UNIQUE DESIGN OF CONCRETE GRAVITY HIGH DAM ON PERMEABLE FOUNDATIONS - APPLICATION OF NUMERICAL SIMULATION TOOL

NEETA ARORA AND GIRISH DEEXIT
Hydro Power & Dams (India), SMEC (Member of Surbana Jurong Group), Gurugram

NARINDER KUMAR JAIN
Shahpurkandi Dam Design Organisation, Water Resources Dept., Punjab, Chandigarh

ABSTRACT

Shahpurkandi Dam Project, a water infrastructure project across river Ravi in India is a National Project of Importance declared by Govt. of India, on completion will deliver significantly to the sustainable growth of Agriculture, Water supply and power needs of the state of Punjab and J&K, India in addition to generating 206MW of Hydropower further helping in efficient management of significant area under Upper Bari Doab Canal system, one of the oldest canal systems in India.

The 50.5m high dam under construction located in foothill sedimentary rocks of Upper Shiwalik formations is founded on permeable boulder bed/conglomerates. The uplift seepage pressures and exit gradient beneath the Dam have been calculated by Khosla's Theory and crosschecked by Goyal's Simplified Analytical Method evolved through independent and successive Schwarz-Christoffel Transformations, further validated by FEM numerical analysis. The foundation streses have been calculated conventionally/analytically further corroborated through structural design by 3D-FEM numerical simulation. Unlike the analytical approach, the numerical approach of analysis, especially the finite element method with the help of design and analysis software tools is capable of accounting for the variation in foundation media, which is a pointer to the advantage of numerical modelling approach of analysis as against analytical conventional method.

1. INTRODUCTION

Shahpurkandi dam project is under construction across river Ravi near Shahpurkandi village in Pathankot district of Punjab state in India. The project envisages construction of 50.50m high concrete dam across river Ravi which is located 11 km downstream of existing Ranjit Sagar dam. The water from the Ravi river will be stored upstream of the proposed dam and diverted so as to feed to the two canals, namely Shahpurkandi Hydel channel taking off from left bank and high level Ravi canal taking off from its right bank. This will harness the supplies released from Ranjit Sagar dam for providing irrigation to high lying areas of J&K and for power generation of 206 MW. This will also act as balancing reservoir for ensuring uniform supplies and to enable the power plant to work during peak hours.

ICOLD Bulletin 61, Dam Design Criteria, defines two objectives for dam safety decision making stated in terms of philosophy. The philosophy of design criteria, stated in terms of two basic criteria is that the objective is to create a "structural form together with the foundation and environment [that] will, most economically:

(i) Perform satisfactorily its function without appreciable deterioration during the conditions expected normally to occur in the life of the structure and,

(ii) Will not fail catastrophically during the most unlikely but possible conditions (extreme conditions) which may be imposed."

The ShahpurKandi Dam, a major component of India's national important water infrastructure project conceived for the sustainable growth of agriculture, water supply and power needs of the state of Punjab and J&K, India, is the first concrete gravity dam more than 50m high to be founded on boulder bed foundation. No other high concrete dam in the world has so far been founded on boulder bed foundations [refer Figure 1]. The Dam is designed consistent with the ICOLD Bulletin stated Dam design criteria.

Neeta Arora & Girish Deexit

Hydro Power & Dams (India), SMEC (Member of Surbana Jurong Group), Gurugram, India

Narinder Kumar Jain

Shahpurkandi Dam Design Organisation, Water Resources Dept., Punjab, Chandigarh,India

ABSTRACT:

Shahpurkandi Dam Project, a water infrastructure project across river Ravi in India is a Nationa Project of Importance declared by Govt. of India, on completion will deliver significantly to th sustainable growth of Agriculture, Water supply and power needs of the state of Punjab an J&K, India in addition to generating 206MW of Hydropower further helping in efficien management of significant area under Upper Bari Doab Canal system, one of the oldest cana systems in India.

