REPORT OF THE

GROUP OF EXPERTS

ON

SEISMIC SAFETY OF TEHRI DAM

CONSTITUTED

BY

GOVERNMENT OF INDIA

MINISTRY OF POWER

VOLUME- I

NEW DELHI

FEBRUARY 1998

CONTENTS

(VOLUME - I)

PART- A

PART - B

PART - A

I. CONSTITUTION OF THE EXPERT GROUP

An expert group consisting of the following members was constituted by the Government of India, Ministry of Power, vide DO No. 7/9/95 dated 25.6.96 (**Annexure-1**).

i) Prof. VK Gaur
ii) Prof. KN Khattri
iii) Prof. RN Iyengar
iv) Prof. Ramesh Chander

Subsequently, DO No. 7/9/95-Hydel.II dated August 2,1996 **(Annexure-2)** was issued adding the name of Prof. NC Nigam to the group and stating that the Group had been constituted on the suggestion of Shri Sunder Lal Bahuguna.

v) Prof. NC Nigam

The Expert Group was advised "to examine the available scientific and technical reports and other information and data relating to the safety of the Tehri Dam" and make available its recommendations within three months time.

II. WORK OF THE EXPERT GROUP

1. The first meeting of the Group was held on August 5, 1996 at Shram Shakti Bhawan, New Delhi. At this meeting, Members were shown a set of reports (list at **Annexure-3**) relating to the design and test performance of the Tehri Dam. However, it was conveyed that Members could only read reports in the meeting room. Members felt that a careful analysis of these documents required deeper study and requested that copies be made available to them for this purpose, but this was disallowed. (Dr. K.N. Khattri could not attend this meeting).

2. The Group subsequently met on 6 occasions. An Aide Memoire was drawn up at the end of each meeting (except first two meetings) to facilitate progress. These are enclosed as **Annexures 4.1 to 4.4**.

III. REVIEW OF AVAILABLE REPORTS

Design basis of Tehri Dam and its dynamic analysis

1. The preliminary design of Tehri Dam (pseudo-static analysis) was based on a seismic design co-efficient of 0.12 g. Dynamic Analysis of the dam was carried out on the basis of a Response Spectrum (10% damping) hereafter called the DEQ-RS, synthesized by the Department of Earthquake Engineering, University of Roorkee with ZPA (Zero Period Acceleration) of 0.25 g. A spectrum compatible ground acceleration record was generated for the dynamic analysis of the dam modelled as a two dimensional structure.

2. An elasto-plastic dynamic analysis and appraisal of the safety of the Tehri Dam was carried out by the Hydro Project Institute, Moscow under an agreement signed between the Governments of India and Soviet Union in 1986. The Soviet Consultants made a review of seismicity, dynamic testing of materials and sequential non-linear elasto-plastic dynamic analysis for the two Reponse Spectra with PGA of 0.5g and 0.4g. Based on this analysis, the dam profile was refined. The study concluded that "the dam structure was seismically stable".

3. In 1992, the Tehri Dam section was also analysed for a field accelerogram actually recorded in the wake of Gazli earthquake, 1976 by Russian consultants using non-linear elastic material behaviour. This accelerogram had a vertical PGA of 1.36 g, a horizontal PGA of 0.72 g, and a strong motion persistence time of about 12 seconds.

4. Based on their studies contained in the Report, "Tehri Dam project on the Bhagirathi River India-Dynamic Stability Analysis for Tehri Dam Applying Accelerogram of Gazli Earthquake". Hydro Project Institute, Mosocw 1992, the Soviet consultants certified, "the Tehri Dam is seismically stable under loading of the Gazli earthquake accelerogram".

N.B. The Expert Group does not certify the results and conclusions of the reports and correctness of various assumptions and procedures

IV. FURTHER STUDIES MADE

1. The Group concluded after a detailed discussion on the various issues related to the seismic safety of the Tehri Dam, that a comprehensive appraisal of the seismic safety of the Tehri Dam required completion of the following two key exercises, employing recent advances in conceptual and computational capabilities :

i) Quantitative estimation of seismic hazard at the Tehri Dam site, and

ii) Evaluation of the performance of the Tehri Dam as currently designed, if it was exposed to the estimated seismic hazard at the site.

