Considerations in the Design and Construction of Fill Dams in Earthquake Zones

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Abstract

Design of Fill dams require several basic considerations especially in earthquake affected regions. Some important considerations for the Fill dams in earthquake affected locations have been discused in the present paper.

Introduction

In the design of Fill dams generally, there are several basic requirements, not all of which are always recognized. Obviously the first consideration should be the types of materials available at site; the next is the optimum use of available materials to ensure a safe structure and economy which is linked to the two above considerations. These considerations apply equally well when designing Fill dams in earthquake affected zones; except besides these general considerations, there are some considerations which are especially important in Fill dams in earthquake affected locations. This paper seeks to draw the attention of Fill Dam Designers to these special considerations. The importance increases in these considerations more with high and very high dams, as also dams with a potential to create a disaster in case of failure, despite height considerations.

Special Considerations in the Design of Fill Dams in Earthquake affected Zones

The special considerations pertain to aspects such as the selection of fill materials and their zoning, the thickness of Core, the design of Filter and Transition Zones, the necessity in special cases, for a thick enough Rip Rap Zone, the Free-Board, the width at top of the dam. This is governed by the necessity to have effective protection at the top of the dam. Equally deserving attention in the design are foundation conditions (example; sand in the foundation), possible fault movement in case a fault crosses the dam and possibility of concentrated leaks through the Fill body or at the Fill-abutment interfaces.

Stability Analysis

Stability studies should also include evaluation of safety of the dam, under earthquake and static forces, along a horizontal plane of the contact of Fill with the foundation or a horizontal plane just above through the Fill or a horizontal plane just below the Fill, in the foundation.

Seismic Stability Analysis: With regard to methods of seismic design and analysis, the earlier methodology of following pseudo-static approach with regard to earthquake forces, has undergone a sea change with great advances made in the areas of estimation of seismic hazard, soil dynamics and methods of dynamic response analysis in the last four decades. Seismic stability of dam is currently determined on the basis of dynamic analysis using site-specific Response spectra / Accelerogram. Dynamic Analysis for assessing the seismic stability of high dams has, by now, become almost mandatory, going by the present trend.

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Choice of Core Material

Concentrated leaks through the core of the embankment can develop after a strong earthquake has shaken the dam, if this factor has not been taken care of in the design and construction of dam. A paper by the Late J. L. Sherard (1967) of a classifications of materials for the core of the dam on the basis of resistance to concentrated leaks and erosion can be referred.

It would be seen that the parameters that guide the classification are the plasticity of fine fraction and the size and gradation of the coarse particles present in the core material.

Zoning of the Embankment

This consideration is important in all cases; in the case of Fill dams, in earthquake affected areas, it is of paramount importance. Following the shaking action of the earthquake, a Fill dam can develop cracks arising from various causes like differential settlement and deformation along Faults. The rigid structures like galleries and conduits etc, within the body of Fill may crack and cause cracking in the adjoining Fill in the core. Zoning, which other than core, has its components in the form of Filter(s)/Transition zones and Shells, is the only form of defense and assurance against failure due to concentrated leaks.

Core Zone

The core need normally be of the order of 50% of the water head, except at the abutment interfaces, especially against rock abutments, it is advisable, necessary to increase the core-abutment contact area to at least double the normal core zone thickness. It is advisable to use a highly plastic core material in such contact areas, with water content one or two percent higher than optimum with a view to improving the ability of core material to deform as necessary and not crack. Most cracking in fill dam cores has been reported from instances where the moisture in the core material at the time of placement was on higher side of the optimum.

Filters

It is advisable to assume in the design that even Low dams may be on strong (rock) foundations, in earthquake zones, could develop concentrated leaks. Hence even homogenous Fill dams, of low heights must have at least one suitable filter adjoining the core, on the upstream as well as downstream to full height of the dam; except in the case of upstream filter, depending on the height of dam, the quality of materials used, the quality of construction and quality control input, the upstream filter may commence somewhat higher than the level of Fill-foundation contact.

A wide enough filter zone is an inviolable rule in earthquake areas, the filter / transition zone must, in the least, be wide enough to permit compaction by vibrating rollers, to ensure a high enough Relative Density (RD), it must be 0.8 and in the case of very high dams, it needs to be even higher. The width of the filter should be comfortably higher than the anticipated deformation, in case of dams sitting on faults or close to faults, considered active. The provision of Filter / Transition should be conservative and generous.