The 50.5m high dam under construction located in foothill sedimentary rocks of Uppe Shiwalik formations is founded on permeable boulder bed/conglomerates. The uplift seepag pressures and exit gradient beneath the Dam have been calculated by Khosla's Theory an crosschecked by Goyal's Simplified Analytical Method evolved through independent an successive Schwarz-Christoffel Transformations, further validated by FEM numerical analysis The foundation streses have been calculated conventionally/analytically further corroborate through structural design by 3D-FEM numerical simulation. Unlike the analytical approach, th numerical approach of analysis, especially the finite element method with the help of design an analysis software tools is capable of accounting for the variation in foundation media, which is a pointer to the advantage of numerical modelling approach of analysis as against analytica

Fig. 1 : Dam construction in Boulder Bed foundation

2. GENERAL DAM AND FOUNDATION DESIGN

2.1 Hydro-Geological set-up

The geological reports of the Project have delineated the Upper Sivalik boulder bed interface in the dam spread and confirmed its compact nature. The report indicates that, the dam site is pre dominated by boulder bed of upper Sivalik formations. The boulder bed is in North West-South east direction with dip angle of 10 degree to 20 degree in South West. A number of thin lenticular sand lenses varying from 0.50m to 2.50m have been encountered in the boulder bed. In general the thickness of overburden comprising river terrace deposits varies from 9m to 22m. The boulder bed comprises about 70% clastics of size <10cm (occasionally reach 30cm) and 30% of matrix.

Plate load tests have been carried out during pre-construction and construction stage on boulder beds, RBM at foundation grade and sand lenses. Safe bearing capacity of 0.68 MPa in boulder bed has been observed for settlement of 6.14mm at EL. 358m at dam axis. Based on latest tests, permeability values of 54 - 64 lugeon have been reported in RBM at foundation grade in OF (Over Flow) section, while that in boulder bed from 4 to 34 lugeon.

2.2 Geo-technical Assessment

Based on the geological data, it is interpreted that the bedrock of boulder beds/ conglomerates is about 16-30m deep with the deepest portion up to EL.350m towards the left bank. However, the bedrock is interpreted to be shallow at about EL. 357m towards the right bank. This is attributed to the undulating profile of the bedrock due to river erosion.

The bedrock permeability range from 4-32 lugeon. Efforts have been made to delineate the low permeability boundary (<10 lugeon) in bedrock. The low permeability boundary is interpreted to be at EL. 345m towards right bank, EL. 340m in the center of the river and EL. 327m towards the left bank. The strata above these is interpreted to be permeable with the permeability values of >10 lugeon. However, higher values of 32 lugeon have also been reported at two places within boulder bed. This may be due to occasional presence of the sand lenses.

2.3 General Dam Design

The dam body mainly consists of Non Overflow (NOF) Section on both flanks and Overflow (OF) Section in between. The foundation level for the dam is EL.357m at which level boulder bed is encountered. For meeting the stability and seepage requirements, the dam section has been keyed into the boulder strata for a depth up to EL. 350m on the upstream. Top level of the dam is fixed at 407.5m. Crest elevation of the spillway is kept at 380m. The proposed spillway arrangement is designed for a Standard Project Flood (SPF).