2. Meeting on Jan 27, 1997

The Group at its meeting on January 27, 1997 received a base paper prepared by Professors Gaur, Khattri and Chander, based on current understanding of the geodynamics of the Himalaya, and state-of-the-art approaches to computing the estimated ground motion histories at the Tehri Dam site.

The Group made the following recommendations :

i) The above paper be refined in the light of suggestions made.

ii) The Tehri Dam be further tested to evaluate its performance under the following conditions to provide further assessment of the safety of the dam:

a) Fundamental time period = 1.25 secs based on the analysis by Prof. RN Iyengar to incorporate 3-dimensional effects

b) Response Spectrum : shape as adopted by Deptt. of Earthquake Engineering, University of Roorkee for 10% damping (DEQ - RS), anchored at PGA of 0.5g.

c) Elasto-plastic modelling.

iii) This study was assigned to the Deptt. of Earthquake Engineering, University of Roorkee. The material properties and geometry etc. of the dam will be provided by THDC, who will be responsible for their correctness. Minutes of a meeting held at Roorkee in this regard and the comments of Prof. R.N.Iyengar on the Minutes are placed at **Annexure-5.**

3. Meeting on June 27, 1997 (Prof. R.N Iyengar could not attend)

i) In the meeting of the Group held on June 27, 1997, Prof DK Paul, Deptt. of Earthquake Engineering, University of Roorkee presented the results of the dynamic response of the dam for the input ground motion specified by the Group in the previous meeting, IV 2(ii) The Group appreciated the ground work done for non-linear dynamic analysis and desired that a detailed report be prepared highlighting the assumptions, methodologies and parameters used.

ii) The Group desired that the Response Spectrum developed by the Deptt. of Earthquake Engineering, University of Roorkee, and used for the analysis of Tehri Dam be reviewed in the light of new information obtained from the records of the 1991 Uttarkashi Earthquake. If the Response Spectrum so obtained is found to be more severe, further testing of the Dam be done for the new Response Spectrum.

iii) The Group received and discussed the final report prepared by Professor Gaur, Khattri and Chander on the estimates of seismic hazard at the Tehri Dam site, using state-of-the-art simulations based on the fundamental principles of fault mechanics and seismic wave propagation **(Annexure-6)**.

Prof. Nigam expressed the view that the acceleration time history records synthesised in the Report are based on the convolution of conservative assumptions at various stages, resulting in extremely severe ground motion, and are based on conditional probability formulation The comments of Khattri et.al on the views of Prof. Nigam are placed at Appendix to **Annexure-6**.

iv) The Group further advised that in view of the scant empirical data on large magnitude earthquake at short distances, the dam may also be tested using the simulated acceleration time histories as given in the report at Annexure-6 for the 50th and 84th percentile, provided the non-linear analysis software used by the Department of Earthquake Engineering, University of Roorkee, which is based on small deformation theory, is valid for the deformations induced in the dam.

v) The Group received the background report prepared by Shri B.L Jatana at its request **(Annexure-7)**

4 Meeting held on Oct. 9, 1997

i) At this meeting, the Group received the report prepared by Prof. D K.Paul (**Annexure-8**) and accepted his analysis. The group noted that the effect of incorporating the record of the 1991 Uttarkashi earthquake on the DEQ-RS was not significant and that it was not necessary to repeat the analysis with the new spectrum.

Comments of Prof. Khattri on DEQ Spectrum are placed at **Annexure-9.**

ii) The Group further desired that the dam be tested for the accelerograms synthesized by Prof. Khattri who will provide these to Prof Paul.

5 Meeting held on December 21, 1997

i) In the meeting held on December 21, 1997, it was noted that for the ground acceleration record generated by Prof. Khattri et.al. the non-linear dynamic analysis of the dam could not be carried out as the level of deformation crossed the limit of validity of the software based on small deformation theory.

ii) Prof. DK Paul of DEQ, UOR, was requested to repeat the dynamic analysis (4(i)) for an actual cross-section of the dam for which the core has the maximum height.

iii) For the ground motion generated by Prof. Khattri et.al other representative samples for a N-S horizontal and vertical accelerogram may be selected by him and provided to Prof. DK Paul for a linear dynamic analysis without regard to large deformation to be followed by a slope stability analysis according to the procedure described by T.Paskalov

iv) The Expert Group noted that the comments of GSI on the Report by Khattri et.al. have been obtained by THDC on its own initiative. It was, therefore, decided that Group will not take cognizance of the GSI comments in making its recommendations.