Often the practice is to use Sub-Zones in the Filter; Fine filter adjoining the Core and a Course Filter, interspersed between the fine filter and the adjoining rock fill. The good grading together with large size particles, imparts self-healing ability to the filter Zone, even when with high flows through cracks in the core material. With sub-zoned separate layering of the Filter, there can be a danger, arising from the following: With a crack in the core following seismic shock, the resulting concentrated leak can find its way bye-passing the coarse sub-zone; this can conceivably lead to erosion of fine filter itself, if conditions permit. However, there can be apprehensions about serious segregation during placement of a wide-band single filter, impairing its internal stability and compromising essential filter criteria. Such apprehensions have perhaps resulted in many designers favoring a multi-layered filter; also with a multi-layered filter there is the advantage of better drain-ability of coarse layer of the filter. In either case, single or multi-layered filter, the adequacy of the width of the filter to withstand the expected order of deformation must be ensured.

In this context, it becomes advisable to slush grout the foundation, if it is a joined rock, much in the same manner as is mandatory for the core-foundation rock interface. It seems also advisable to extend this slush grout treatment in the foundation rock well enough into the shell zone – foundation rock contact.

There are many criteria used for ensuring compatibility between the filter and protected material. In case of core material other than fine silts and clays, the one over-riding requirement, irrespective of any other, is that D_{15} of Filter material shall not exceed preferable four times (and not in any case 5 times) the d85 of the protected material. So long as this requirement is met, there can be no migration of protected material into or through the Filter.

Even if a crack results in the core of dam due to earthquake, the core material in the first instance will be adequately erosion – resistant and self-healing; in addition any flow from the reservoir into the crack will be considerably moderated by the upstream filter, whose permeability is low enough for this purpose. At the downstream filter again, there would be further reduction in the quantum and force with which the flow through the crack emanates across the downstream filter; and when this greatly moderated flow enters the downstream shell zone, it will just flow out harmlessly. In case of very high dams in areas of severe seismicity, the Rip Rap compacted to very density should he made adequately thick (10m or more) and care must be taken to ensure that the Rip Rap material :

- Does not contain more than 10% of fines (no. 4 Material),
- The Fines, if present, are not cohesive
- The fines do not have any cementitious material.

Top of Dam

All the considerations in respect of zoning of the Embankment apply with increased relevance and importance at the top of Embankment. The reasons are that

- The structure encounters the highest force at the time of earthquake.
- In the top part of the dam, for about 15($\pm$)m below the top, the minor principal stress on a plane normal to axis of the dam is close to nil, often enough, even tensile and therefore, easily susceptible to hydraulic fracturing.
- Susceptibility to slumping leading to reduction or even elimination of the normally considered Free-board.

The last factor, therefore, calls for increase in free board provision, the first two factors call for special attention to zoning, the width of the zones and choice of materials for the zones and the necessity to extend the zoning practically right to top of dam. These also necessitate increased top width, compared to requirement in areas free from earthquake effects. The higher the dam and the higher the expected seismic intensity, the more is the need for the greatest conservatism.

Compaction

Much more importantly than for dams in non-seismic areas, all the zones in the Fill dam in a seismically active area need to be compacted to a very high degree. This would ensure the minimum deformation to mobilize the required shear resistance; also the total settlement of the dam during construction and in the post construction period will be low. The lower the total settlement, the less will be the proneness for differential settlement.

3. The above discussions lead to the conclusion that in an earthquake area, a properly designed and constructed rock-fill type of dam would be preferable, unless the foundation conditions and non-availability of suitable material for rock fill dam otherwise dictate.

4. The following paragraphs illustrate the application of considerations discussed above in the design and construction of some recent Rockfill Dams completed or under construction, across rivers originating in Himalayas. Himalayas, as is well-known, constitute region of high seismic activity, all along its 2500 km arc; this region has been the locale of four great earthquakes of Magnitude 8(+), which have occurred in the last 110 years, at Shillong (1896), Kangra (1905), North Bihar (1934) and Assam (1950).

Two large Fill dams, of very high dam category were taken up in 1970s.These are India's highest dam – the 252m high Gravel / Rockfill dam at Tehri across river Bhagirathi (Ganga), Kol Dam across Satluj – 163 m high. The mega dam at Tehri, since it was conceived in 1960s has been constantly in the eye of storm; the objection of Environmental Groups was on various grounds mainly safety in the event of occurrence of severe earthquake. This necessitated several appraisals of the dam design; the adequacy of design for withstanding very large earthquake safely, was demonstrated more than once. In the event the Designers have adopted most conservative criteria and State-of-the-Art design methodology, fully taking into account the global experience of very high dams constructed world-wide, in seismically active regions.