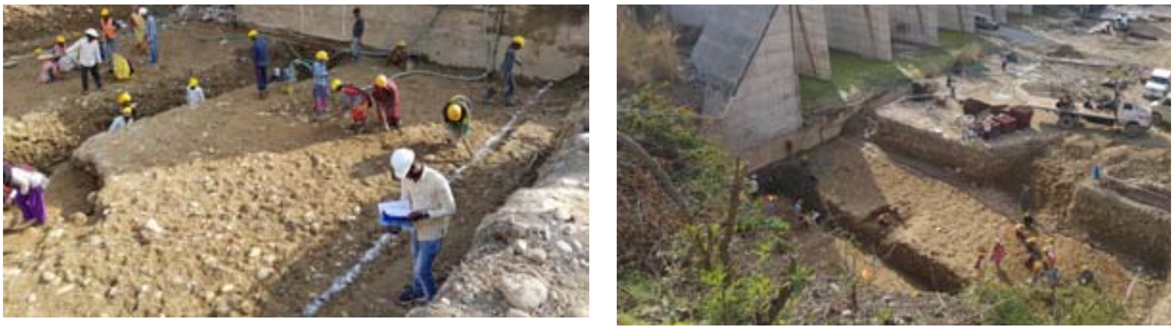

Figure. 1 Dam construction in Boulder Bed foundation

Fig. 2 : Boulder Bed with River borne Material delineated for excavation

2.4 Design Assumptions

The Dam blocks have been designed by making appropriate design assumptions based on engineering judgement of available data, reports, and relevant Indian Standard (IS) Codes and standard design practices. The Overflow, Non Overflow, Guide walls and Divide walls are designed as gravity structure and following aspects are considered while designing the various components.

(i) Analysis of stresses in the body of dam and in foundation follows elastic laws.

(ii) No lateral stress transfers to the abutments due to load transfer.

(iii) Factor of safety against sliding mainly governs the stability checking. The foundation for a Gravity Dam must be capable of resisting the applied forces without overstressing Dam or foundation itself.

Based on the geological data, it is interpreted that the bedrock of boulder beds/ conglomerates is about 16-30m deep with the deepest portion up to EL.350m towards the left bank. However, the bedrock is interpreted to be shallow at about EL. 357m towards the right bank. This is attributed to the undulating profile of the bedrock due to river erosion.

The bedrock permeability range from 4-32 lugeon. Efforts have been made to delineate the low permeability boundary (<10 lugeon) in bedrock. The low permeability boundary is interpreted to be at EL. 345m towards right bank, EL. 340m in the center of the river and EL. 327m towards the left bank. The strata above these is interpreted to be permeable with the permeability values of >10 lugeon. However, higher values of 32 lugeon have also been reported at two places within boulder bed. This may be due to occasional presence of the sand lenses.

2.3 General Dam Design

Fig. 3 : Dam Maximum over flow section

2.5 Foundation Design - Seepage Design

The longitudinal section of the dam shown in Figure-3 is considered for the seepage analysis. The length of upstream floor is 108 m comprising of 45m length of clay blanket and 63m length of overflow block and downstream floor constituting stilling basin is 70.5m. Clay blanket is proposed on the upstream to increase the seepage path of the sub-surface flow.

Conventionally Khosla's method or Lane's weighted creep theory are used to determine the uplift pressure and exit gradient. Calculations have also been done for uplift pressure using numerical simulation through FEM analysis and crosschecked by Goyal's Simplified Analytical method [ref.1] evolved through independent and successive Schwarz-Christoffel Transformations.

Results of numerical simulations show that floor thickness computed based on FEM works out less than that calculated from Khosla theory except near the downstream cut off.

2.5.1 *Seepage analysis using finite element method*

Seepage analysis was performed using SEEP-W software developed by Geo-Slope Inc. SEEP/W is a finite element CAD software for analyzing groundwater seepage and excess pore-water pressure dissipation problems within porous materials.

Finite element model was created from the dam geometry. The upstream and downstream water head was modeled using hydraulic boundary conditions.

3. APPLIED MODELS, PARAMETER AND ANALYSIS

3.1 FEM Models, Input Parameter and Analysis

3.1.1 *3-Dimensional FEM Analysis of Overflow Dam Block*

Commercially available structural numerical analysis software STAAD Pro, v 8i, has been used to model the overflow Dam Block between two contraction joints which was verified using two other FEM tools LUSAS and MIDAS. Same was also cross checked by a proof agency using ANSYS model. The 3-D finite element model of Intermediate 19m overflow block consists of two intermediate piers, breast wall and the bottom spillway concrete. The piers are 3.5m thick. The Dam has been modelled using 6 and 8 noded solid elements. The variations in geometry are taken into consideration for deciding the mesh density and element size. In general mesh size of 2m x 2m x 2m has been maintained in uniform geometry region of spillway and breast wall [refer figure 4, 5a and 5b]. For piers, mesh size of 0.5m has been provided in Z direction for close to actual modelling of u/s curved portion. Areas where stress concentrations were found to be abnormal were identified in the model. Element shape and size in such areas were modified to get desirable stress patterns. Geometric optimization has been carried out in the model for stress convergence.

