mexico which have withstood five earthquakes of upto magnitude 8.1 without suffering damage of any serious consequence. What needs to be appreciated here is that no dam structure designed and constructed on the basis of modern technology has ever failed as a result of earthquake shaking. A case in point is the example of Maneri Bhali project in our country. This project located within 10 km of epicentre of 1991

Uttarkashi earthquake suffered no damage whereas buildings and bridges around Uttarkashi had suffered serious damages.

FAIL-SAFE DAM DESIGNS FOR SEISMIC REGIONS

The choice of type of dam at a particular location – gravity or embankment type and their variants – is ordinarily dictated by foundation condition, topography, material availability, technical considerations such as spillway arrangement, layout of appurtenant structures, diversion arrangement, etc., and costs. These considerations would govern the choice in case of dams in seismic areas too. Both types of dams can be adequately designed to withstand seismic activity.

However, from point of view of safety in earthquake zones, embankment dams – earth-cum-rockfill or rockfill are favoured by designers due to their large inertia, flexibility and high damping in absorbing the earthquake energy and also because of their inherent ability to undergo large strains without cracking. This type of design has been adopted for almost all the high dams in seismic regions of the world. Most of large dams planned in Himalayas are embankment type – earth-cum-rockfill or rockfill dams with impervious clay cores.

1. Seismic Design of Embankment Dam – Some Important Aspects

Some important aspects of earthquake-resistant embankment dam design that receive particular attention from the designers are

- evaluation of seismic stability
- incorporation of defensive design measures.

1.1 Seismic Stability Evaluation:

Evaluation of seismic stability is done taking into account the following:

- Potential for earthquake-induced generation and dissipation of pore water pressure in the embankment and foundation.
- Embankment slope stability for earthquake loading condition.
- Potential for earthquake-induced large deformation in the embankment.
- Identification of key aspects and parameters affecting the seismic behaviour of the dam, on which attention must be focussed in the design phase of the project.

Some key aspects affecting seismic stability of a dam, which are the focus of attention during design phase are:

- relative density of rockfill and core material
- permeability of the rockfill
- potential for development of pore water pressure during earthquake shaking and potential for dissipation and redistribution of pore pressure during the following shaking
- pre-earthquake static state-of-stress (affects potential for pore pressure development, strength characteristics of material and potential for deformation)
- dynamic response estimate

1.2 Defensive Design Measures

Designers all over the world are unanimous about the need to incorporate some defensive measures in design to assure safety of structure against strong earthquake shaking. These are :

Liberal Freeboard

Liberal provision is made to provide for crest settlement during a strong earthquake. Crest settlement of 1 to 2 % of dam height is considered as acceptable performance under severe earthquake shaking.

Increase in Crest width and Flattening of Dam Slopes near Crest

To safeguard against local sliding of material due to high acceleration, some designers go for wider dam crest and flattening of dam slope near the crest.

Rockfill Surcharge

Rockfill surcharge is provided on dam slopes (in case of gravel-fill dam shells), to prevent sliding during an earthquake.

Compaction of Dam Shell Materials

The shell materials are compacted to high density for prevention of dynamic pore pressure in the upstream dam shell. This constitutes a major defensive measure against earthquake action. Very high shell material densities of 2.25 t/m^3 and 2.36 t/m^3 have been specified for Nurek and Tehri dams.

Self-Healing Filters

For sealing of any cracks in dam core due to seismic activity, designs now envisage a conservatively designed downstream filter and a filter upstream, which would move into core in event of cracking. In addition, a conservative drainage system is provided downstream to take any concentrated leak that may occur due to cracking of core.

The size of filters and drain is designed taking into account possible movements due to earthquake as well as normal deformation of dam so that the size is not necessarily limited to dimensions calculated from the flow conditions.

