

RESULTS AND DISCUSSIONS

5.0 General

Formulation of transient uplift model is validated using the data from Javanmardi et. al. (2005b). CMOD rate generating function, derived in Chapter 4 has been used to show and discuss the transient uplift pressures for opening and closing mode of the crack located at slope-changing point and dam-foundation interface of the dam. Validation of the transient uplift pressures due to reservoir level variation in different cracks located at different locations along the upstream face of the dam is ensured through the comparison of calculated and field data of dam-crown deflections. Because of lack of data, various assumptions regarding crack geometry, crack locations etc., are made and validated through the results obtained for dam-crown deflections. Finally, stability against sliding, using USACE factor of safety criteria, in sliding, is compared with present result of transient uplift pressure.

5.1 Verification of Transient Uplift Pressure Formulation

In present study, transient uplift pressure plays an important role in mathematical modeling of dam-crown deflection and sliding stability. Therefore, it is important to verify the present uplift pressure formulation described in Chapter 3. Experimental data for transient uplift pressure in Javanmardi et. al. (2005b) for existing 4m long wedge shaped crack is adopted to verify the present model. Crack mouth subjected to a constant pressure of 500kPa, was imparted to a sinusoidal motion of 2 Hz with residual and maximum crack mouth opening of 0.5mm and 1.0mm

respectively. Thus CMOD function and CMOD-rate (also called Crack Mouth Opening Velocity (CMOV)) is represented respectively as

$$b_m = 1.0 + 0.5 \sin(1.5 + 4t)\pi \text{ mm} \quad (5.1)$$

and

$$\dot{b}_m = 2\pi \cos(1.5 + 4t)\pi \text{ mm/s} \quad (5.2)$$

Where, t is the time in seconds. Above functions are represented graphically in Figs.5.1 and 5.2.

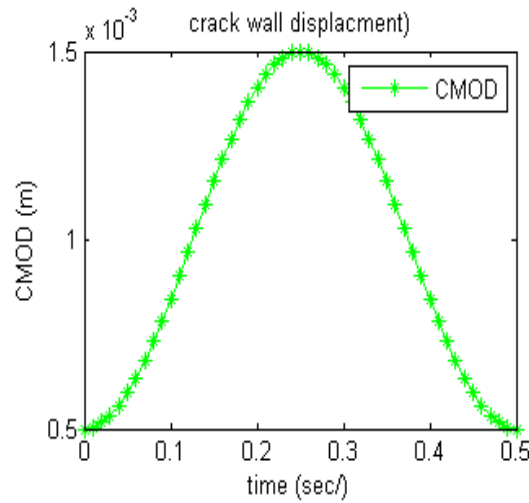


Fig.5.1. CMOD Vs. time plot of Equation 5.1.

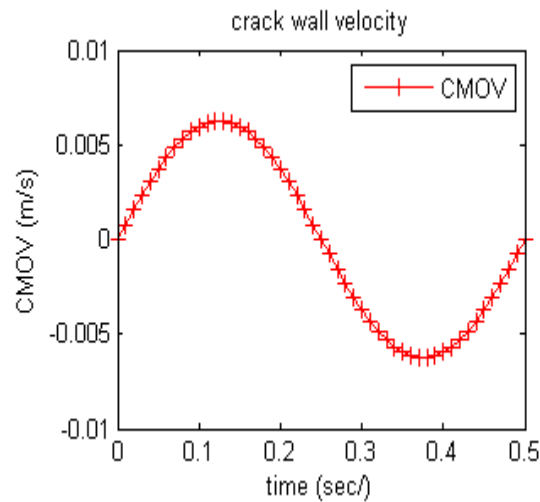


Fig.5.2. CMOV Vs. time plot of Equation 5.2.

At the beginning, uplift pressure in the crack is assumed to be uniform and equal to crack mouth pressure i.e 500kPa. From time $t=0s$ crack mouth opens at residual opening of 0.5mm and reaches to its maximum value of 1.5mm to at $t=0.25s$. At end of one cycle i.e. at time $t=0.5s$, crack mouth acquires its initial crack mouth of 0.5mm and uniform pressure of 500kPa. Time independent constants in pressure formulation for water at $25^{\circ}C$ are given in the Table 5.1. These constants will also be used in the uplift pressure calculations in cracks of the dam problem.

Table 5.1 Time Independent constants used in the transient uplift pressure formulations.

Time Independent Constants	SI Unit	Value
Unit weight of water, γ	$[ML^{-2}T^{-2}]$	10000
Kinematic Viscosity ν	$[L^2T^{-1}]$	7.24×10^{-7}
Relative Roughness ε/D_h	-	0.5
Transitional Reynolds No. R_e	-	2300
C_2	$[L^{-1}T^{-1}]$	2.762×10^5
C_3	$[L^{-1}T^{-2}]$	52.7612

Result of present formulation and few of the experimental data of Javanmardi et. al. (2005b) are compared and shown in Figs.5.3 and 5.4.

A difference between computed and measured value of uplift pressure seems a slightly more (less than 5%) at the beginning ($t=0.001s$) and at the end ($t=0.43s$) of the cycle in comparison to other point of time. The differences between computed values from the present model and measured values by Javanmardi et. al. (2005b) for beginning and end of the cycles may be due to

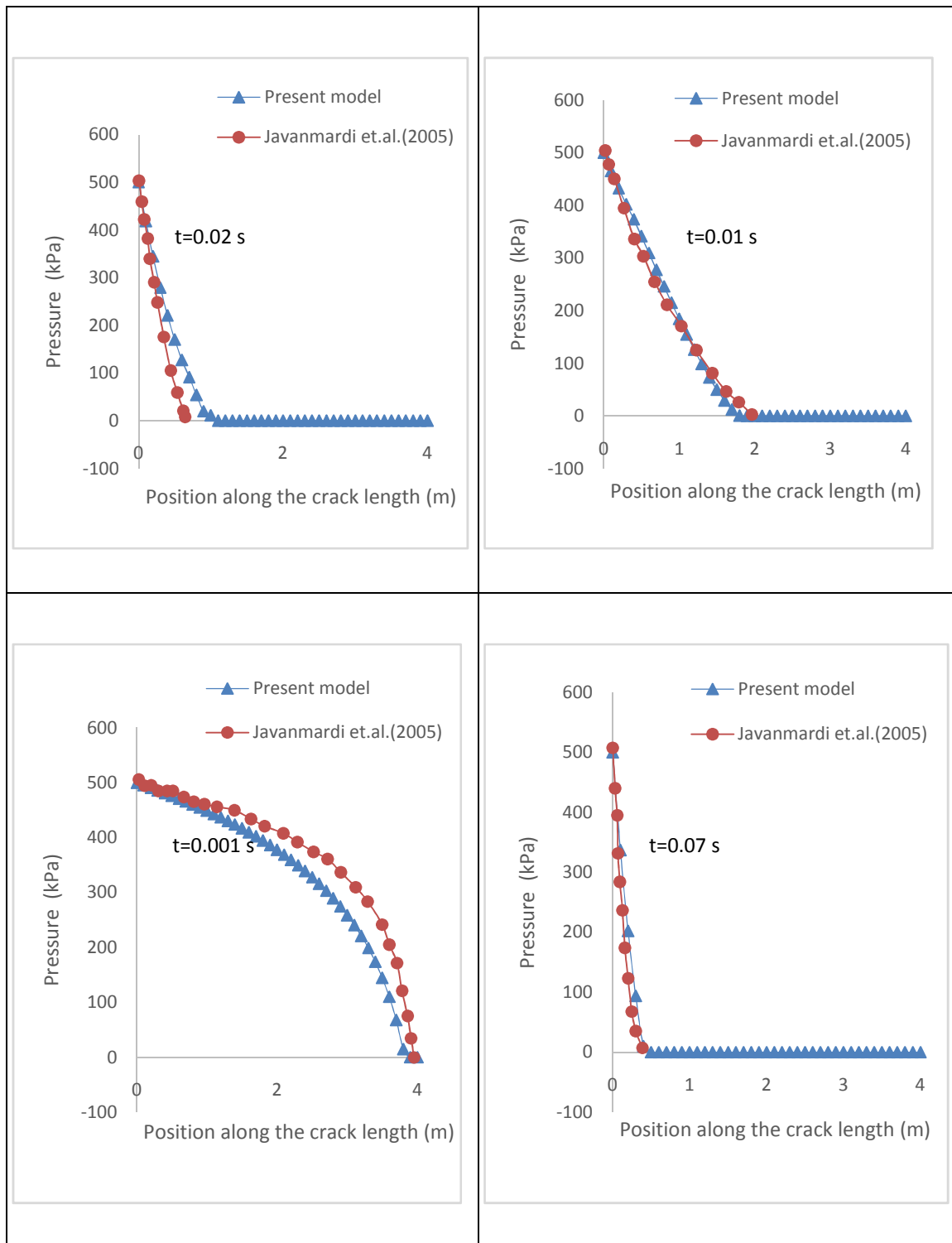


Fig.5.3. Pressure variation along the crack during opening mode at time $t=0.001, 0.01, 0.02$ and $0.07s$.