A 3-D Finite element model has been used to examine the behavior of piers, breast wall and spillway structure. The dam is presumed to be resting on flexible foundation having modulus of subgrade reaction of 60000 kN/m2/m. The value of subgrade modulus is based on the plate load test results. The various views and components as modelled have been shown below:

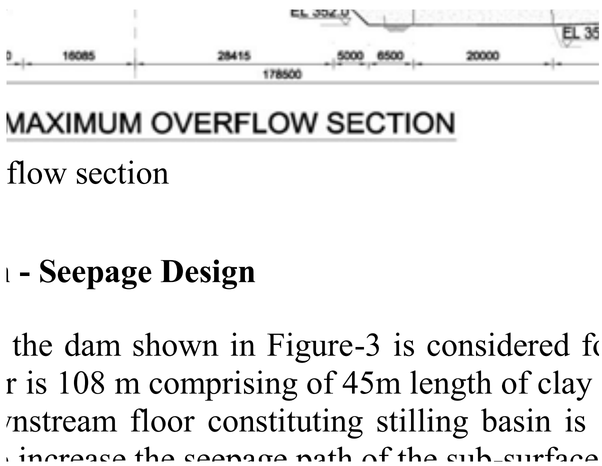

Fig. 4 : Finite Element Mesh and Boundary conditions - 3D Overflow section

umerical simulation through FEM analysis and crosschecked by Goyal's Simplified Analytical nethod [ref.1] evolved through independent and successive Schwarz-Christoffel 'ransformations.

Results of numerical simulations show that floor thickness computed based on FEM works ut less than that calculated from Khosla theory except near the downstream cut off.

.5.1 Seepage analysis using finite element method

eepage analysis was performed using SEEP-W software developed by Geo-Slope Inc. EEP/W is a finite element CAD software for analyzing groundwater seepage and excess pore- vater pressure dissipation problems within porous materials.

Finite element model was created from the dam geometry. The upstream and downstream vater head was modeled using hydraulic boundary conditions.

Fig. 5a : Overflow Block perspective view

Fig. 5b : Finite Element Mesh

The variation of magnitude of the seismic force is proportional to inertia component which is maximum at the top and reduces as per the variation of the z coordinate. Hydrodynamic effects due to reservoir have been calculated and applied to the model as per the provisions of Cl. 7.2 of IS 1893: 1984.

Apart from self-weight of the structure and hydro-mechanical loads, hydrostatic pressures, earth pressure on U/S side has been considered in the analysis for fill level up to EL 372m. Uplift forces as per cl. 3.3.5 of IS 13551:1992 has been applied as a body force. The displacement, vertical, major, minor principal stress and maximum shear stress contours have been studied for various load combinations described in Cl. 4.1 of IS: 6512-1984.

3.1.2 *Load Combinations & permissible stresses*

Load combinations considered in the analysis cater to the normal situations without any earthquake and normally functioning foundation drains and extreme situations when the Dam experiences Design Basis Earthquake with non-functional foundation drains. Accordingly, numerical simulations for the stress-deformation analysis for following operating conditions as per cl. 4.1 of IS 6512:1978 has been considered as A - Construction condition; D - Construction condition with earthquake; B-Normal operating condition; E- Normal operating condition (drains operative) with earthquake; G - Normal operating condition (drains inoperative) with earthquake C-Flood discharge condition; F-Flood discharge condition with extreme uplift (ie., drains inoperative). Correspondingly, for load condition A,B & D no tensile stresses in mass concrete of grade M20 are permitted while, for load condition C,E,F & G, tensile stress of 0.2MPa,0.4MPa,0.4MPa and 0.8MPa is permitted.