6 Meeting held on January 31, 1998

i) At this meeting, Prof DK Paul presented the results of the analysis carried out by him as per decision of the Expert Group in its meeting held on December 21, 1997 (**Annexure-10**).

The Group noted that for a cross-section of the dam corresponding to maximum core height (B-11) and DEQ ground motion, the performance for the nonlinear analysis in terms of deformations and plastic strains are of the same order as for the cross-section (B-15) analysed earlier.

ii) The slope stability analysis based on Paskalov method was attempted. However, it could not be carried through in view of some basic question regarding the method in relation to Tehri Dam.

iii) Prof. Paul reported that he has been able to carry out the non-linear dynamic analysis of the dam for the ground motion synthesized by Prof. Khattri et.al., within the validity of his programme. He presented the results of the analysis. He was requested to submit the report of his analysis (**Annexure-11**). He was requested to indicate the transverse stresses also. The Group decided that the ground motion synthesis by Prof. Khattri et.al. be treated as a sample function of MCE for Tehri Dam.

iv) Prof. R.N. Iyengar placed on the table brief extracts, including the Executive Summary of the document : "Safety of Dams : Flood and Earthquake Criteria" (National Research Council, Washington DC, 1985). A Note prepared by Prof. Iyengar on the safety issues of large dams is placed at **Annexure-12**.

7. Meeting held on February 18, 1998

I) The Group received the report on the non-linear dynamic analysis of the Dam from Prof. D.K. Paul based on the ground acceleration record synthesised by Prof. Khattri.

ii) The Group decided that tables contining the ground acceleration values of digitized time interval be added to the report.

iii) The contours of permanent displacement of the dam at the end of the dynamic analysis be added to the report.

iv) A Note on difficulties experienced in carrying through the slope stability analysis using Paskalov's paper be included as **Annexure-13**.

PART-B

V. PERSPECTIVE AND RECOMMENDATIONS

Perspective

The terms of reference of the Group was the assessment of seismic safety of the current design of Tehri Dam. Safety must be defined with reference to a criterion. The design of critical structures such as large dams in seismic regions, is based on the concept of Operation Basis Earthquake (OBE) and safety is based on Maximum Credible Earthquake(MCE). The criteria for choosing OBE & MCE are specified in the Codes. The International Commission On Large Dams (ICOLD - 57, Bulletin 46) has specified that to ensure the satisfactory performance and safety of dam it should be ensured that :

a) the dam does not suffer significant damage, when subjected to OBE; and

b) damage to the Dam is limited and no catastrophic failure occurs leading to uncontrolled release of water when subjected to MCE.

The Group adopted the following ICOLD - 72 (Page 25) guideline for the choice of MCE.

"The MCE is generally defined as an upper bound of expected magnitude or as an upperbound of expected earthquake Intensity".

Based on this criteria the Group accepted the ground motion synthesized by Khattri et al as MCE for Tehri Dam.

Seismic risk of dams for earthquakes has two components :

i) Structural systems and components inclusive of the Dam body;

ii) Socio-economic component.

The Group has addressed only the first component.

While considering the question of the safety of the Dam, the Group noted the performance of the Dam in the previous studies conducted in India and in Soviet Union made available by THDC

The Group noted the following features of the Dam behaviour based on further studies carried out by the Department of Earthquake Engineering as per its directives :

(1) Non-linear dynamic analysis for a response spectra based on 0.5g ZPA, and the shape of DEQ spectra

The response of the dam exhibits the following features :

i) Maximum vertical displacement of the dam crest is 14.78 cm. against a free board of 9.5m. The maximum horizontal displacement at the crest is 38.7 cm.

ii) The plastic deformations are confined to the upper surface of the u/s and d/s slopes, and to a few local pockets near the top of the dam. The maximum plastic strain in body of the dam is of the order of 0.05.