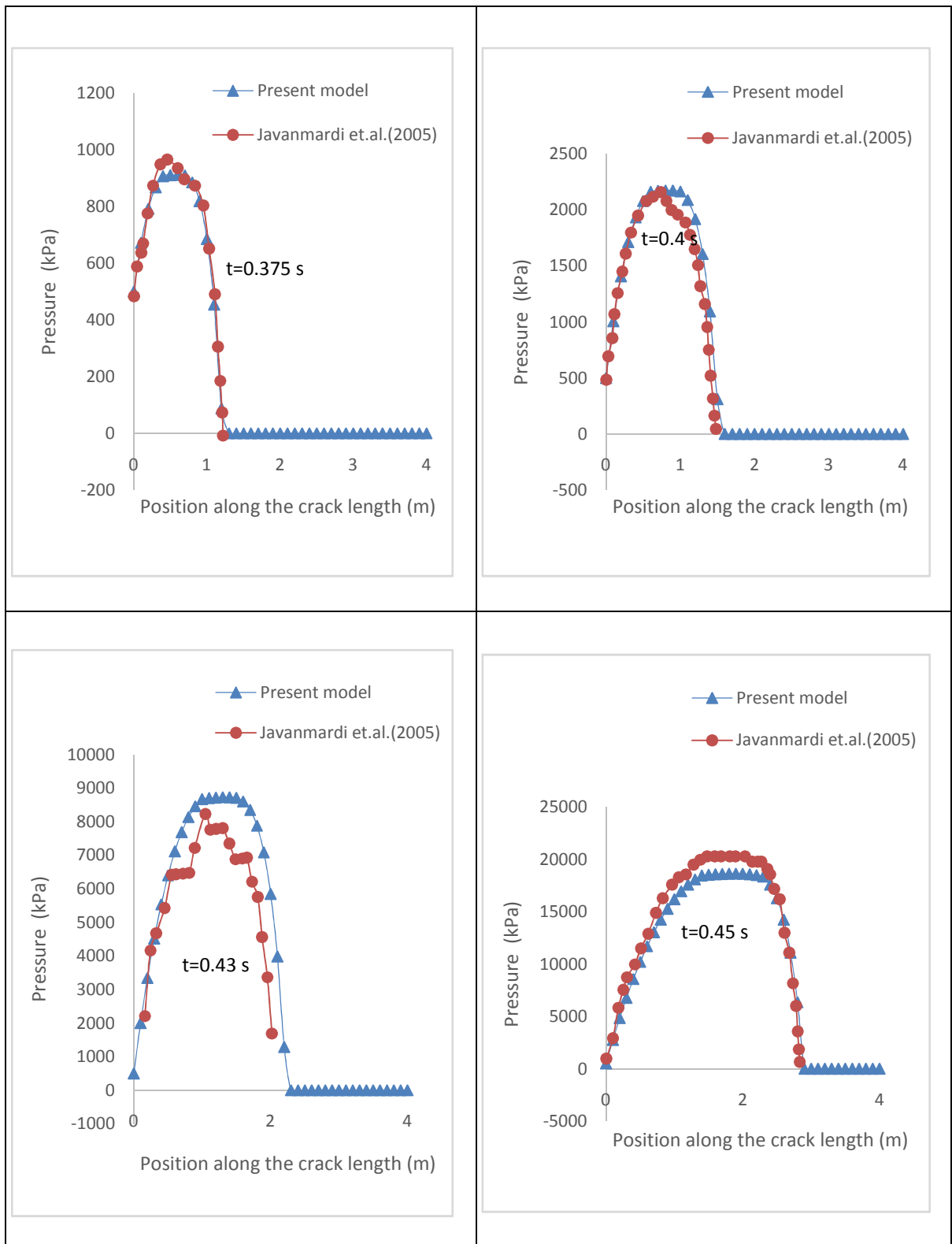


Fig.5.4. Pressure variation along the crack during closing mode at time $t=0.375, 0.4, 0.43$ and 0.45 s.

error in experimental measurement or due to difference in the assumed boundary conditions used in the mathematical formulation (e.g. vapor pressure at point of saturation may not be zero and two-phase flow may occur in unsaturated portion of the crack) and needs verifications. However, overall computed pressure variation, obtained using present formulation are in good agreement with measured data of Javanmardi et. al. (2005b).

After validation of present formulation for transient uplift pressure calculation, it is adopted subsequently for cracks in the dam with suitable concept of CMOD-rate generating function under the reservoir level variation.

5.2 Uplift Pressure in Cracks

The uplift pressures are calculated for each year by adopting the crack parameters described in Chapter 4. Monthly reservoir level variations are given in Fig.5.5(a) to 5.5(f). Pressure at the crack mouth is assumed to be hydrostatic. In present problem, it is assumed that, the crack mouth pressure changes at end of each month due to reservoir level variation and remains constant in subsequent month. This month-wise crack mouth pressure is applied each time at the beginning of each ensuing month. However, the CMOD rate, calculated using functions, discussed in chapter 4, assumed to be continuous and same as in prototype.

Here, the result of uplift pressure at heel (crack-1) and at slope changing (crack-4) point for all years of record is presented and discussed after assuming a crack length of 10 m at each of these points. Uplift pressure at crack-1 and crack-4 are shown in the Figs. 5.6 and 5.7.

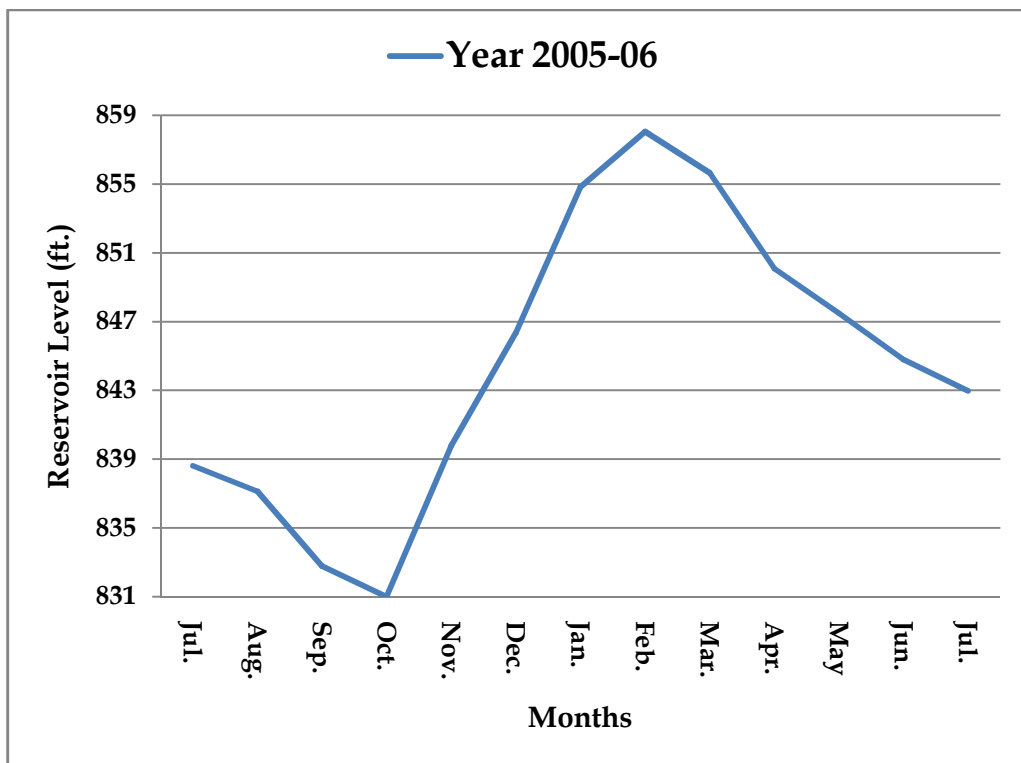


Fig.5.5(a). Monthly reservoir level (ft.) variation for the year 2005-06.

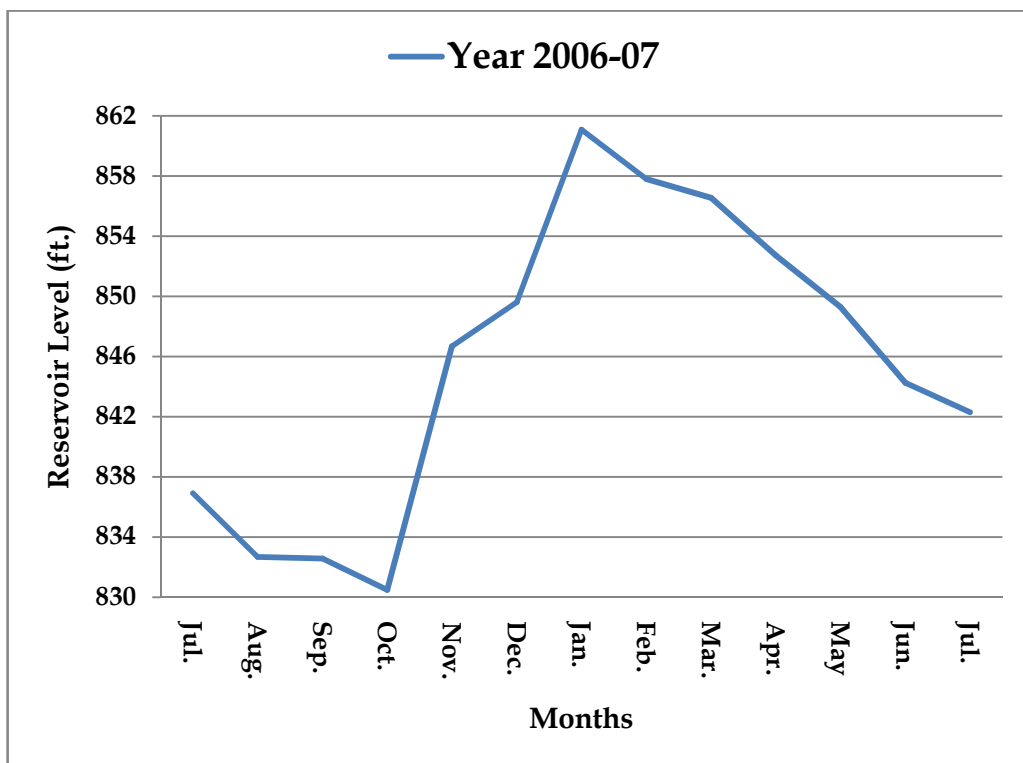


Fig.5.5(b). Monthly reservoir level (ft.) variation for the year 2006-07.

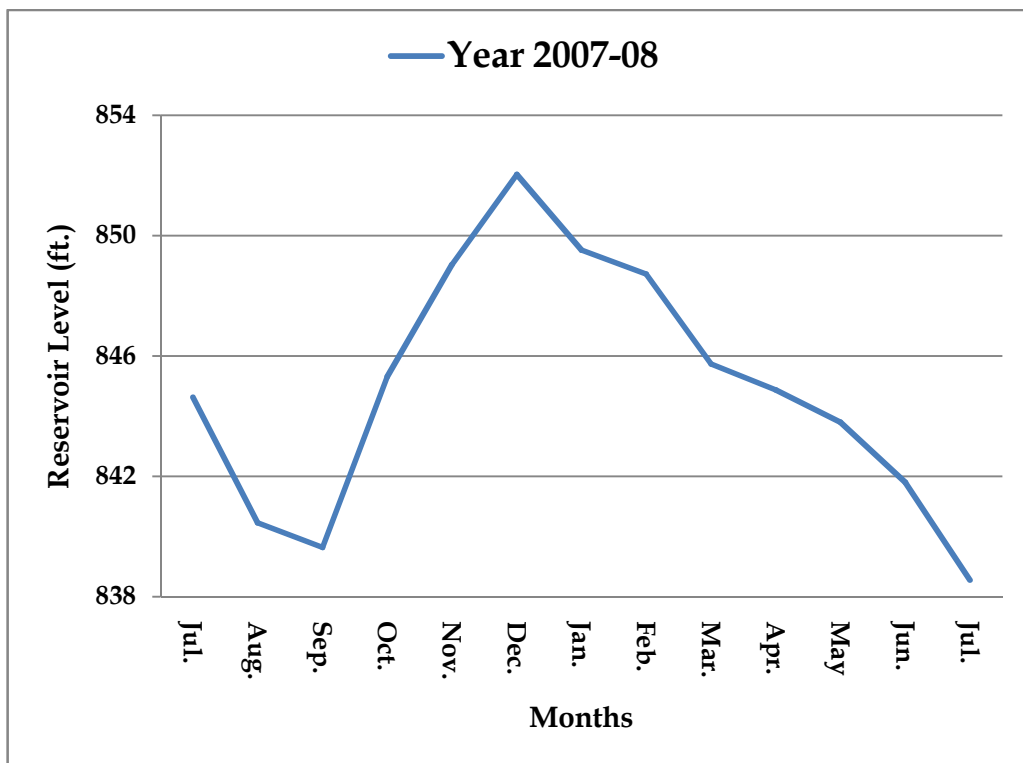


Fig.5.5(c). Monthly reservoir level (ft.) variation for the year 2007-08.