This paper, therefore, discusses in greater detail the design, construction and monitoring of the performance of the Tehri Dam.

Tehri Dam

The dam is constructed across river Bhagirathi, 1.5 km. downstream of its confluence with river Bhilangana, near Tehri town (now submerged under the reservoir created behind the dam) in Uttarkashi district of Uttarakhand. The Tehri reservoir commenced storage towards the end of 2005; power generation started in 2006; the reservoir is expected to reach full level in 2009.

Geology of Dam site

The rock formations at the dam site are phyllites of Chandpur series – forming uninterrupted sequence of phyllites having variable proportions of argillaceous and arenaceous materials. These have been classified as Phyllites quartzite, thinly bedded (PQT), Phyllitic Quartzite – massive (PQM), quartzitic phyllites (QP) and sheared Phyllites (SP). PQM and PQT are more competent rocks, geomechanically grouped into grade – I phyllites, while QP and SP have been considered grade II and grade, in decreasing order of rock strength. These phyllites are traversed by numerous major and minor shears. The major shears in the area have been classified as D (Diagonal) and L (Longitudinal) shears on the basis of their geometric relationship with the bedding and foliation. The geometry, orientation, frequency and interplay of D and L shears have considerably affected the geomechanical behaviour of the rockmass and provided scope for dividing the area into different tectonic blocks. Tehri dam is seated on a single such tectonic block.

Seismicity

The Tehri dam site is in seismically active area and falls in Zone IV of seismic Zoning Map of India. The Tehri area falls between two main regional tectonic features of Himalayas – Main Boundary Fault (MBF) on the South-Western Side and Main Central Thrust (MCT) on the north-eastern side. Besides there are some other tectonic features in the vicinity of dam site, the important among them being the Srinagar. Thrust, this has strike continuation of over

100 km and lies at a distance of 6 km towards east from the dam site. About 80 earthquakes have been recorded in the past years, with their epicenters falling within 320 km radius from Tehri dam site, the nearest epicenter was located 35-40 km north-east of dam site. Most of these earthquakes had a magnitude of 5 to 7 on Richter scale.

Design of Tehri Dam

Type of Dam

On the basis of detailed investigations done and design studies, carried out, an embankment Dam-Gravel/Rockfill with an earth Core, was considered appropriate from considerations of safety, geology, seism city, available materials and project economy. This type of dam was particularly favored, keeping in view the well-recognized concept that embankment dams-Gravel/Rockfill, because of their large inertia, flexibility and high damping in absorbing earthquake energy and because of their inherent ability to undergo large strains are generally considered a better design option in areas prone to high seismic activity.

Dam Geometry & Layout

The dam, as completed, is a Gravel cum Rock fill structure with slightly inclined earth core. It is 252m high above the deepest foundation. It has a zoned dam section, with an upstream slope of 2.5 (H) : 1 (V), with 10m wide beam at e/n. 681.0 m and downstream slope of 2.0(H) : 1.0 (V). Top e/n. is 839.50 m; crest width is 25.5 m, flared to 30.5 m near the abutments.

In the initial design, to reduce differential settlement and tendency of transverse cracking, dam axis curved towards upstream (curvature of about 3000m) was thought of, to create additional stability through arching effect. A linear 3D FEM analysis carried out for both the straight as well as curved configuration for the dam did not indicate any significant difference in dam stability. The dam layout with straight line axis was adopted.

Upstream shell heel portion of the dam was designed to serve as upstream Coffer dam, for construction.

Zoning of Dam section

Core

Shape of core

After considering both vertical and sloping profile, sloping core with a maximum width of about 0.3 H (where H is the maximum water head) was initially adopted, with core slope of 0.6:1 on upstream and 0.3:1 downstream both sloping upstream, the core width at dam top being 10m, increasing to 15m near abutments. Subsequently to reduce the hydraulic gradient, the width of the core at the foundation level was increased to 0.5 H. This was done by changing the upstream slope of the core from 0.5:1 to 1:1 from around mid-height downwards. The inclined core profile was adopted on account of its better resistance to transverse cracking.

Dynamic analysis carried out, with inclined core profile indicated formation of plastic zones on upstream face of dam, attributed to the sloping profile of core. Optimization studies were carried out to determine the most optimal geometry of core which would lead neither to formation of plastic zone under dynamic load nor to excessive transfer of stress from core to shell, leading to possibility of hydraulic fracture. The optimized shape of core, as executed is of near-vertical shape.