3.1.3 *Allowable bearing pressures*

Plate load tests have been carried out during pre-construction and construction stage on boulder beds, RBM at foundation grade and sand lenses. Safe bearing capacity of 0.68 MPa in boulder bed has been observed for settlement of 6.14mm at El. 358m at dam axis.

Tests in NOF and OF sections on boulder bed show the values of 1.37MPa for a settlement ranging between 13.3mm to 16.68 mm. Bearing capacity of 1.02MPa was obtained for settlement of 29.5mm in sand lens at foundation grade. For RBM at foundation grade, bearing capacity comes out to be 1.37 MPa for a settlement of 20.06mm. Exceptionally high bearing capacity of 1.77MPa has also been reported in calcareous conglomerates.

3.1.4 *Results of Analysis & Discussion*

The structural analysis results showed that the designed overflow section is safe against sliding for all the loading conditions for the given input material and loading data based on site specific investigations. The bearing pressures at the heel and toe of the dam are within acceptable limits i.e. less than 0.69 N/mm2 for non-seismic condition and 0.92 N/mm2 for seismic condition.

It is observed that Load conditions A, B, D and E are most critical for analyzing behavior of dam. Typical stress distribution (+ve stress indicates tension in solid Elements, whereas - ve stress indicates compression in solid Elements) for load case E is shown below [refer figure 6,7,8 & 9]:

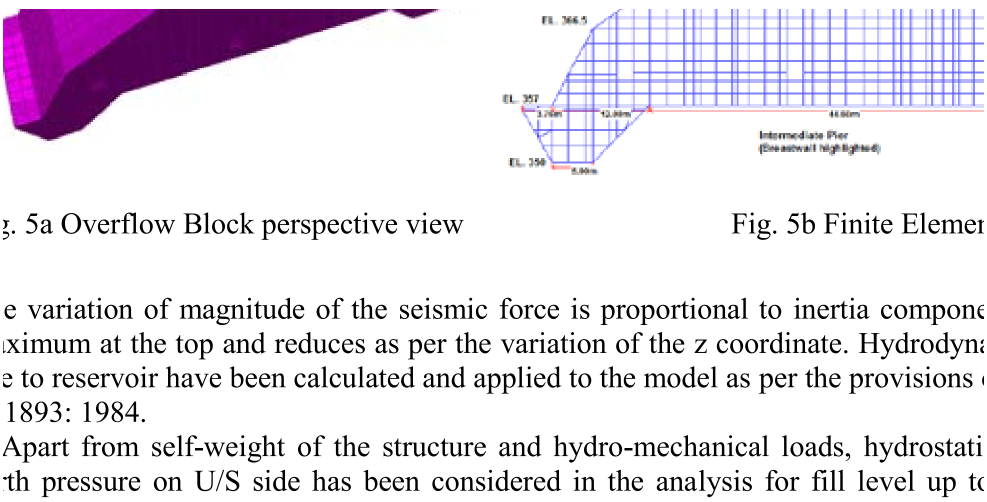

Fig. 6 : Stress distribution in Piers for vertical Reinforcement for Load Case E With +Z Earthquake

It can be seen that the junction zone of pier and spillway experience tensile stresses and hence need to be steel reinforced as vertical and horizontal anchorages which has been evaluated for the tension area. Anchorages are extended at least up to the zero tensile contours obtained from the model. Breast wall also has been reinforced in accordance with stress distribution.

experiences Design Basis Earthquake with non functional foundation drains. A
numerical simulations for the stress-deformation analysis for following operating c
per cl. 4.1 of IS 6512:1978 has been considered as A - Construction condition; D - C
condition with earthquake; B-Normal operating condition; E- Normal operatin
(drains operative) with earthquake; G - Normal operating condition (drains inope
earthquake C-Flood discharge condition; F-Flood discharge condition with extrem
drains inoperative). Correspondingly, for load condition A,B & D no tensile stres
concrete of grade M20 are permitted while, for load condition C,E,F & G, tens
0.2MPa,0.4MPa,0.4MPa and 0.8MPa is permitted.