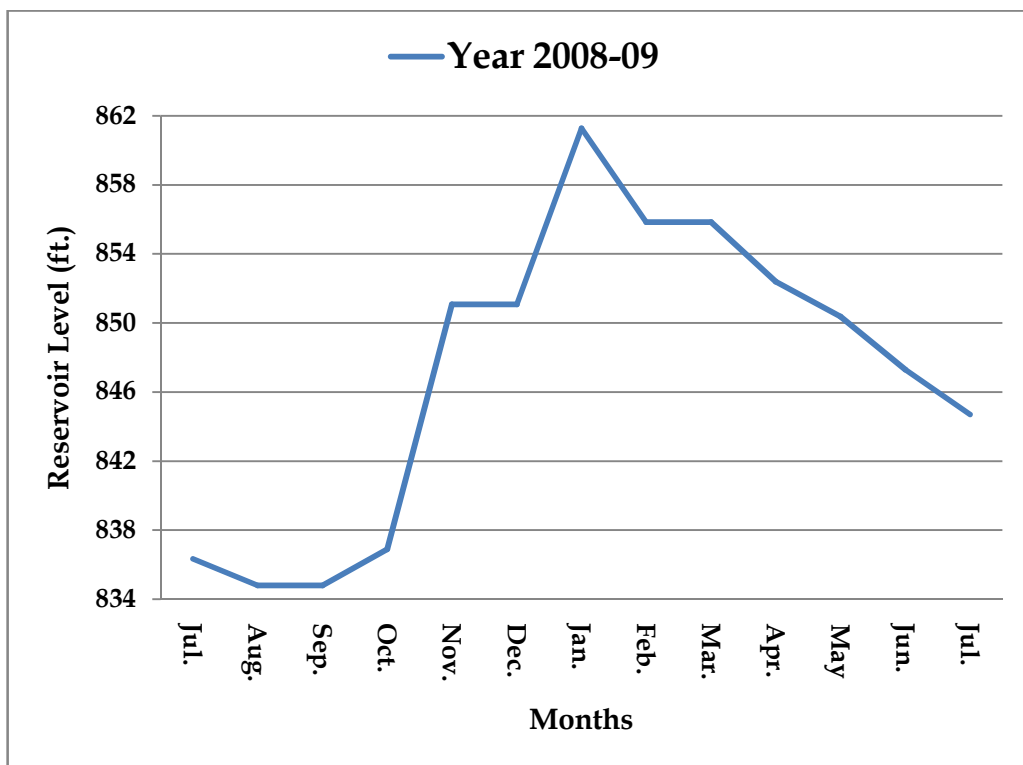


Fig.5.5(d). Monthly reservoir level (ft.) variation for the year 2008-09.

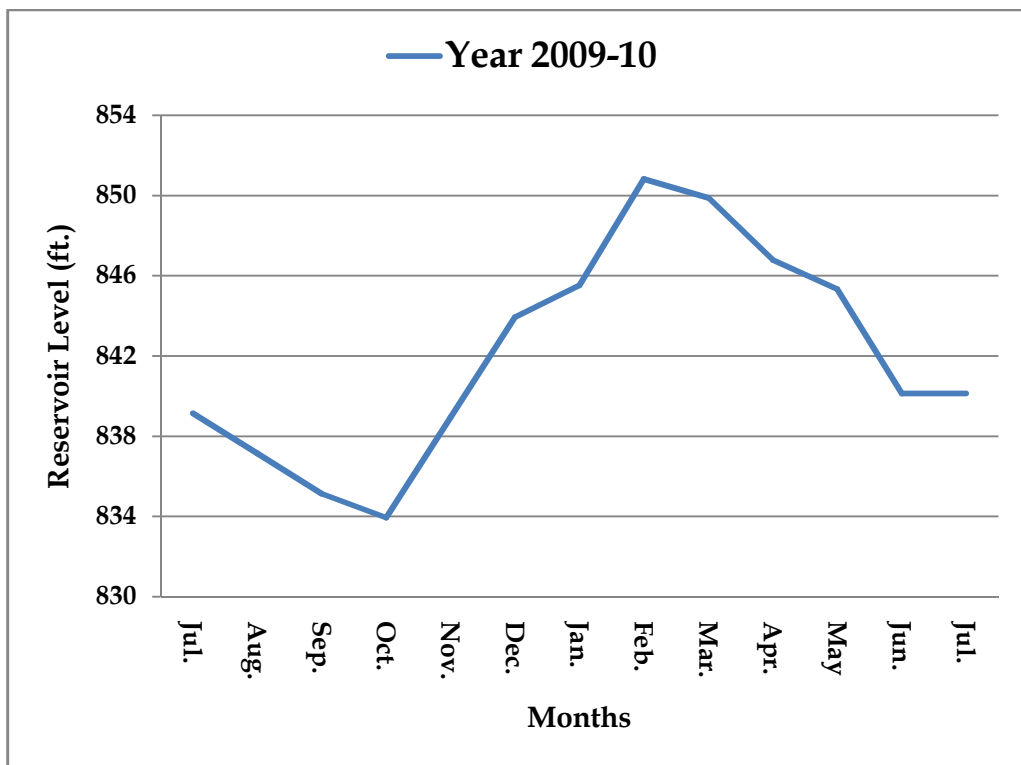


Fig.5.5(e). Monthly reservoir level (ft.) variation for the year 2009-10.

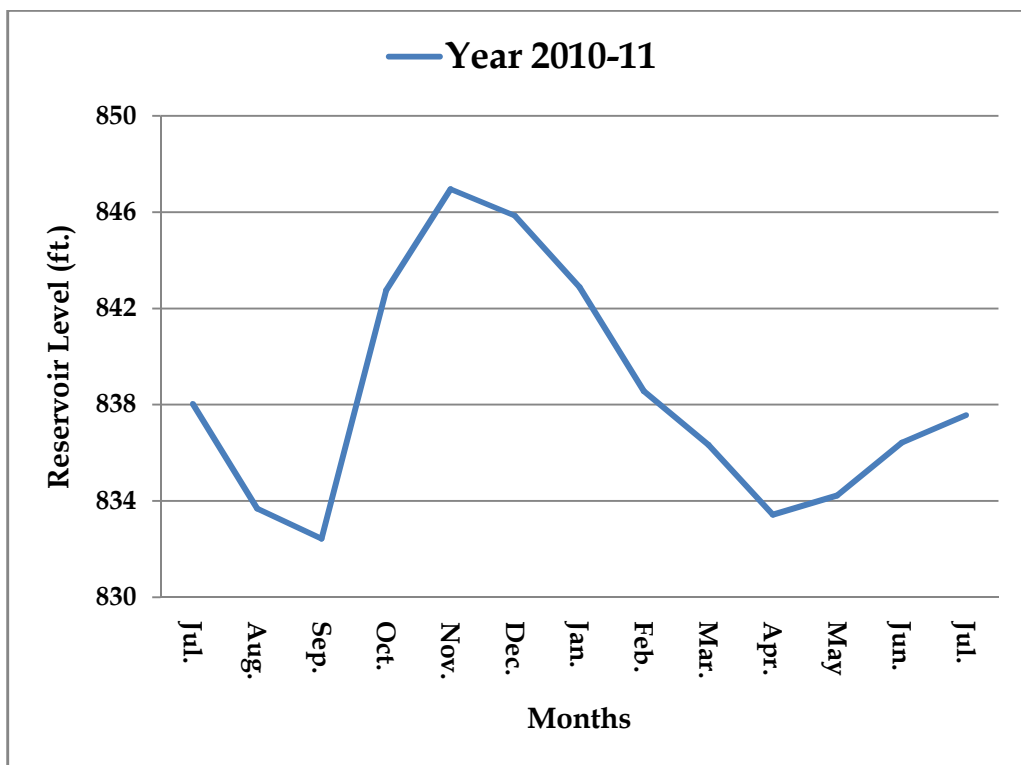


Fig.5.5(f). Monthly reservoir level (ft.) variation for the year 2010-11.

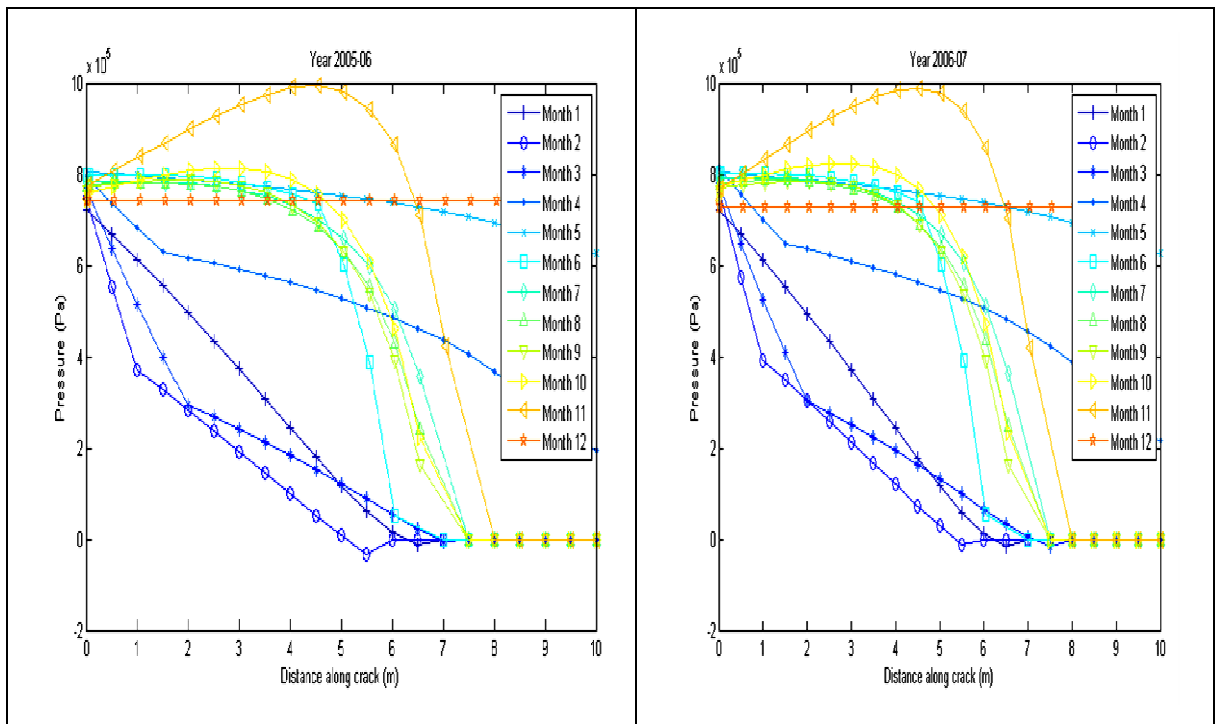


Fig.5.6(a). Uplift pressure variation at crack-1 (At the heel of the dam) for the year 2005-06 and 2006-07.