Prevention of Cracking due to Differential Settlement

For prevention of cracking due to differential settlement the earlier design criteria stipulated practically the reshaping of the entire abutment in case of dams in narrow valleys. This required extensive excavation, making embankment dam option a costly alternative for such situations. Current design practice which has successfully proved itself in case of very high dams in narrow valleys is

- to provide at abutment contact, a zone of core material compacted at higher water content or using more plastic material in this zone
- compaction of bottom portion of impervious core with relatively lower water content to high density and compaction of upper portion with higher water content to make it flexible and capable of taking imposed strains, without cracking

Adopting these measures, high embankment dams (Chicoasen, Guavio, Chivor – 260 to 240 m high) have been built with very steep canyon walls and with abrupt change of slope, without provoking any cracking at the dam crest. This measure is of direct interest for design of Tehri dam and future high dams in Himalayas that are proposed in narrow valleys, both in context of ensuring safety and economical construction.

Provision of Galleries below Dam Seat and Abutments for Foundation Grouting and Drainage

Such galleries have been provided on a number of dams, for grouting of dam foundations and weak strata, in dam abutments for high dams in former U.S.S.R., Japan, Mexico and Columbia. A further 'rationale' for such galleries is monitoring of dam's performance during operation. Most of the recent dams have this feature.

Inspection Galleries and Shafts in Dam Core

A rather bold and usual feature of high dams constructed in central Asia, e.g., Nurek, Rogun and Charvak dams, is the provision of inspection galleries and shafts running along most vital part of the dam, i.e., its core, to constantly monitor dam performance and, in event of any distress, to take prompt remedical action. Such galleries have also been provided at Aswan High dam and one such gallery is proposed in the core of Tehri dam at mid-height.

Most of the defensive design measures discussed above have been incorporated in the Tehri dam which is presently under construction. Future dams in Himalayas are expected to be designed on the basis of most conservative parameters incorporating all such measures to ensure maximum level of safety under earthquake occurrences.

2. New Design Option for Himalayan Dams – Concrete Faced Rockfill Dam (CFRD)

This type of dam design is becoming increasingly popular in recent years. A number of such dams have been built in Brazil, Columbia, Australia and, nearer home, in Sri Lanka, Malayasia and Thailand. In this type of dam design, the reinforced concrete slab on the upstream face constitutes the impervious membrane, with main dam body consisting of exclusively rockfill. Structurally this design is different from the conventional earth core rockfill dam. In case of CFR dam, the water thrust acts externally on reinforced concrets face, contributing to increasing the stiffness and stability of the dam. As a result, much steeper dam slopes (1:1.4 to 1.6) are attainable in case of such dams, making this design a least cost option in may situations.

The successful performance of this type of dam depends on

- material quality
- degree of compaction of rockfill
- successful construction of face and toe slab, and water-tightness of their various joints.

Detailed guidelines on design and construction of CFR dams are now available. Based on these guidelines, modern CFR dams have been constructed all over the globe and are giving very satisfactory performances.

With regard to behaviour of this type of dam under strong earthquake motion, the design is considered inherently safe by many designers against potential seismic damage on following counts:

- The entire embankment in case of CFR design is dry and hence earthquake shaking cannot cause pore-water pressure build-up and strength degradation.
- Unlike a conventional earth core rockfill dam, water pressure acts externally on the upstream face and hence, entire rockfill mass acts to provide stability.

Many researchers (Seed, Gazetas, Bureau et.al.) have carried out extensive analytical studies on the anticipated response and performance of modern CFR dam, thus bringing out some important aspects of behaviour of CFR dam under seismic excitation. Seed has also recommended slopes for CFR dams for earthquakes of upto 8.5 magnitude in seismic areas. On the basis of these studies, the conclusion is that crest settlements of modern CFR dams would not exceed 1 % or 2 % of dam height under the most severe earthquake. According to Sherard and Cooke, this would be an acceptable performance, since a sudden crest settlement of 0.01H (H is the dam height) will not threaten the safety of a modern CFRD.

Theoretical response analyses carried out for a CFRD by Gazetas, to study the 3D stiffening effect due to presence of rigid abuments, indicate the possibility of sharp increase in acceleration in near-crest portion of the dam, which increases as canyon becomes narrower. This may result in deformation problems-profile distortion, cracking etc. To minimise such problems, a number of defensive measures-ample freeboard, widening of dam crest, flattening of slopes have been suggested. No corroboration of such conclusions is possible from actual experience, since so far, no CFR dam has been subjected to any substantial ground shaking. It is, however, obvious that defensive measures can be inbuilt into CFRD design to withstand the most severe earthquake shaking, taking care of any possible adverse impact.