Core Material

The source of material for core available for Tehri was the Koti Terrace deposit, comprising of medium plasticity silty clay (CL), followed by sandy gravels down to bed rock, with average Plasticity Index of 11%. A major issue of design was whether to use naturally available material from Koti or to blend it with coarse material, to improve its shear strength parameters. Extensive laboratory investigations/tests were carried out to determine the erodibility and dispersivity of

Koti material, which confirmed its erosion resistance and its non dispersive characteristic.

The preference was for core of gravelly material particularly for core of very high dams, Designers, on advice of Specialists and Consultant, opted for core material, of specified gradation, obtained by blending in suitable proportion finer material from Koti borrow area with coarse material underlying it or coarse material from Dobata area.

Blending resulted in a plastic material which at the same time has high shear strength and low consolidation characteristics. It was specified that fine fraction (£ 0.075) would not he less than 20% with clay content (£ 0.002 mm) not less than 7%. The maximum particle size is 200 mm.

To reduce the effect of abutment – core interaction, more plastic material in a zone of 2-3m thickness normal to abutment, with clay (£ 0.002m) not less than 10% and silt (0.075mm) not less than 40% and maximum particle size – 63 mm was specified.

Filter / Transition Zones

Filter/Transition zones were initially proposed both upstream and downstream of clay core. The filter zones comprised of a uniform coarse gravel drain encompassed on either side by a uniform medium to coarse sand. Between the coarse sand filter layer and the core, a layer of uniform sand was proposed. The four layer filter zone was designed on the basis of Terazaghi criteria and its variant USBR criteria.

In 1970s & 1980s, studies relating to a number of dams built in England, Norway, U.S.A. Canada and Sweden brought out that these dams had shown distress due to piping even when their filters would satisfy the usual Terazaghi criteria. More conservative criteria were spelt out for design of filters by Sherard (1984), and Vaughan (1982), For Tehri dam, too, considering both analytical and experimental approaches, a very conservative design was finally adopted.

The criterion for selection of gradations of first layer of filter adopted was that it should be capable of successfully blocking the flocculated material of the core. Criteria for the second layer of filter gradation in contact with first layer was that it should be such that it satisfies the Terazaghi Criteria as well as it is coarse enough that it can act as drain. The first filter layer designed on these criteria was well graded sand layer with silt content of 5% having all fractions-fine to coarse sand with maximum particle size of 4.75 mm. The second filter layer was a sandy gravel layer with 20% sand and maximum particle size of 80 mm. Laboratory tests for testing the gradations of fine filter layer were carried out on the lines of Vaughan(1982) and this gave a very fine gradation for the filter material (D_{15} = 0.2 mm). Considering that such a fine material might have some cohesion and may itself sustain a crack, this recommendation was not adopted. Sherard (1984) recommends for broadly graded coarse gravelly core, a filter material with D_{15} = 0.7 mm; the gradation adopted for Tehri fine filter was D_{15} = 0.3 mm, This gradation was checked in the laboratory under high heads and found to be satisfactory.

The design of filter was further fine-tuned on the basis of Soviet norms, which are more elaborate. The gradation of fine filter as specified and executed is silt content less than 3%; maximum size less than 20mm; for coarse filter gradation are-silt content not more than 3%. Maximum size less than 60 mm.

The dam, as executed, has downstream filters comprising of fine and coarse filters. Fine filter layer has uniform thickness of 5m from near dam top up to foundation level; coarse filter is of varying thickness-from 6.0m (eln.818.0m) to 17m at foundation level (~595.0m). The upstream Transition zone (filter) has two layers each 3.5m thick - One fine filter layer between upstream shell zone and u/s face of core. A coarse filter layer is provided between first layer and u/s shell from MDDL upwards to dam crest level.

Horizontal Filter Drain

Dam zoning initially had a horizontal filter blanket comprising of 1.5 thick fine filter, overlain by coarse filter layer of thickness varying from 1.5m at upper elevations to 8.5m in the river bed beneath the Downstream shell; this provision was made in view of downstream shell material being not very pervious, as per Tests carried out in the borrow area. Later, the permeability of this material used in Test fills was determined in the range of 1.4 x 10^{-4} cm/sec to 9.6 x 10^{-4} cm/sec. In view of such high permeability, provision of horizontal filter drain in the downstream shell was not considered necessary. Instead a more pervious material in the downstream shell area upto eln. 635 m (40m(~) depth) was specified. This material was expected to have fines (£ 4.75 mm) upto about. 16%, permeability of 0.5 cm/sec; the material was to be obtained by selective borrowing in the borrow area (Zone 2 C).