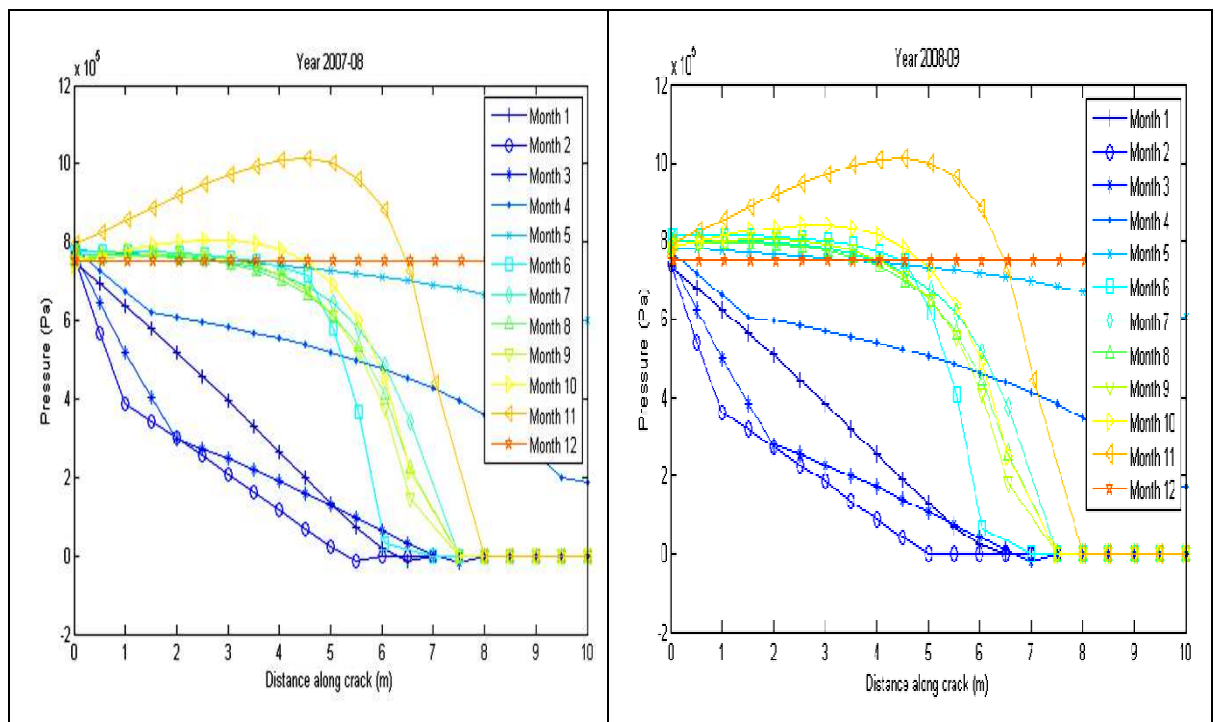


Fig.5.6(b). Uplift pressure variation at crack-1 (At the heel of the dam) for the year 2007-08 and 2008-09.

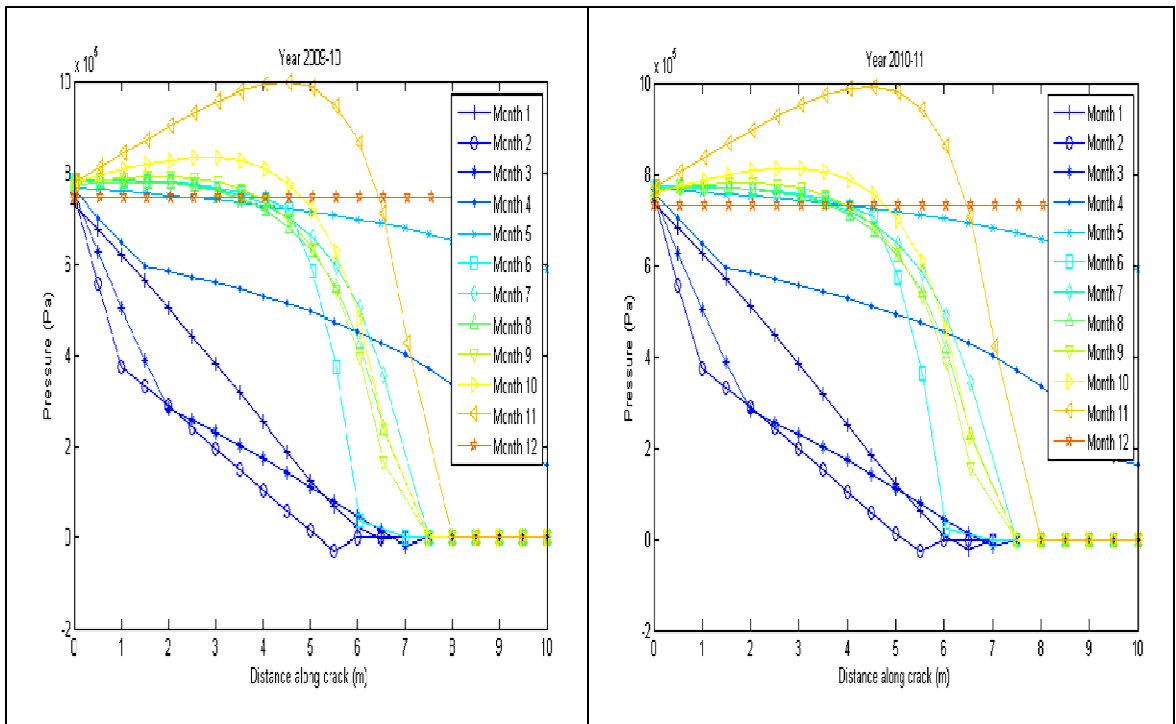


Fig.5.6(c). Uplift pressure variation at crack-1 (At the heel of the dam) for the year 2009-10 and 2010-11.

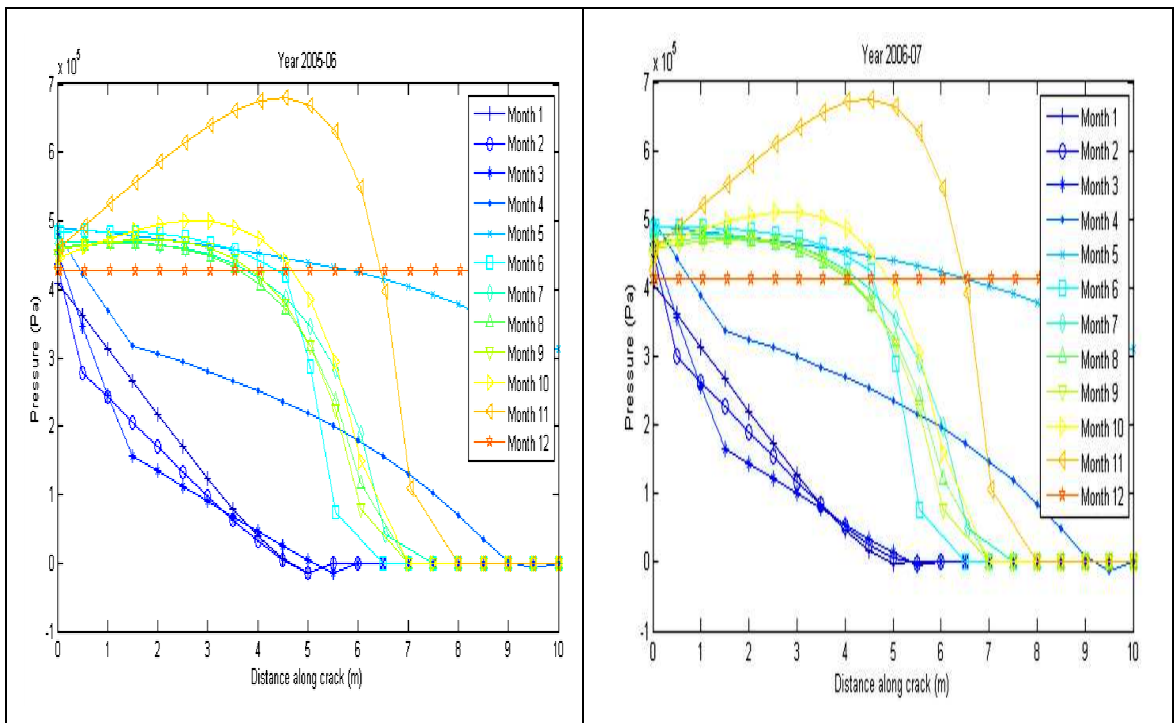


Fig. 5.7(a). Uplift pressure variations at crack-4 (Slope changing point) for the year 2005-06 and 2006-07.

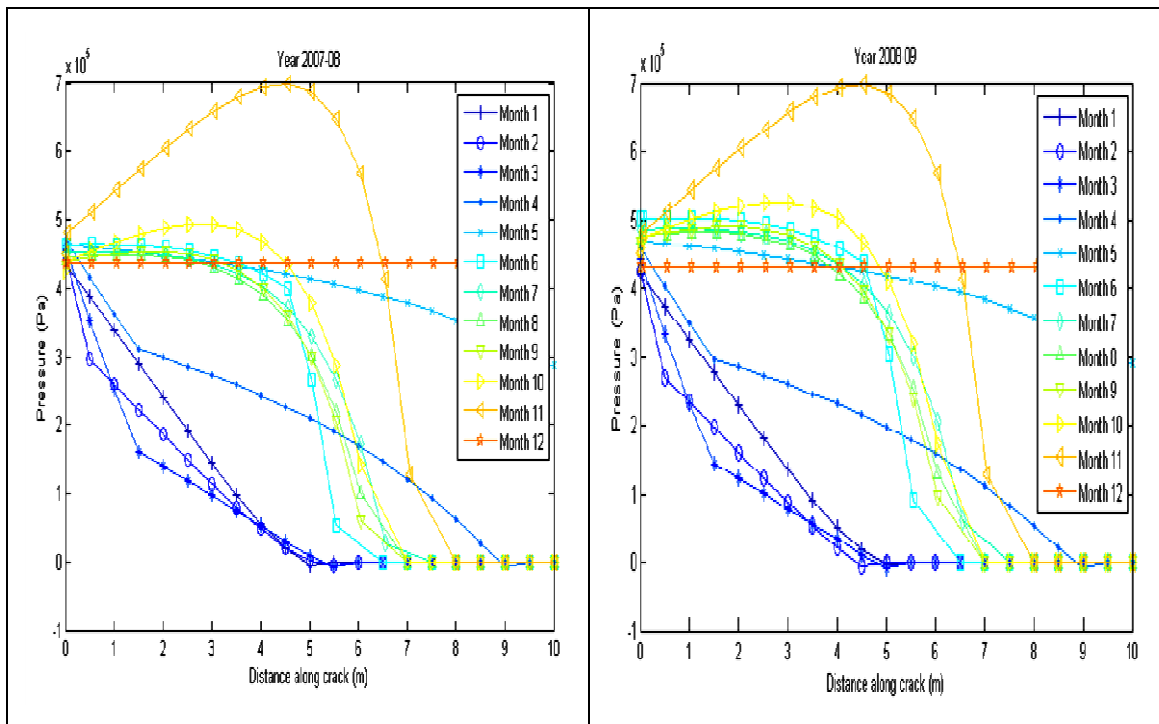


Fig. 5.7(b). Uplift pressure variations at crack-4 (Slope changing point) for the year 2007-08 and 2008-09.