(2) Non-linear dynamic analysis for the ground motion synthesized by Prof.Khattri et.al.

The response of the dam exhibits the following features as per two dimensional analysis :

i) The maximum vertical displacement of the dam crest is 119.80 cm against a free board of 9.5M. The maximum horizontal displacement at the crest is 58.92 cm.

ii) The plastic displacements are confined to the upper surface of the u/s and d/s slopes and to a few local pockets near the top of the dam. The maximum plastic strain in the body of the dam is of the order of 0.1. The principle transverse stresses in the body of the dam are compressive precluding the possibility of cracking.

VI. RECOMMENDATIONS

i) Based on a review of the reports made available to the Group and further studies conducted by DEQ-UOR on the behaviour of the idealised two dimensional model of the dam to the ground acceleration corresponding to MCE, the Group came to the conclusion that the present design of the dam is expected to be structurally safe to withstand the MCE during the economic performance life of the dam-reservoir system.

ii) Additional recommendations of some of the members are enclosed.

VII. ACKNOWLEDGEMENTS

The Expert Group acknowledges the assistance of the Ministry of Power, Government of India, THDC and Prof. D.K. Paul of the Department of Earthquake Engineering, University of Roorkee.

(V.K. GAUR)

N.C. Nigam

(N.C. NIGAM)

(K.N. KHATTRI)

(R.N. IYENGAR)

(RAMESH CHANDER)

REPORT OF THE

GROUP OF EXPERTS

ON

SEISMIC SAFETY OF TEHRI DAM

CONSTITUTED

BY

GOVERNMENT OF INDIA

MINISTRY OF POWER

VOLUME- I

NEW DELHI

FEBRUARY 1998

CONTENTS

(VOLUME - I)

PART - A

I. CONSTITUTION OF THE EXPERT GROUP

An expert group consisting of the following members was constituted by the Government of India, Ministry of Power vide DO No. 7/9/95 dated 25.6.96 (**Annexure-1**).

i) Prof. VK Gaur
ii) Prof. KN Khattri
iii) Prof. RN Iyengar
iv) Prof. Ramesh Chander

Subsequently, DO No. 7/9/95-Hydel.II dated August 2.1996 **(Annexure-2)** was issued adding the name of Prof. NC Nigam to the group and stating that the Group had been constituted on the suggestion of Shri Sunder Lal Bahuguna.

v) Prof. NC Nigam

The Expert Group was advised "to examine the available scientific and technical reports and other information and data relating to the safety of the Tehri Dam" and make available its recommendations within three months time.

II. WORK OF THE EXPERT GROUP

1. The first meeting of the Group was held on August 5, 1996 at Shram Shakti Bhawan, New Delhi. At this meeting, Members were shown a set of reports (list at **Annexure-3**) relating to the design and test performance of the Tehri Dam. However, it was conveyed that Members could only read reports in the meeting room. Members felt that a careful analysis of these documents required deeper study and requested that copies be made available to them for this purpose, but this was disallowed. (Dr. K.N. Khattri could not attend this meeting).

2. The Group subsequently met on 6 occasions. An Aide Memoire was drawn up at the end of each meeting (except first two meetings) to facilitate progress. These are enclosed as **Annexures 4.1 to 4.4**.

III. REVIEW OF AVAILABLE REPORTS

Design basis of Tehri Dam and its dynamic analysis

1. The preliminary design of Tehri Dam (pseudo-static analysis) was based on a seismic design co-efficient of 0.12 g. Dynamic Analysis of the dam was carried out on the basis of a Response Spectrum (10% damping) hereafter called the DEQ-RS, synthesized by the Department of Earthquake Engineering, University of Roorkee with ZPA (Zero Period Acceleration) of 0.25 g. A spectrum compatible ground acceleration record was generated for the dynamic analysis of the dam modelled as a two dimensional structure.