The material was accordingly placed in the dam in the first Filling season upto eln. 615.0 m. The 'in-situ' field tests conducted indicated actual fines content being higher - 25% and permeability in the range of 10^{-3} to 10^{-2} cm/sec. In the following season a still coarser material with Fines in the range of 10 to 18% (obtained by processing of Borrow Area Material by segregation cone method) was placed upto eln. 635.0 m (Zone 2D).

Shell Zones

Terrace material from Dobata, comprising of sand, gravels and boulders has been used for dam shells, initially it was proposed to utilize only 75mm (+) size material, which would have entailed huge effort at processing. Later on, fines to limited extent were permitted in the gravels to be placed in dam shells as under:

For the upstream shell, well graded terrace gravels comprising sand, gravels and boulders with silt content not exceeding 6% maximum size upto 600 mm; Shell zone above MDDL (eln 740.0m) of same specification but silt – free. This zone was specified silt-free to ensure no pore pressure development during drawdown condition.

For the downstream shell, well graded terrace gravels and boulders with maximum size 600 mm. No restriction on Fines, with the requirement that construction pore pressure are not seen to develop Later, after laboratory testing of shell material from borrow area in large Triaxial machine, the design strength parameter of this material were assessed as £ = 38^0, C =0 (with fines content not exceeding 35%). On this basis the specifications for the Shell materials were revised as indicated below.

Upstream Shell

Well graded gravelly material, maximum size 600 mm and 200 mm in central and near-abutment zone respectively; Fines (£ 4.75 mm) not more than 35%, silt content (£ 0.075 mm) not more than 5%, provided further that 80% of the material should not have fines (aleurite) content exceeding 30%.

Downstream Shell

Well graded gravelly material, maximum size 600 mm and 200mm in central portion and near-abutment portion respectively. Fines (£ 4.75 m) not more than 35% and silt content (£ 0.075 mm) not more than 5%.

Rip Rap

Ten meter thick normal to slope, Rip Rap zones have been provided along upstream and downstream slopes of dam. Initially material for these zones was proposed to be oversize boulders and phyllite-I rocks with sizes up to 600 mm; not more than 25-30% material smaller than 300 mm with minimum size restricted to 150 mm. On appraisal of design by the Consultant to improve the seismic stability of dam, near-crest portion of blasted rock-fill material was suggested for upstream and down stream shells, the limit of this zone to be determined on the basis of further studies. The dynamic analysis carried out subsequently, did not establish the need for such zones. The design as executed, has 10m thick (normal to slope) Rip Rap on upstream and down stream slopes, of blasted rock-fill of quartzite rock.

Dam Foundation

The core in the entire height of dam has been founded on sound rock. The maximum allowable longitudinal and transverse slopes specified were

Longitudinal shope : 0.75(H):1.0(V)'

Transverse slope : Upstream-0.20 (H): 1.0 (V)

Downstream-No downward slope permitted

Maximum allowable rate of change of slope in the longitudinal direction was limited to 20°

The seat for dam core was excavated up to fresh, firm and un weathered rock; rock surface exposed, after clean-up and dental treatment, was shot-created – 5 cm thick covering the entire core seat area.

This paper does not cover foundation treatment, consolidation and curtain grouting.

Tehri Dam – A seismic Design

In preliminary designs, stability analysis was carried out by pseudo – static method, adopting seismic design co-efficient of 0.12 g. This was followed up with dynamic analysis, which was carried out by Department of Earthquake Engineering, 1.1 T. Roorkee.

Seismic Design Parameters

Considering the seismo – tectonic set-up around Tehri Region, study of seismogenicity of tectonic features was done based on micro – earthquakes occurrence using short-term recording through portable instruments. Considering various tectonic features around, estimates for effective peak ground acceleration for various source zones were made and response spectra selected for all the source zones and envelope of this adopted as response spectra for design, Artificial Accelerogram was generated to match this Spectra.

For Dynamic analysis, value of dynamic shear modulus, at various strain levels, was determined by carrying out field tests in borrow areas.

Dynamic Analysis

Dynamic stability analysis was carried out using the following approaches.

- Plastic displacement analysis
- Linear gravity 'turn-on' two-dimensional Analysis by FEM, both for static and dynamic conditions.

Dynamic stress analysis indicated dam section to be safe from seismic consideration.