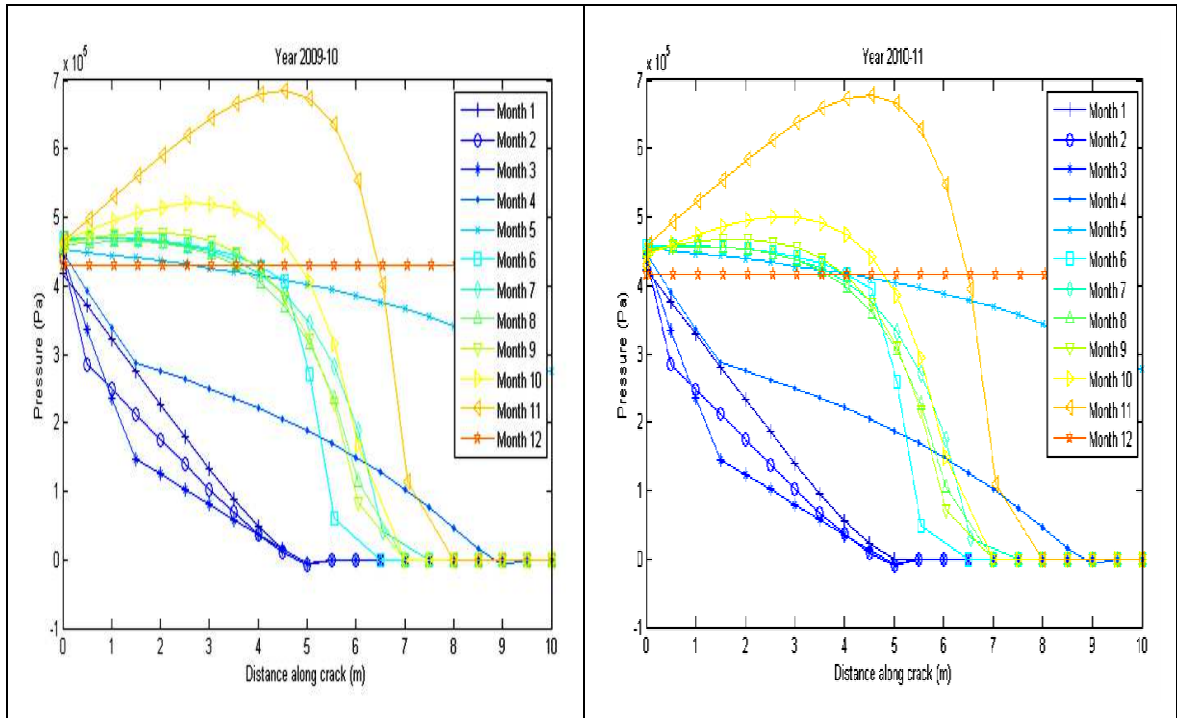


Fig. 5.7(c). Uplift pressure variations at crack-4 (Slope changing point) for the year 2009-10 and 2010-11.

During first three months, crack opening saturation length at the heel (crack-1) is 70-75% while the saturation length at the slope- changing point (crack-4) is 60-65%. This indicates that total uplift pressure during this period decreases. But in fourth month, total uplift pressure begins to increase with increased saturation length, more than 90% of crack length at both crack-1 and crack-4. However, in fifth and sixth months of opening phase, both the cracks are subjected to increased uplift pressure with decreased saturation length. During opening phase, the peak pressure always remains equal to mouth pressure. But during closing phase, peak uplift pressure begin to go beyond applied crack mouth pressure and reaches maximum value in eleventh month. During the closing period, total uplift pressure increases with increasing saturation length.

5.3 Dam-Crown Deflection versus Reservoir Level Variations

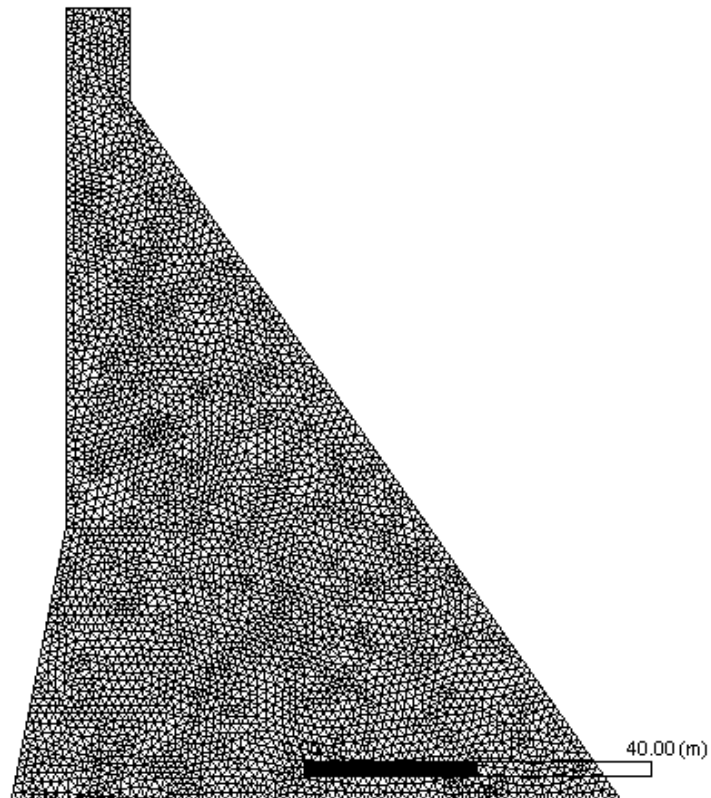
Assuming the applicability of linear elastic fracture mechanics, FEM formulation for plane-strain condition is implemented using the ANSYS software.

5.3.1 Finite Elements.

A plane strain triangular element has been used in ANSYS 15.0 workbench. Two degree of freedom (u, v), in plane displacement, at each node of triangular element has been used for obtaining the convergent solution. Discretization of dam section with triangular elements is shown in Fig.5.8. Several trials with different number of elements were taken. Finally the initial mesh size of 0.2 m was taken and then reduced to 0.001 m where convergence was reached. The details of element size and convergent criteria have been summarized in Table 5.2.

Table 5.2. Element properties and convergence criteria.

Element Properties	Description
Element Type	Triangular
Mesh Size (m)	0.001
Aspect ratio	Min. 1.0006, Max. 165.98
Number of Nodes	21201
Number of elements	9356
Error criteria for Convergence	≤ 0.0001 m in dam-crown deflection

**Fig.5.8. Discretization of dam-section with triangular element.**

5.3.2 Results for Dam-Crown Deflections

Present formulation is solved under following set of assumptions.

- Creep in the dam-body is neglected.
- Crack length during each opening-closing cycle remains constant. Crack length changes only from one cycle to other.
- Drains are inoperative.
- Silt and tail-water pressure is zero.
- Earthquake is absent.
- Dam concrete is isotropic and homogeneous.

The concrete properties used in present problem are summarized in the Table 5.3.

Table 5.3. Dam-concrete properties

S.N.	Concrete Property	Value	SI Unit
1	Density	2300	kg m ⁻³
2	Coefficient of Thermal Expansion	1.40E-05	Per °C
3	Reference Temperature	22	°C
4	Young's Modulus	3x10 ¹⁰	Pa
5	Poisson's Ratio	0.18	-
6	Bulk Modulus	1.5x10 ¹⁰	Pa
8	Shear Modulus	1.3x10 ¹⁰	Pa
9	Tensile Yield Strength	0.0	Pa
10	Compressive Yield Strength	0.0	Pa
11	Tensile Ultimate Strength	4x10 ⁶	Pa
12	Compressive Ultimate Strength	11x10 ⁶	Pa

Here, the problem is solved only for horizontal dam-crown deflection. The result of dam-crown deflections versus reservoir level variations has been represented and compared in graphical form (Figs. 5.9 to 5.14) for different years.

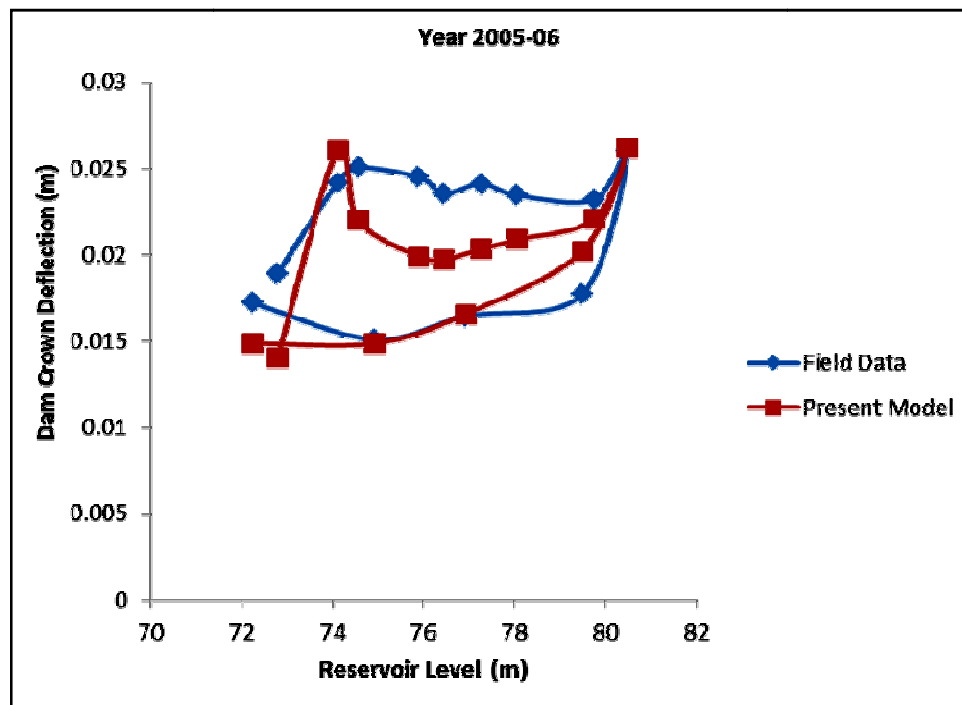


Fig.5.9. Comparison of computed and field values of dam-crown deflection versus reservoir level for year 2005-06.

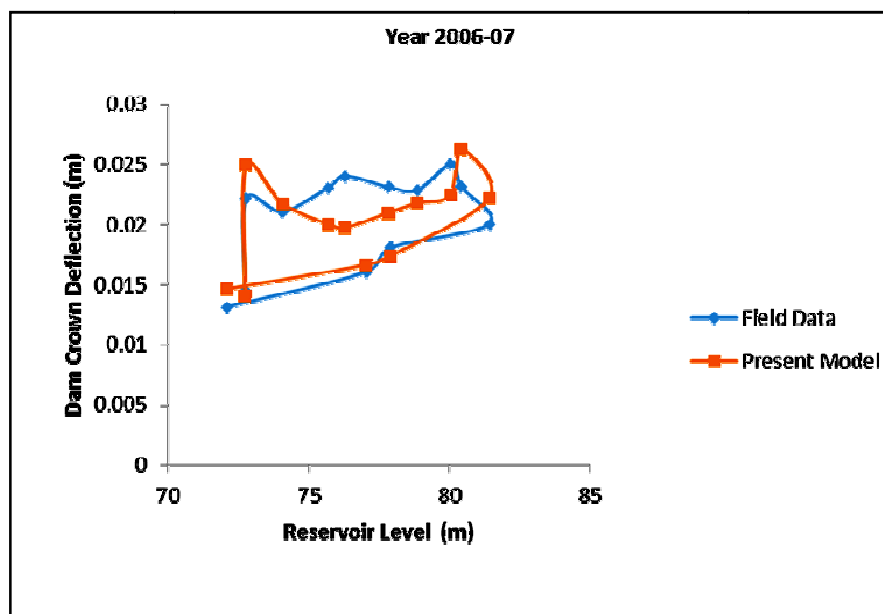


Fig.5.10. Comparison of computed and field values of dam-crown deflection versus reservoir level for year 2006-07.