2. An elasto-plastic dynamic analysis and appraisal of the safety of the Tehri Dam was carried out by the Hydro Project Institute, Moscow under an agreement signed between the Governments of India and Soviet Union in 1986. The Soviet Consultants made a review of seismicity, dynamic testing of materials and sequential non-linear elasto-plastic dynamic analysis for the two Reponse Spectra with PGA of 0.5g and 0.4g. Based on this analysis, the dam profile was refined. The study concluded that "the dam structure was seismically stable".

3. In 1992, the Tehri Dam section was also analysed for a field accelerogram actually recorded in the wake of Gazli earthquake, 1976 by Russian consultants using non-linear elastic material behaviour. This accelerogram had a vertical PGA of 1.36 g, a horizontal PGA of 0.72 g. and a strong motion persistence time of about 12 seconds.

4. Based on their studies contained in the Report, "Tehri Dam project on the Bhagirathi River India-Dynamic Stability Analysis for Tehri Dam Applying Accelerogram of Gazli Earthquake", Hydro Project Institute, Mosocw 1992, the Soviet consultants certified, "the Tehri Dam is seismically stable under loading of the Gazli earthquake accelerogram".

N.B. The Expert Group does not certify the results and conclusions of the reports and correctness of various assumptions and procedures.

IV. FURTHER STUDIES MADE

1. The Group concluded after a detailed discussion on the various issues related to the seismic safety of the Tehri Dam, that a comprehensive appraisal of the seismic safety of the Tehri Dam required completion of the following two key exercises, employing recent advances in conceptual and computational capabilities

i) Quantitative estimation of seismic hazard at the Tehri Dam site, and

ii) Evaluation of the performance of the Tehri Dam as currently designed, if it was exposed to the estimated seismic hazard at the site.

2. Meeting on Jan 27, 1997

The Group at its meeting on January 27, 1997 received a base paper prepared by Professors Gaur, Khattri and Chander, based on current understanding of the geodynamics of the Himalaya, and state-of-the-art approaches to computing the estimated ground motion histories at the Tehri Dam site.

The Group made the following recommendations :

i) The above paper be refined in the light of suggestions made.

ii) The Tehri Dam be further tested to evaluate its performance under the following conditions to provide further assessment of the safety of the dam:

a) Fundamental time period = 1.25 secs based on the analysis by Prof. RN Iyengar to incorporate 3-dimensional effects.

b) Response Spectrum : shape as adopted by Deptt. of Earthquake Engineering, University of Roorkee for 10% damping (DEQ - RS), anchored at PGA of 0.5g.

c) Elasto-plastic modelling.

iii) This study was assigned to the Deptt. of Earthquake Engineering, University of Roorkee. The material properties and geometry etc of the dam will be provided by THDC, who will be responsible for their correctness. Minutes of a meeting held at Roorkee in this regard and the comments of Prof. R.N Iyengar on the Minutes are placed at **Annexure-5.**

3 Meeting on June 27, 1997 (Prof. R.N Iyengar could not attend)

i) In the meeting of the Group held on June 27, 1997, Prof. DK Paul, Deptt. of Earthquake Engineering, University of Roorkee presented the results of the dynamic response of the dam for the input ground motion specified by the Group in the previous meeting, IV.2(ii). The Group appreciated the ground work done for non-linear dynamic analysis and desired that a detailed report be prepared highlighting the assumptions, methodologies and parameters used.

ii) The Group desired that the Response Spectrum developed by the Deptt. of Earthquake Engineering, University of Roorkee, and used for the analysis of Tehri Dam be reviewed in the light of new information obtained from the records of the 1991 Uttarkashi Earthquake. If the Response Spectrum so obtained is found to be more severe, further testing of the Dam be done for the new Response Spectrum.

iii) The Group received and discussed the final report prepared by Professor Gaur, Khattri and Chander on the estimates of seismic hazard at the Tehri Dam site, using state-of-the-art simulations based on the fundamental principles of fault mechanics and seismic wave propagation **(Annexure-6)**.