Seismic Risk at Tehri has also been evaluated taking into account data of Earthquake occurrence from 1917 onwards indicating probability of actual Peak Ground Acceleration (P.G.A.) exceeding the effective P.G.A. assumed in 100 years of service life.

Liquefaction Potential of Shell and Core Materials

To assess the liquefaction potential of the fill materials due to excessive pore pressure build-up during occurrence of Maximum Credible Earthquake (MCE) studies were conducted based on Shake Table tests. These confirmed that there would be no significant loss of shear strength under MCE Condition.

Appraisal of Seismic Design by Consultant

To allay concerns about dam safety during earthquake, the aseismic design of dam was also got appraised by the Project owner by Hydroproject Institute, Moscow (The organisation responsible for design of all major dams built in the USSR).

For carrying out the dynamic analysis, Soviet Consultant, made his own site-specific assessment of seismicity of Tehri area. Considering various source zones for generation of earthquake, two worst-case response spectra were chosen for carrying out the analysis :

- One for Magnitude 6.5 earthquake originating from Srinagar Thrust with PGA of 0.5 g.
- Other for Magnitude 8.0 earthquake, originating from Main Boundary Fault (MBF) with 0 PGA of 0.4 g.

Non – linear, sequential (static as well as dynamic) stress analysis by Finite Difference Method, using Elasto-Plastic Model, was carried for the adopted dam section to optimize the dam section and core geometry under conditions of static as well as dynamic loading. It established the dam section would be safe, when subjected to assessed dynamic loading. The maximum settlement due to earthquake was worked out as 55 cm, which corroborated the value assessed earlier by I. I. T. Roorkee.

Further Scrutiny of Seismic Stability of Dam

Even after such extensive independent re-appraisal of a seismic design and taking up of dam construction in 1990, there were repeated campaigns mounted by the Environmentalists against the dam, on ground of dam safety during very large earthquakes, Adequacy of the design has been further appraised assuming hypothetical, exaggerated and more stringent scenarios with regard to occurrence of a big earthquake at Tehri dam location and upgraded design seismic design parameters. Studies / analyses carried out have demonstrated :

- Adopted dam section is safe even when an earthquake of Magnitude 8(+), occurring at a depth of 15 km below the dam seat.
- Dam would be stable, when subjected to dynamic loading corresponding to that of earthquake which occurred at Gazli (Karakyr) in the U. S. S. R. in 1976, where accelerations of 1.36 g (vertical) and 0.72 g (horizontal) were actually recorded.

Finally project Designers were asked to prove the adequacy of dam design for seismic parameters set by a Group of Seismologists, which were :

- Adopting a given value for fundamental time period for dam (to incorporate three dimensional effects)
- Test the dam section for enhanced PGA (0.5 g) for Response Spectra used by I. I. T. Roorkee earlier.
- Test the dam section as per their estimate of Seismic hazard at Tehri (MCE – Magnitude 8.5 (+) earthquake); input ground motion suggested were

PGA – horizontal	:	1.02 g
PGA – vertical	:	0.8715 g

I.I.T., Roorkee accordingly carried out a 2-D Non-linear analysis. For the given seismic scenario, dam section was found to be structurally safe, with maximum vertical displacement of dam crest being 119.8 cm (against a freeboard of 9.5 m provided) and maximum horizontal displacement at crest of about 59 cm, occurring under Maximum Credible Earthquake (MCE) of 8.5 Magnitude.

Freeboard

A freeboard of 9.5 m has been provided, above Full Reservoir level (FRL), making following assumptions:

- Reservoir is Full i. e. at FRL
- A squall of sufficient duration with a sustained velocity of 184 km. per hour is blowing over the reservoir surface creating waves.

Earthquake occurs when this wind is blowing.

Thus both the extreme value conditions (Squall and Earthquake) have been assumed

Wave height including wave Run-up and wind set- up (calculated by Saville's method)	: 4.06 m
Freeboard for Earthquake effects (Settlement, earthquake seiches)	: 5.44 m
Total	**9.50 m**

to occur when reservoir is at FRL; the break-up for the two components of the freeboard being as under:

Compaction of Dam Fills

Dam Fills were compacted to following specifications:

With dam fill materials compacted to such very high densities, resulting in low post-construction settlement are expected to lead to lower differential settlements.

Core-Main body	Average Dry density – Aleurite fraction (<4.75 mm)	1.90 t/m^3 1.85 t/m^3 (minimum),
	Moisture content	1% ($\pm$) O.M.C.
Core-Contact zone with abutments	Average dry density-Aleurite fraction (<4.75mm)	1.80 t/m^3
	Moisture	2 to 3% (+) O.M.C.
Dam Shells	Average Dry Density	2.36 t/m^3 2.30 t/m^3 (Minm.)