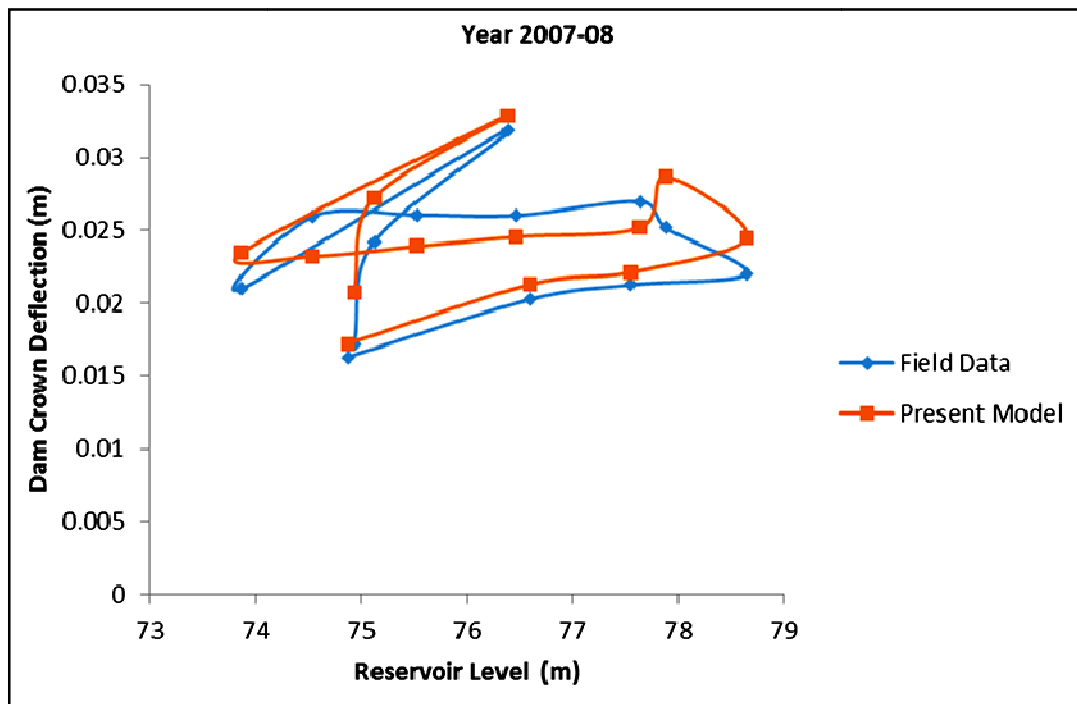


Fig.5.11. Comparison of computed and field values of dam-crown deflection versus reservoir level for year 2007-08.

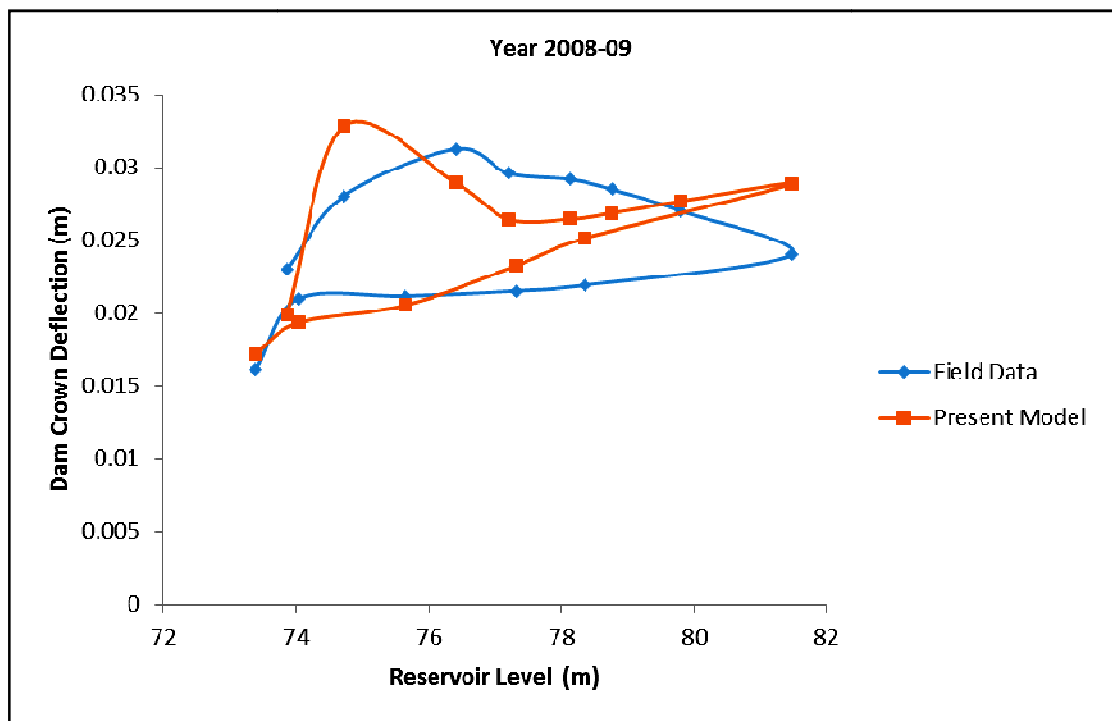


Fig.5.12. Comparison of computed and field values of dam-crown deflection versus reservoir level for year 2008-09.

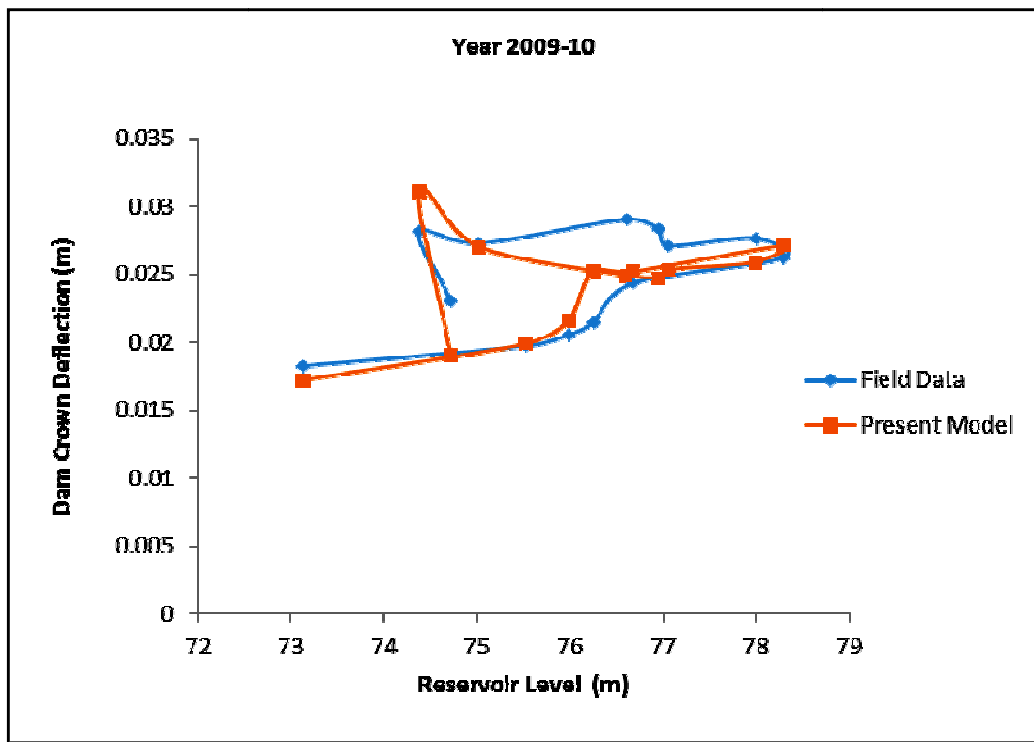


Fig.5.13. Comparison of computed and field values of dam-crown deflection versus reservoir level for year 2009-10.

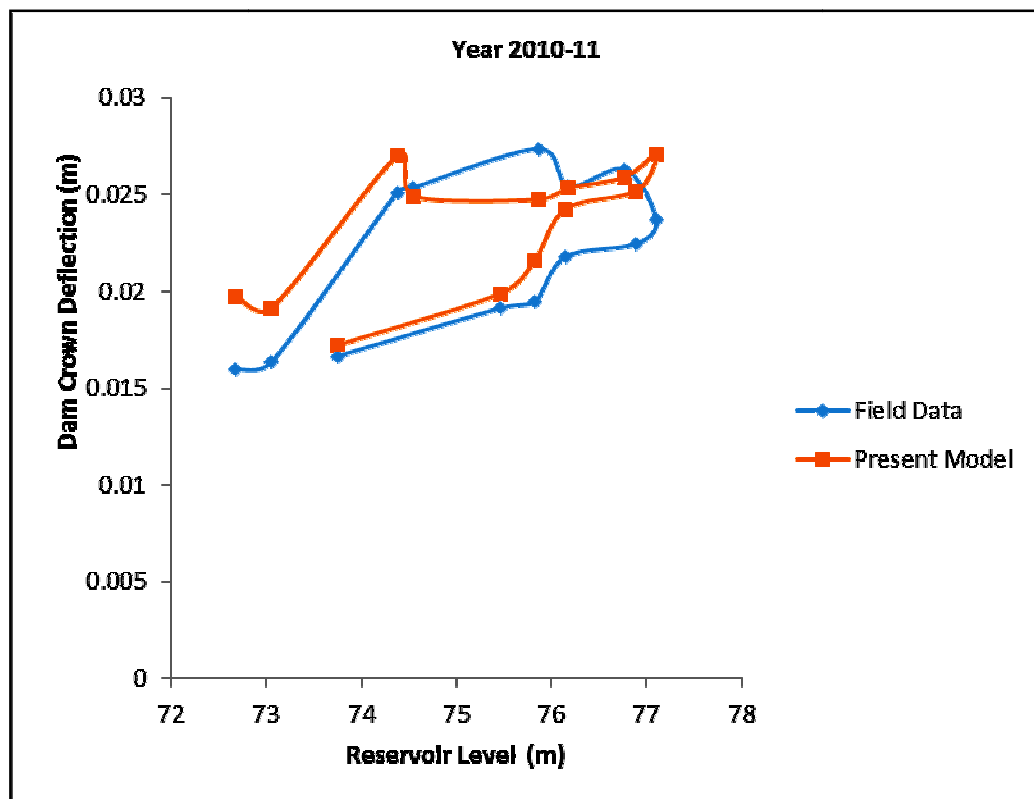


Fig.5.14. Comparison of computed and field values of dam-crown deflection versus reservoir level for year 2010-11.