The popularity of CFR dam is bound to increase in the coming years. At Himalayan dam sites, where impervious material for the clay core (required for a conventional rockfill dam design) may not be always available at nearby locations, such design would offer the most economical solution. Dam designers have, therefore to think of this design for many of the future dam sites in Himalayas. To begin with, this design can be adopted for diversion and storage dams of moderate height (say upto 100 m). As more experience builds up, this design can be considered even for higher dams. Cooke advocates this design concept for dams of even upto 250 m height. Our national earthquake engineering research centre at Roorkee can also focus more attention on applied research on CFRD design to provide the needed inputs to dam designers in future.

NEED FOR PUBLIC AWARENESS ABOUT VITAL ROLE OF DAMS AND DAM SAFETY IN HIMALAYAS

In view of the frightening increase in our population, development of our water resources in Himalayas to meet our needs, is going to be an over-riding priority in future. The relentless propaganda by environmentalists about large dams and their safety in Himalayan earthquake prone region has created a fear psychosis in public mind. What is particularly annoying and unacceptable is the intolerable one-sidedness of dam opponents who refuse to accept the enormous, quantifiable, contribution made by dam projects to growth of national economy in last many decades. Dam projects in Himalayas are sought to be opposed by using what may be called 'seismic whip' by painting doomsday scenarios of dam failures and consequent colossal damages, with absolutely no thought to stakes involved in abandoning the dam building in Himalayas.

The vital role which dams are going to play in future makes it incumbent that the nation should be made aware about the true picture in this regard. There is, therefore, an immediate need to launch a public awareness compaign and to project a total, unbiased picture about the issues involved. Such compaign should focus on

- huge benefits which have accrued from water resources projects so far and the role which dams have played in growth of Indian economy
- our future needs for water and power and how these can be met only by exploitation of Himalayan water resources
- true picture about the seismic risk in Himalayas
- availability of technology to design and construct fail-safe dams in Himalayas
- our expertise and record of successful construction of mega dam projects in complex geological terrain of Himalayas
- safety record of successful performance of dams and major structures in highly seismic regions of the world
- continuing improvements being made in earthquake engineering technology for building safe structures in seismicity prone areas
- environmental safeguards which are currently 'in-built' as part of dam building programmes, to minimise adverse impact of dam building.

The Indian Society of Earthquake Technology can play a pivotal role in countering misinformation about the role of dams in general and in dispelling any genuine doubts in public mind about the safety of such structures in Himalayas. We owe it to our future generations to leave a legacy, which ensures a better quality of life. Full development of Himalayan water resources alone holds the promise and power to transform for the better, lives of millions of our people. This is possible only by creation of storages, wherever these are technically feasible. ISET can organise regional seminars and symposia with participation of public persons and media, to educate public on this issue of vital importance which would determine the quality of our existence in future. I would urge each member of this learned Society to actively take up this cause. Let this be a sacred mission for all of us, who are involved in one way or the other, with this challenging task.

Table 6: Design Features of Some High Dams in Highly Seismic Regions of the World