Prof. Nigam expressed the view that the acceleration time history records synthesised in the Report are based on the convolution of conservative assumptions at various stages, resulting in extremely severe ground motion, and are based on conditional probability formulation. The comments of Khattri et.al on the views of Prof. Nigam are placed at **Appendix to Annexure-6A.**

iv) The Group further advised that in view of the scant empirical data on large magnitude earthquake at short distances, the dam may also be tested using the simulated acceleration time histories as given in the report at Annexure-6 for the 50th and 84th percentile, provided the non-linear analysis software used by the Department of Earthquake Engineering, University of Roorkee, which is based on small deformation theory, is valid for the deformations induced in the dam.

v) The Group received the background report prepared by Shri B.L Jatana at its request **(Annexure-7)**

4. Meeting held on Oct. 9, 1997

i) At this meeting, the Group received the report prepared by Prof. D.K.Paul (**Annexure-8)** and accepted his analysis. The group noted that the effect of incorporating the record of the 1991 Uttarkashi earthquake on the DEQ-RS was not significant and that it was not necessary to repeat the analysis with the new spectrum.

Comments of Prof. Khattri on DEQ Spectrum are placed at **Annexure-9.**

ii) The Group further desired that the dam be tested for the accelerograms synthesized by Prof. Khattri who will provide these to Prof. Paul.

5. Meeting held on December 21, 1997

i) In the meeting held on December 21, 1997, it was noted that for the ground acceleration record generated by Prof. Khattri et.al. the non-linear dynamic analysis of the dam could not be carried out as the level of deformation crossed the limit of validity of the software based on small deformation theory.

ii) Prof. DK Paul of DEQ, UOR, was requested to repeat the dynamic analysis (4(i)) for an actual cross-section of the dam for which the core has the maximum height.

iii) For the ground motion generated by Prof. Khattri et.al other representative samples for a N-S horizontal and vertical accelerogram may be selected by him and provided to Prof. DK Paul for a linear dynamic analysis without regard to large deformation to be followed by a slope stability analysis according to the procedure described by T.Paskalov.

iv) The Expert Group noted that the comments of GSI on the Report by Khattri et.al. have been obtained by THDC on its own initiative. It was, therefore, decided that Group will not take cognizance of the GSI comments in making its recommendations

6. Meeting held on January 31, 1998

i) At this meeting, Prof DK Paul presented the results of the analysis carried out by him as per decision of the Expert Group in its meeting held on December 21, 1997 (**Annexure-10**).

The Group noted that for a cross-section of the dam corresponding to maximum core height (B-11) and DEQ ground motion, the performance for the nonlinear analysis in terms of deformations and plastic strains are of the same order as for the cross-section (B-15) analysed earlier.

ii) The slope stability analysis based on Paskalov method was attempted. However, it could not be carried through in view of some basic question regarding the method in relation to Tehri Dam.

iii) Prof. Paul reported that he has been able to carry out the non-linear dynamic analysis of the dam for the ground motion synthesized by Prof. Khattri et.al., within the validity of his programme. He presented the results of the analysis. He was requested to submit the report of his analysis (**Annexure-11**). He was requested to indicate the transverse stresses also. The Group decided that the ground motion synthesis by Prof Khattri et.al. be treated as a sample function of MCE for Tehri Dam.

iv) Prof. R.N. Iyengar placed on the table brief extracts, including the Executive Summary of the document : "Safety of Dams : Flood and Earthquake Criteria" (National Research Council, Washington DC, 1985). A Note prepared by Prof. Iyengar on the safety issues of large dams is placed at **Annexure-12**.

7. Meeting held on February 18, 1998

I) The Group received the report on the non-linear dynamic analysis of the Dam from Prof. D.K. Paul based on the ground acceleration record synthesised by Prof. Khattri.

ii) The Group decided that tables contining the ground acceleration values of digitized time interval be added to the report.

iii) The contours of permanent displacement of the dam at the end of the dynamic analysis be added to the report.

iv) A Note on difficulties experienced in carrying through the slope stability analysis using Paskalov's paper be included as **Annexure-13**.