5.4 Discussion of Result for Dam-crown Deflection versus Reservoir Level Variations

Result has been computed and compared with field data for different set of cracks and their lengths for each year. Further for each calculation, maximum and minimum CMOD and its rate function for calculating the transient pressure in each crack has been explored. The validity of these assumptions is ensured through comparing the computed dam-crown deflection with field data. At the end of each trial, root mean square error (RMSE) values are calculated. The present result is adopted for minimum RMSE values tabulated in Table 5.4.

Table 5.4. RMSE values for dam- crown deflection for different years.

Year	2005-06	2006-07	2007-08	2008-09	2009-10	2010-11
RMSE	0.00297	0.00234	0.00236	0.00288	0.00257	0.00229

Computed dam- crown deflection during first six month (when reservoir level increases) shows difference with field data. These differences in result may be due to: (i) small saturation length over which uplift pressures are acting, (ii) effect of creep occurring in body of the dam which has not been considered in present model and (iii) more or less number of cracks than assumed.

But during crack closing phase (reservoir level decreases), the computed values almost follows the field data. This approves the assumption of exponential CMOD rate function during closing phase.

However, the overall smaller values of RMSE almost validate the various assumptions made to achieve the present result. Therefore, on the basis of these results it may be concluded that:

- Formulation of uplift pressure in cracks gives closer result.

- Generated CMOD rate function on reduced time scale is a good representation of creep effect in FPZ.
- LEFM assumption is valid.
- There is a likelihood of existence of four effective crack located on upstream face of the dam.
- Crack lengths at each of these locations change annually which are likely to pass through the dam section after some year.
- Crack length change may also increase the sliding instability.

5.5 Stability against Sliding

USACE criteria for factor of safety against sliding (FSS) have been used.

USACE criteria assume:

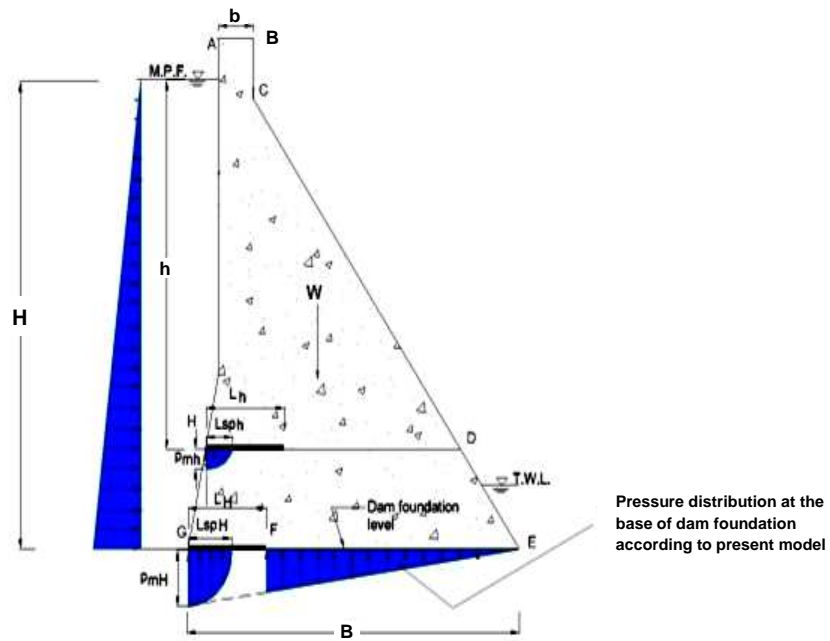
- The uniform uplift pressure in cracks of the dam body.
- Triangular uplift pressure at the base of the dam.

Factor of safety against sliding has been calculated using present approach of uplift pressure calculation in cracks. The result is compared with factor of safety against sliding, calculated using USACE criteria of uplift as given in Fig.5.15.

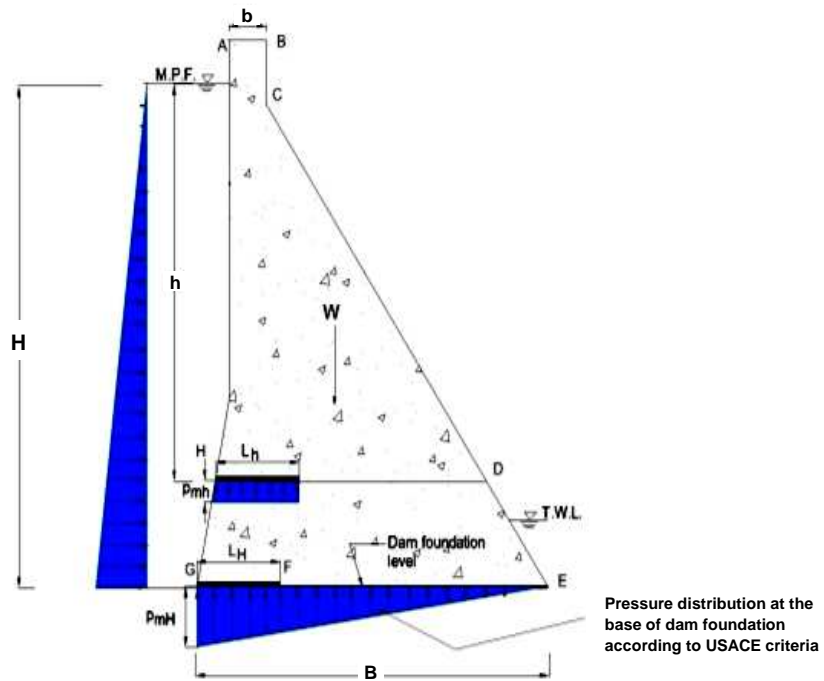
The comparative result has been shown for two sections: (i) at the base of dam and (ii) at slope changing point at upstream face of the dam. For each case of analysis, friction factor of dam-foundation interface has been assumed as 0.70.

5.5.1 FSS at the Base of the Dam

Factor of safety against sliding along the base of the dam has been calculated after taking into account the uplift pressures at the base of dam foundation and all the four cracks lying above this section. The result of FSS has been shown in the Fig. 5.16.



(a) Present model



(b) USACE criteria

Fig.5.15. Uplift pressures in cracks located in body and at the dam foundations for (a) present model and (b) USACE criteria.

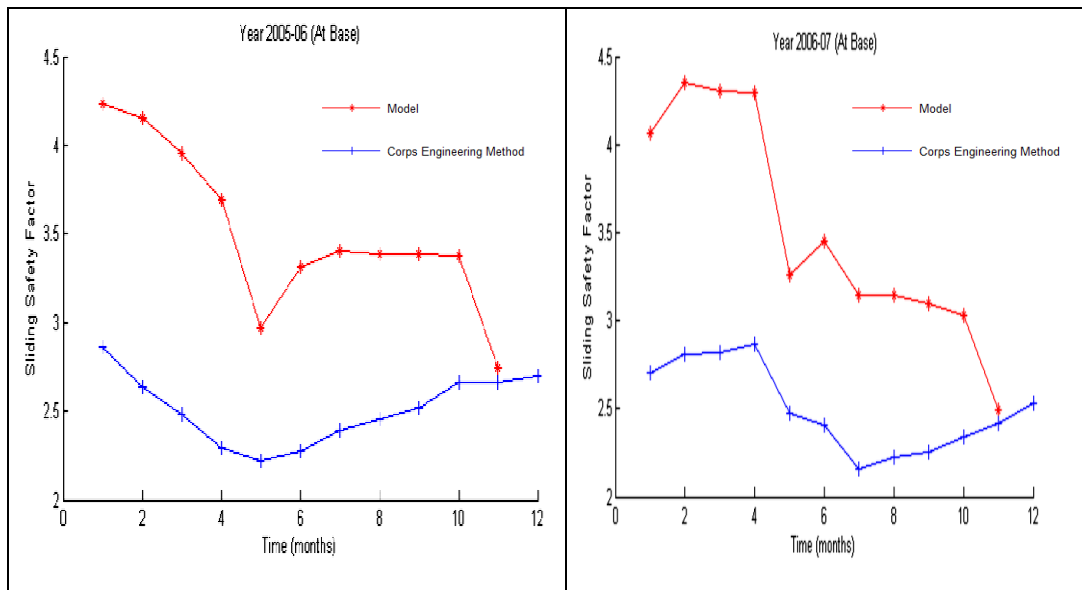


Fig.5.16(a). Factor of safety against sliding along the base of the dam for year 2005-06 and 2006-07.

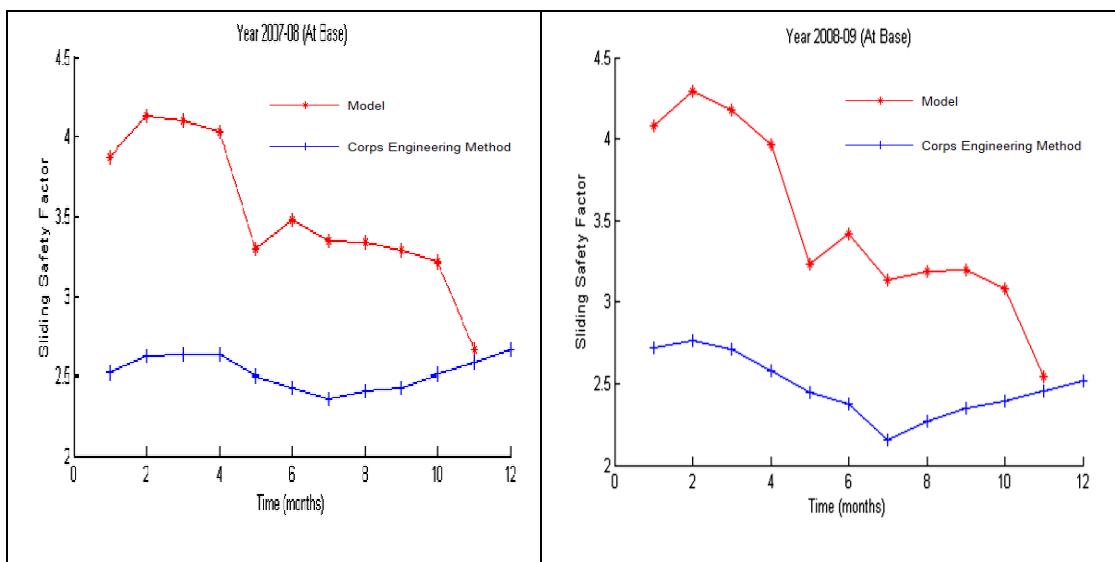


Fig.5.16(b). Factor of safety against sliding along the base of the dam for year 2007-08 and 2008-09.