Monitoring Safety of Dam

To monitor the behaviour of dam, elaborate instrumentation has been provided to measure pore pressures, stresses, deformations, settlements and seepage through dam body and along dam abutments.

A very novel feature in the dam is provision of inspection gallery (of 2.2m dia.) in the centre of core, at about mid-height of dam. (Such galleries have been provided at Nurek and Charavak dams in USSR and Asswan High dam in Egypt) for long-term visual inspection and monitoring of horizontal and vertical deformations which take place in the body of core. Another gallery near the crest level has been provided to enable direct, continuous visual examination of core surface at top, with a view to identifying possible transverse cracks, especially in the reaches close to dam abutments, due to differential settlement.

Additional Measures for Prevention of cracking of Dam Core

Besides incorporating all the measures to prevent/reduce possibility of transverse cracking of core, due to differential settlement, based on centrifuge model studies, specially commissioned for the project, which indicated possible development of transverse cracks near abutments, a crack preventive measure with fill material placement in the near-abutment zone with a time-lag compared with main body of the core, has been implemented during fill placement in the dam.

Tehri Dam Design – A Sum-up

Sherard while discussing the problem of controlling concentrated leaks because of erosion of core and design measures used to reduce differential settlement and likelihood of concentrated leak, had observed (1984) that the trend was towards conservatism and to consider Downstream Filter as primary line of defence; (design measures to reduce settlement were considered of secondary importance). Seen in that light, the design of Tehri dam is most conservative on every count. The filters have been designed on the most conservative criteria which are even more severe than what have been indicated by Sherard for filters for silt and clays. The design measures to reduce the differential settlement have been implemented with equal attention. As a measure to prevent the stress transfer between core and shell and related problem of hydraulic fracturing, core is of blended material, which has high shear strength, yet it is plastic enough to withstand imposed strain due to any differential settlement without cracking. Core has been generously proportioned; ample freeboard has been provided, Fill material (shells) have been compacted to very density – measures aimed at safeguarding the dam safety during occurrence of very big Earthquake.

Kol Dam

Location, Dam Site Geology

Kol dam- a Rockfill Dam, 163 m high is presently in advanced stage of construction across river Satluj, in Bilaspur district, Himachal Pradesh. The dam is sited, just at the lip of Bhakra reservoir, in South-west Lesser Himalayas.

The rock under the dam consists of near vertical beds of hard limestone and dolomite, with thin completely sheared shale (clay) interbeds striking across the river.

Seismicity, Seismic Design Parameters:

The project area lies in active seismic Zone in Zone V of Seismic Zoning map of India. Dam site is located in north-east border of Frontal Folded Belt bounded by MBT (Main Boundary Thrust) towards north-east and the Bursar Thrust and its homologous thrust in south-east. Site lying in active seismic belt, was affected by earthquakes occurring in Himachal Pradesh at frequent intervals. The epicentre of 8 (+) Magnitude earthquake which occurred at Kangra in 1905 was 100 km north of Kol dam site. Seismic hazard assessed for Kol dam site is

MCE – Magnitude 8 Earthquake occurring at 12 km

depth below dam site – PGA 0.49 g.

DBE - Magnitude 7 Earthquake occurring 20 km away– PGA 0.20 g.

Adopted Dam Design

It is a zoned Rockfill structure with a central clay core. Salient features of dam are:

Crest Elevation	:	648 m
Maxm. Height above river bed	:	150 m
Maxm. Height above foundation	:	163 m
Crest length	:	474 m
Crest width	:	14 m
Upstream Slope (average)	:	2.25 (H) : 1.0 (V)
Downstream Slope (average)	:	2.0 (H) : 1.0 (V)

Road have been provided on upstream and downstream faces of dam, initially 14 m wide, for transporting fill materials during construction; these would be suitably modified after construction is over.

The detail of zones, as envisaged, are indicated in the typical cross section of dam. These comprise Impervious Core, Fine Filter, Coarse filters, Transition / Filter, Gravels/ drains, Rockfill shell and Rip Rap. Ten types of fill materials (designated as no. 1 to no. 10) are being placed in the dam.

The heel portion of upstream shell has been designed to serve as Upstream Coffer dam.

Geometry of Dam Zones

Dam Core Profile

Central clay core (material # 1) with a width of 4.6 m at top, the width of increased to 10m (+) at abutment – dam fill interface, the u/s and d/s slopes both being identical are 2.5 (V) : 1.0 H from top upto 10m depth and thereafter 4.0 (V) : 1.0 (H), upto bottom.