PART-B

V. PERSPECTIVE AND RECOMMENDATIONS

Perspective

The terms of reference of the Group was the assessment of seismic safety of the current design of Tehri Dam Safety must be defined with reference to a criterion. The design of critical structures such as large dams in seismic regions, is based on the concept of Operation Basis Earthquake (OBE) and safety is based on Maximum Credible Earthquake(MCE). The criteria for choosing OBE & MCE are specified in the Codes. The International Commission On Large Dams (ICOLD - 57, Bulletin 46) has specified that to ensure the satisfactory performance and safety of dam it should be ensured that :

a) the dam does not suffer significant damage, when subjected to OBE; and

b) damage to the Dam is limited and no catastrophic failure occurs leading to uncontrolled release of water when subjected to MCE.

The Group adopted the following ICOLD - 72 (Page 25) guideline for the choice of MCE.

"The MCE is generally defined as an upper bound of expected magnitude or as an upperbound of expected earthquake Intensity".

Based on this criteria the Group accepted the ground motion synthesized by Khattri et.al as MCE for Tehri Dam.

Seismic risk of dams for earthquakes has two components :

i) Structural systems and components inclusive of the Dam body;

ii) Socio-economic component.

The Group has addressed only the first component.

While considering the question of the safety of the Dam, the Group noted the performance of the Dam in the previous studies conducted in India and in Soviet Union made available by THDC

The Group noted the following features of the Dam behaviour based on further studies carried out by the Department of Earthquake Engineering as per its directives :

(1) **Non-linear dynamic analysis for a response spectra based on 0.5g ZPA, and the shape of DEQ spectra**

The response of the dam exhibits the following features

i) Maximum vertical displacement of the dam crest is 14.78 cm against a free board of 9.5m. The maximum horizontal displacement at the crest is 38.7 cm.

ii) The plastic deformations are confined to the upper surface of the u/s and d/s slopes, and to a few local pockets near the top of the dam. The maximum plastic strain in body of the dam is of the order of 0.05.

(2) **Non-linear dynamic analysis for the ground motion synthesized by Prof.Khattri et.al.**

The response of the dam exhibits the following features as per two dimensional analysis :

i) The maximum vertical displacement of the dam crest is 119.80 cm against a free board of 9.5M. The maximum horizontal displacement at the crest is 58.92 cm.

ii) The plastic displacements are confined to the upper surface of the u/s and d/s slopes and to a few local pockets near the top of the dam. The maximum plastic strain in the body of the dam is of the order of 0.1. The principle transverse stresses in the body of the dam are compressive precluding the possibility of cracking.

VI. RECOMMENDATIONS

Based on a review of the reports made available to the Group and further studies conducted by DEQ-UOR on the behaviour of the idealised two dimensional model of the dam to the ground acceleration corresponding to MCE, the Group came to the conclusion that the present design of the dam is expected to be structurally safe to withstand the MCE during the economic performance life of the dam-reservoir system.

However, a number of crucial questions could not be settled, notably the slope stability on account of the difficulties reported in Annexure-13, and the response of the dam to MCE in the longitudinal direction. Keeping in view, therefore, of the sensitivity of non-linear behaviour to possible variations in the values of seismic parameters such as PGA, duration, frequency content and material properties, still larger displacements cannot be ruled out. In fact as per the Soviet Report (Tehri Dam Project on the Bhagirathi river, India, Contract No. 53032/67652, 9,G,P.73-74) to which attention was drawn by one member of the Group, the idealised section of a 200 m high dam fails for the earthquake impact with PGA equal to $a_z = 0.64g$; $a_h = 1.28g$. Whereas there are differences in the sections analysed in the above report and the current design of the Tehri Dam, attention is drawn to the fact that for some fortuitous combination of inputs combined with particular reservoir-dam conditions, the performance of the dam to hold water at a future date, may get affected.

It is, therefore, further recommended that as a matter of abundant caution, the following work be carried out :

i) 3-D non-linear analysis of the dam to evaluate its performance against the MCE.
ii) A simulated dam break analysis to ensure that in the unlikely event of an uncontrolled release of water, the consequences are minimum.

VII. ACKNOWLEDGEMENTS

The Expert Group acknowledges the assistance of the Ministry of Power, Government of India, THDC and Prof. D.K. Paul of the Department of Earthquake Engineering, University of Roorkee.

(V.K. GAUR) **(N.C. NIGAM)**

(K.N. KHATTRI) **(R.N. IYENGAR)**

(RAMESH CHANDER)