S.No.	Name of Dam	Type	Maximum Height (m)	Geometry		Seismic Environment & Design Seismic Parameters	Special Features of Design
				U/s Slope	D/s Slope		
1.	Nurek Dam, Tadjikstan (formerly U.S.S.R.) – (1979-80)	Earth and Gravel Fill	300	1:2.25	1:2.0	High seismicity earthquake intensity 9; Design tested for 1971 San Fernando earthquake accelerogram with peak acceleration of 1.1g.	• Material densities Shell: 2.24-2.30 t/m^3 Core: 2.05-2.15 t/m^3 • Crest width - 20 m • Rock fill surcharge on dam slopes 20 to 40 m on u/s 25 to 10 m on d/s • Provision of antiseismic collors in top 80 m u/s zone and top 20 m d/s zone for absorbing and uniform distribution of shear stresses during earthquake
2.	Rogun Dam, Tadjikstan (formerly U.S.S.R.) - under construction	Earth and Gravel Fill	335	1:2.4	1:2.0	High seismicity (Intensity 9); Adopted maximum design crest acceleration - 0.35g; Design tested for 1976 San Fernando earthquake accelerogram.	▪ Two inspection galleries in dam core ▪ Material densities: Shell to be compacted to high density to prevent development of dynamic pore pressures ▪ 3 inspection galleries in dam for monitoring behaviour of dam core ▪ A hydraulic curtain for preventing chemical removal of rock salt layer existing below dam seat and probable subsequent foundation deformation
3.	La Honda Dam Venezuela	Embankment	130	-	-	Highly seismic region; Active fault lies 20 km from site; capable of generating 8.25 M earthquake.	Dam designed to tolerate shear displacement in foundation rock of 1 m horizontally and 0.75 m vertically. Features include • a system of thick filters & drains at base of dam • a wide chimney drain with protective filters • a 13 m freeboard above normal maximum operation pool level
4.	Guavio Dam, Columbia - (1986)	Zoned Rockfill	240	1:2.00	1:1.8	Highly seismic region; seismic design coefficient taken as 0.23g.	• Grouting & drainage galleries in core seat area & along abutments • 10 m freeboard over FRL
5.	Puelo Viejo, Guatemala - (1985)	Rockfill	134	1:2.00	1:1.75	Most severe seismicity; Active Fault at project site passes through power tunnel very close to site; Design acceleration 0.68 g; duration 60 seconds.	• Wide surface drainage zone on upstream slope

Table 6 (cont.): Design Features of Some High Dams in Highly Seismic Regions of the World

S.No.	Name of Dam	Type	Maximum Height (m)	Geometry		Seismic Environment & Design Seismic Parameter	Special Features of Design
				U/s Slope	D/s Slope		
6.	Chicoasen, Mexico - (1979)	Rockfill	264	1:2.00	1:2.20	Moderate seismicity area.	• Crest width - 25 m • Concrete core block
7.	Bourca Dam Costa Rica - (Feasibility Design:1980)	Earth and Gravel Fill	302	1:2.25	1:2.00	High seismicity site in the proximity of several major plate boundaries; Three potential earthquake sources at site, subduction zone 30 km below dam site & range fault at 8 km, capable of 8.5 M & 7.5 M earthquakes with PGA of 0.6 and 0.75 g respectively.	▪ 20 m wide crest ▪ Wide core ▪ Freeboard of 12 m above FSL
8.	Kamali (Chisapani), Nepal - (Final Feasibility: 1989)	Earth and Gravel Fill	270	1:2.25	1:1.90	Location in high seismicity Himalayan terrain; Dam location is ▪ 25 km from main boundary thrust, in the north ▪ 5 km from Himalayan frontal fault to the south ▪ seismic design parameters adopted are MBT 8.0 M, 0.57 g and 6.5 M, 0.70 g respectively	▪ 15 m crest width ▪ 30 m freeboard above FSL ▪ Drainage layers in the upstream dam shell completely free draining in top quarter of dam
9.	San Roque, Philippines - (Designed: 1979)	Earth and Gravel Fill	206	1:2.00	1:2.00	Highly seismic site close to Philippines fault; Design PGA is 0.6g	▪ 11 m wide crest
10.	Tehri, India (under construction)	Earth and Gravel Fill	260	1:2.50	1:2.00	▪ Location is in seismically active Himalayan terrain ▪ Design seismic parameters MCE PGA MBT 8.0 M 0.5 g Srinagar Thrust 6.5 M 0.4 g ▪ Design tested for Gazli earthquake accelerogram with PGA of 1.1g (vertical) & 0.72g (horizontal) ▪ Design adequate for M8 (+) earthquake with PGA of 1.1 g and 60 s duration	▪ 20 m wide crest, widened to 25 m near abutments. ▪ 9.5 m freeboard ▪ Shell material density - 2.36-2.38 t/m^3 ▪ Conservatively designed filters ▪ Inspection galleries in dam core for performance monitoring ▪ Flatter dam slopes