Filters and Drain:

Fine Filter:

Core encased with fine filter layer (material # 2) – 4 m thick both upstream and downstream, thickness of filter increased to 8m in top 15m of dam; the thickness of filter increased from 4m to 8m in the bottom 15m, depth upto foundation.

Coarse Filter

Downstream of core, coarse filter layer

(material # 4) of 6m thickness, between fine filter and d/s shell.

Transition layer

Upstream fine filter layer is covered by a transition layer (of material # 7), 4 m thick.

Drain

Under the downstream shell, and at the bottom of valley, a drainage zone (upto eln. 515.0), of material # 6.

Upstream Shell

The entire upstream cofferdam has been designed as part of upstream shell and has sub zones.

The rest of the shell comprises of rockfill material (material # 8) – upto eln. 600; above it a zone of harder Rockfill (material #9)of 18m minimum thickness.

Above eln. 620.0m, the upstream face is protected with Rip Rap – 2 m thick.

Downstream Shell

It is mainly composed gravels (material#5). The upper layer of shell is composed of harder rockfill (material #8) – 18m thick. 2 m thick Rip Rap has been provided along downstream slope.

Fill Material Gradations

The gradations for various Fill materials, as finally adopted are indicated in figure.6, 7&8.

Compaction of Dam Fills

Fill placement acceptance criteria as laid down, on the basis of Test Sections results, is as under:

Dhauliganga Dam

This is a diversion dam built across Dhauliganga River, a tributary of river Sarda, near Chirkila in Pithoragarh district of Uttarakhand. The project site is, deep in Central Himalayas: Project falls geologically in the Chiplakot Formation comprising augengneiss and biotite gneiss with sub-ordinate mica schist and amphibolite. The dam location is in a wide asymmetrical valley with rocks exposed on both banks. There was overburden in the river bed portion of the order of 60m. The valley configuration is controlled by massive to moderately jointed biotite gneiss.

Seismic Design Parameters

The project is situated in a highly seismic area and falls within Zone V of Seismic Zoning Map of India. The Main Central Thrust (MCT) lies about 16 km north of Project area; Close to project, a big earthquake occurred in 1916 – Dharchula Earthquake which had a magnitude of 7.5. Seismic design parameters suggested at tender stage were – PGA of 0.36 g in (horizontal direction) for MCE and 0.18 g for DBE. These were reportedly further, upgraded at detailed design stage.

Clay (Material # 1)	:	(Proctor) Density – 1.71t/m^3-1.81t/m^3 @OMC Moisture Content – 1 to 3% (+) OMC at Fill-foundation interface
Fine Filter (Material # 2),& Coarse Filter (Material # 4)	:	Relative Density (RD) > 87% water addition – 100 litres/m^3
Gravel for Downstream shell (Material # 5)	:	'In-place' dry density >2.35 t/m^3, No water addition.
Gravel for Drainage (Material #6)	:	Water addition – 250 litres/m^3, 'In-place' Dry density >2.40 t/m^3
Transition (Material #7)	:	Water addition –100 litres/m^3, Relative Density (RD) >87%
Hard Rockfill (Material #8)	:	Water addition – 250 litres/m^3, 'In-place' Dry density >2.30 t/m^3
Shell Rockfill (Material #9)	:	Water addition – 250 litres/m^3, 'In-place' Dry density >2.10 t/m^3

Dam Design

The dam is the first concrete – faced Rock fill dam (CFRD) built in India. The dam is 52 m high (above the plinth level) Higher CFRDs have been built in many parts of world, since 1970s with heights in the range of 140 to 190 m in Brazil, Columbia, Mexico and other countries.

Structurally this design is different from a conventional earth core rockfill dam. In case of CFRD, water thrust acts externally on Reinforced Concrete Face. The concrete slab contributes to increasing the stiffness and stability of dam. As a result, steeper dam slopes (1:4 to 1:6) are attainable in case of such dam, making this design a least cost option in many situations.

None of the CFRDs built so far have experienced an actual earthquake of large magnitude, as far as known to the authors. Many Researchers (Seed, HB (1978), Gazete, et. al., (1992) have carried out extensive analytical studies on the anticipated response and performance of a modern CFRD, under seismic excitation; conclusion drawn from these studies is that crest settlement in modern CFRD would not be unacceptable even under the most severe earthquake, and the safety of the dams will not be jeopardized.

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