3.1.3 Allowable bearing pressures

Plate load tests have been carried out during pre-construction and construction stag
beds, RBM at foundation grade and sand lenses. Safe bearing capacity of 0.68 MP
bed has been observed for settlement of 6.14mm at El. 358m at dam axis.

Tests in NOF and OF sections on boulder bed show the values of 1.37MPa for
ranging between 13.3mm to 16.68mm. Bearing capacity of 1.02MPa was c
settlement of 29.5mm in sand lens at foundation grade. For RBM at foundation gr
capacity comes out to be 1.37 MPa for a settlement of 20.06mm. Exceptionally l

Fig. 7 : Stress distribution in Breast wall for Vertical Reinforcement for Load Case E with Earthquake force acting from U/S to D/S

The structural analysis results showed that the designed overflow section is
sliding for all the loading conditions for the given input material and loading data b
specific investigations. The bearing pressures at the heel and toe of the dam
acceptable limits i.e. less than 0.69 N/mm^2 for non-seismic condition and 0.92
seismic condition.

It is observed that Load conditions A, B, D and E are most critical for analyzing
dam. Typical stress distribution (+ve stress indicates tension in solid Elements, v
stress indicates compression in solid Elements) for load case E is shown below
6,7,8 & 9]:

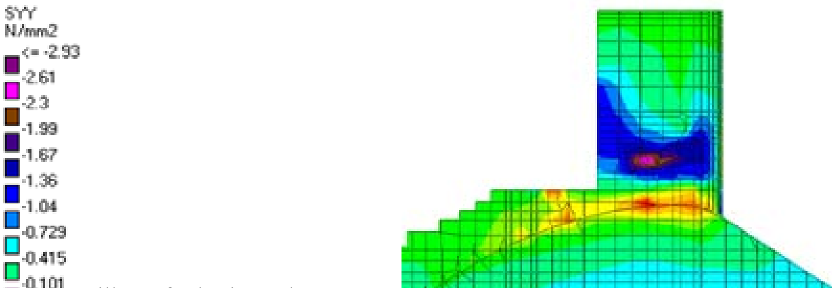

Fig.8 : Stress distribution in spillway for horizontal anchorages for Load Case E with Earthquake in –Z direction U/S SIDE FACE

hat the junction zone of pier and spillway experience tensile stresses and hence
einforced as vertical and horizontal anchorages which has been evaluated for
Anchorages are extended at least up to the zero tensile contours obtained from
wall also has been reinforced in accordance with stress distribution.

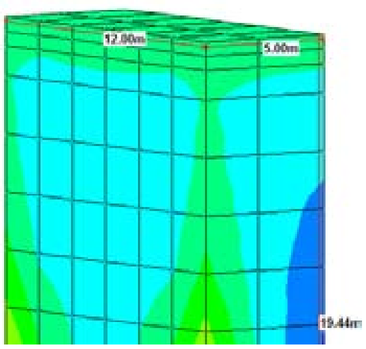

Fig. 9 : Stress distribution in spillway for horizontal anchorages for Load Case E with Earthquake in + Z direction

3.1.5 *Seepage Analysis using Finite Element simulation*

Finite element model was created from the dam geometry. The upstream and downstream water head was modeled using hydraulic boundary conditions.

Seepage analysis using commercial software SEEP/W has been carried out to observe the effect of upstream clay blanket on exit gradient and uplift pressure distribution over the foundation to estimate the floor thickness required with a parametric study of the effect of conductivity on uplift pressure.

The hydraulic conductivity of the layered foundation has been idealized based on site specific investigation into four layers namely layer 1 as RBM (River Born Material) in terms of 1000 lugeon, second layer as boulder bed with permeability values of 20 lugeon third layer 12 lugeon and fourth deep foundation layer with 10 lugeon.

Based on available geological information, the seepage analysis has been performed on possible three cases described above section simulated as per the hydro-geology of the foundation, so as to cater to the critical conditions for uplift and exit gradient. Calculations have been done for uplift pressure using both FEM (Finite Element Analysis) analysis and Khosla theory. Results of calculations show that floor thickness by FEM is comparable to that calculated from Khosla theory except near the downstream cut off.

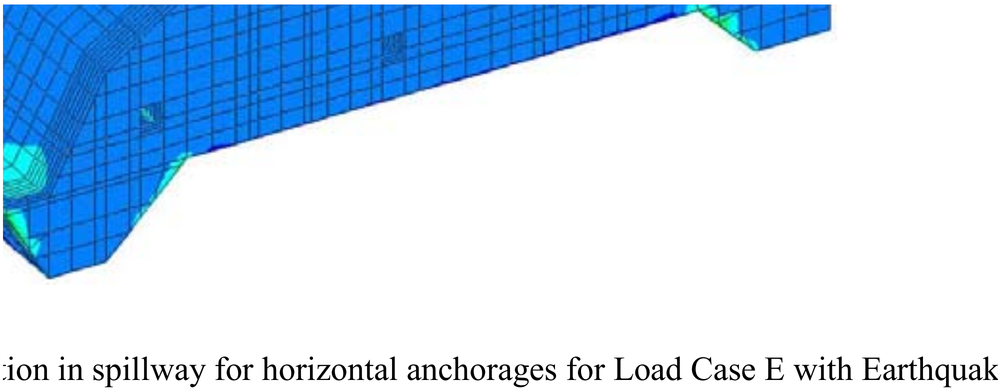

Fig. 10 : Flow net Diagram for Case 1 type permeable foundation to semi-infinite extent

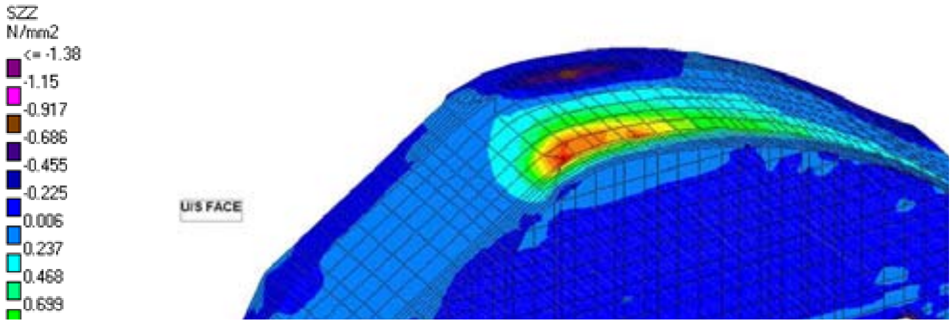

Fig. 11 : Case 2 type foundation Strata

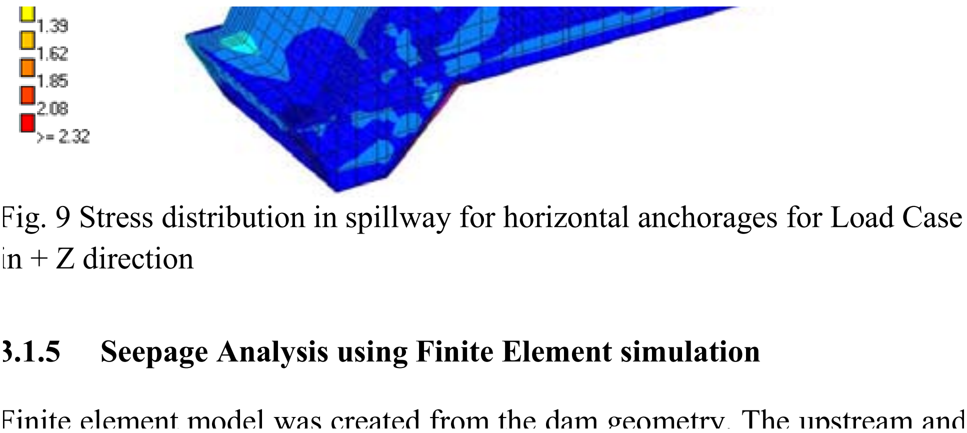

Fig. 12 : Flow net Diagram for Case 2 type foundation (Drains Inoperative)

:ct of upstream clay blanket on exit gradient and uplift pressure distribution over the ndation to estimate the floor thickness required with a parametric study of the effect of .ductivity on uplift pressure.

'he hydraulic conductivity of the layered foundation has been idealized based on site specific estigation into four layers namely layer 1 as RBM (River Born Material) in terms of 1000 eon, second layer as boulder bed with permeability values of 20 lugeon third layer 12 lugeon l fourth deep foundation layer with 10 lugeon.

3ased on available geological information, the seepage analysis has been performed on sible three cases described above section simulated as per the hydro-geology of the ndation, so as to cater to the critical conditions for uplift and exit gradient. Calculations have n done for uplift pressure using both FEM (Finite Element Analysis) analysis and Khosla

Fig. 13 : Case 3 type foundation strata

calculated from Khosla theory except near the downstream cut off.

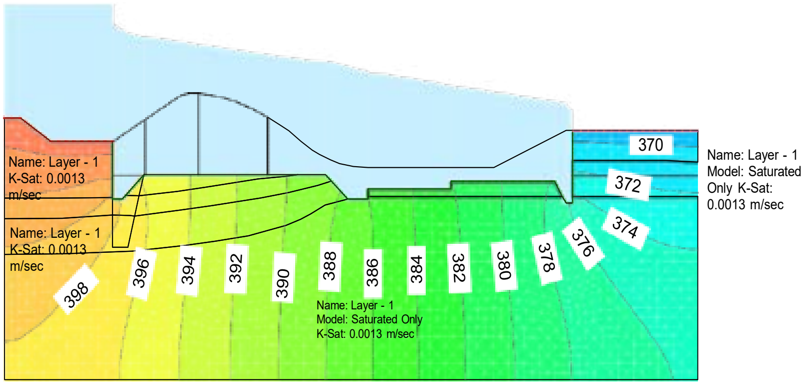

Fig. 10 Flow net Diagram for Case 1 type permeable foundation to semi-infinite extent

Fig. 14 : Flow net Diagram for Case 3 type foundation (Drains Inoperative)

Case-1simulates situations of entire Dam being founded on higher permeable foundation, case-2 being the Dam founded on boulder bed of low permeability while case-3 corresponding to medium permeable foundation. Case-2 results in higher uplift pressures for downstream raft thickness design.

Table 1 : Comparison of floor thickness using FEM Analysis with Khosla's Theory

S. No.	Distance from d/s cut off towards upstream 'm'	Floor Level of Barrage	Floor thickness using Khosla Theory after accounting for weight of water 'm'	Floor thickness using Seep/W after accounting for weight of water 'm'
1	10	365.50	2.10	4.36
2	20	360.50	0.56	2.28
3	30	359.00	0.77	1.67
4	40	359.00	1.64	2.52
5	50	359.00	2.52	2.53
6	60	359.00	3.39	2.54
7	70	359.38	4.37	3.97

4. CONCLUSIONS

The design of the more than 50m high concrete gravity dam on boulder foundation, discussed in this paper is unique in following aspects:

(a) This is the first high concrete dam in the world to be founded on boulder bed foundation.

(b) Numerical simulation tools are of great help in iterative design of Dam while modeling the site specific in-put parameters which otherwise incur greater approximations in manual computations.

(c) FEM analysis of the seepage flow through the foundation has been carried out in addition to the conventional Khosla's method and Lane's weighted creep theory further cross checked by Goyal's simplified analytical method to determine seepage uplift pressure on the Dam structure and the exit gradient.

(d) FEM analysis of stress and strains in the concrete dam and in the foundation material has been carried out considering their material elastic properties and found that the stresses and strains in the concrete structure remain within the permissible limits under all conditions of loading.

REFERENCES

Goyal, Mangat R. Seepage uplift pressures beneath structures on permeable foundations in Volume 5B/RNI, No.2 May 2015, Water and Energy International, Central Board of Irrigation & Power, New Delhi