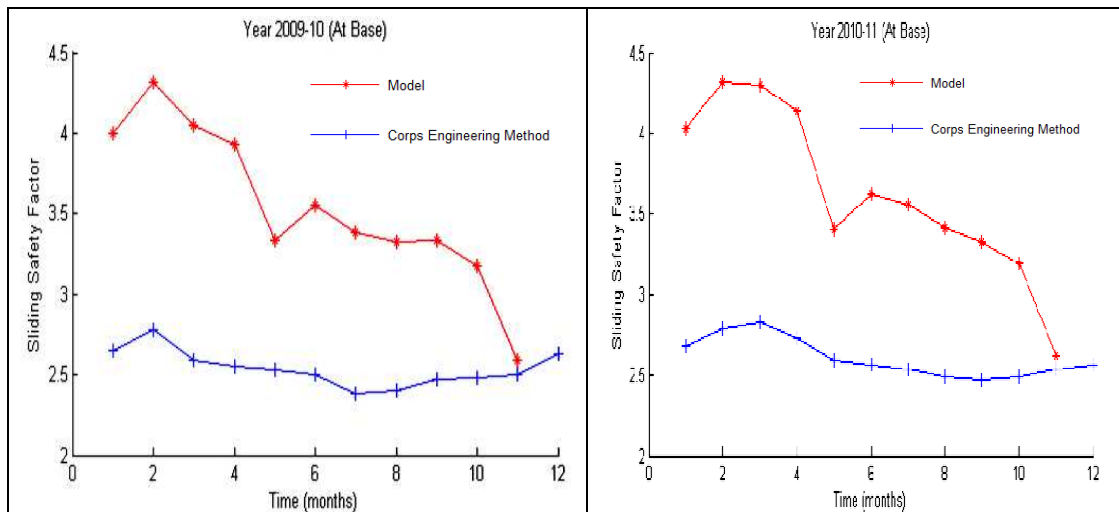


Fig.5.16(c). Factor of safety against sliding along the base of the dam for year 2009-10 and 2010-11.

5.5.2 FSS at Slope-Changing Point

In calculating the FSS at slope changing point, the uplift pressures are assumed to be effective only in cracks and pressure in un-cracked portion of the section, taken along the length of the crack, is assumed to be zero due to Bazant (1975).

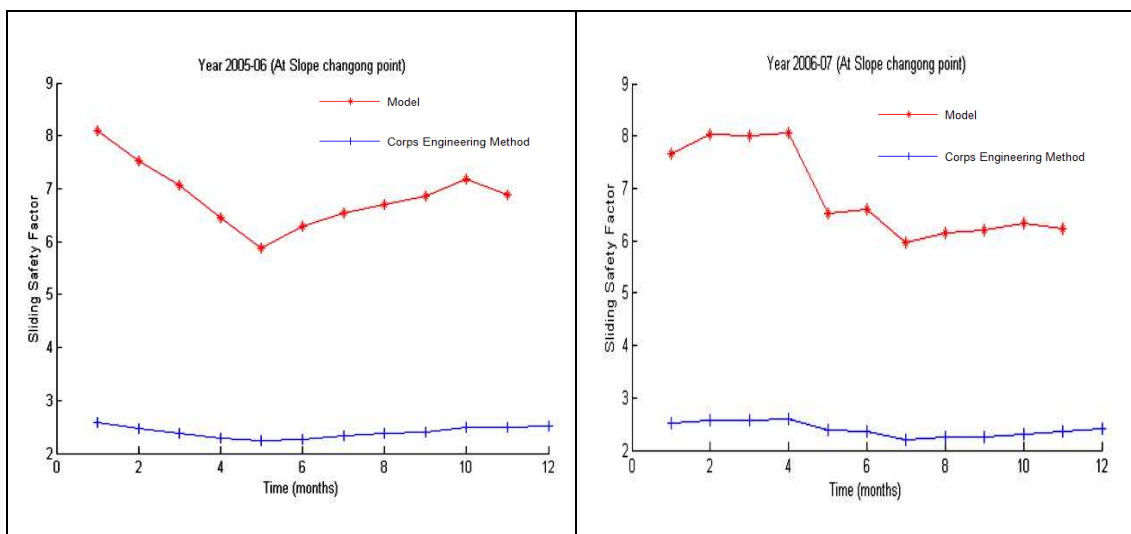


Fig.5.17(a). Factor of safety against sliding along the upstream slope-changing point of the dam for the year 2005-06 and 2006-07.

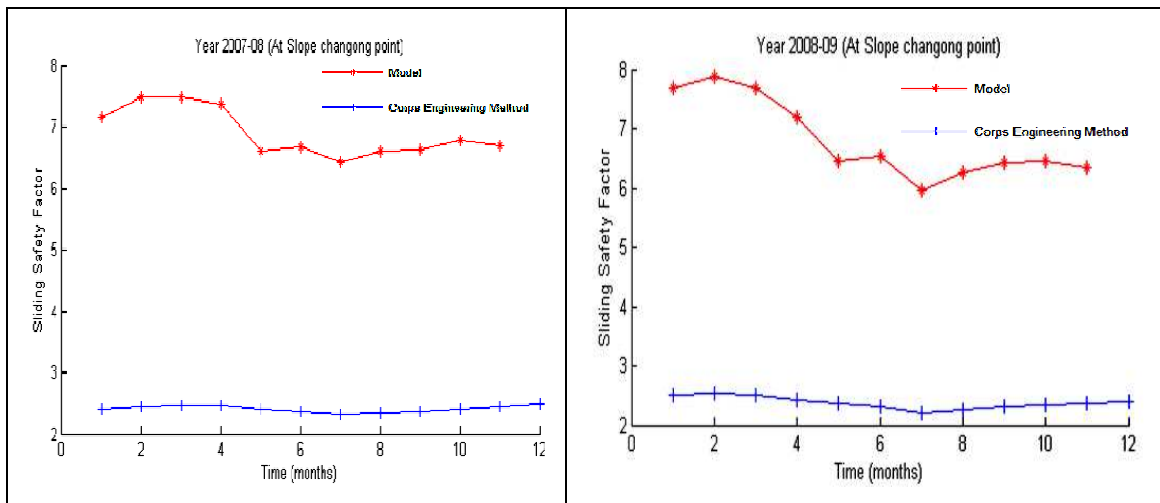


Fig.5.17(b). Factor of safety against sliding along the upstream slope-changing point of the dam for the year 2007-08 and 2008-09.

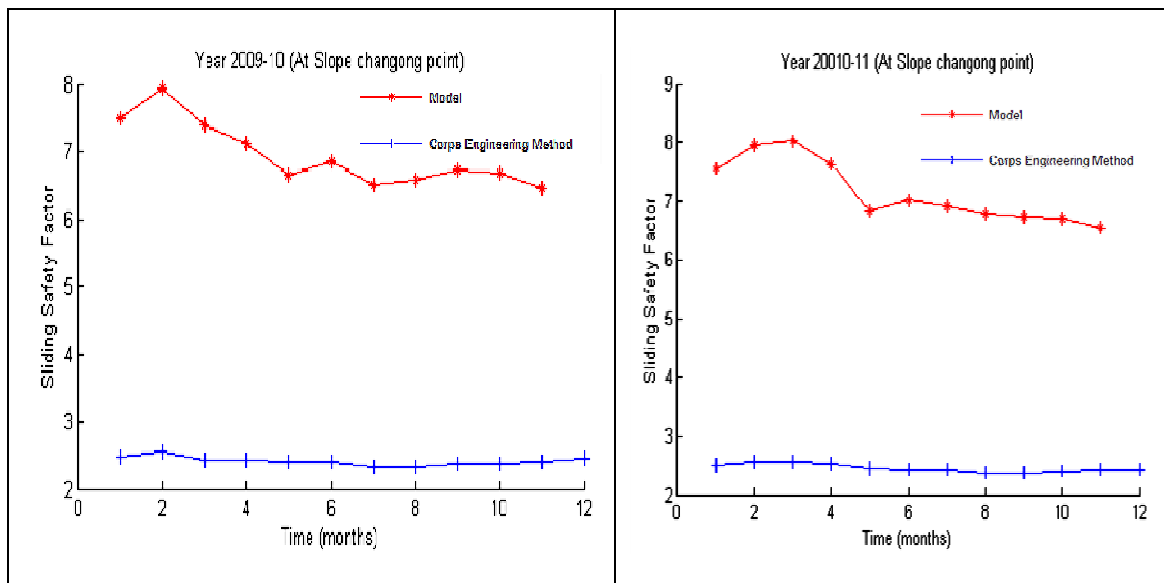


Fig.5.17(c). Factor of safety against sliding along the upstream slope-changing point of the dam for the year 2009-10 and 2010-11.

5.5.3 Discussion of Factor of Safety against Sliding (FSS).

It is observed that FSS at slope changing point (Fig.5.17) by present model is very high in comparison to FSS value calculated using USACE uplift criteria in the cracks. This is because, the calculated uplift pressures are effective only in saturated portion of the model crack with peak values almost closer to the crack

mouth pressure. But in USACE criteria rectangular uplift pressure occupies the whole crack length for any given reservoir level. This difference in uplift pressure calculation in crack at slope changing point makes a large difference in the FSS values. This result gives a very important insight that safety of the dam at slope-changing point is more conservative by present method than used by USACE.

At dam foundation interface FSS value of USACE criteria changes very slowly (Fig. 5.16) in each year. But uplift values in cracks in present study makes the trend of FSS value to decrease faster and at end of each cycle (eleventh month) it tries to go even below the FSS value calculated by USACE. The reason of this may be following.

- The crack lying at or closer to the bottom have greater stagnation pressure during closing phase than uplift pressure as suggested by USACE (always rectangular or triangular with maximum pressure equal to the crack mouth pressure).
- During closing phase (reservoir level decreases) total uplift force decreases by USACE criteria while in present model total uplift force increases. This fact makes the FSS values calculated by USACE criteria to increase while FSS values calculated for present model of uplift pressure decreases over a year.

For the same uplift formulation average FSS values for USACE uplift criteria decreases in upward direction while same increases for present uplift model in cracks.

This sliding is of major concern for the protection of power house and its appurtenances located at the toe of the dam. Therefore, it may be suggested to take some curative measures to close these cracks to prevent the further sliding of the dam and thus powerhouse may be protected.

5.6 Summary

Mathematical modeling of transient uplift pressure in single crack is validated using data from the literature. Uplift pressures, computed at different time during opening and closing phases of crack wall motion, are in good agreement with published data in the literature. These validated formulations are then used to calculate the transient uplift pressures in cracks at slope-changing point and dam-foundation interface, under crack wall motion, caused due to creep in FPZ and monthly reservoir level variation. During first quarter of the year, saturation length at the heel is more than saturation length at the slope-changing point and uplift pressure during this period also decreases. But in second quarter of the year, uplift pressure begins to increase. In third and fourth quarter of the year, both the cracks are subjected to increased uplift pressure with peak uplift pressure going beyond the applied crack mouth pressure and reaches maximum value in eleventh month of each year.

The results for dam-crown deflections adopted correspond to minimum RMSE values for each year of recorded data. Computed dam-crown deflection during first six month (when reservoir level increases) shows larger difference with field data. But during crack closing phase (reservoir level decreases), computed values almost follows the field data. This approves the assumption that : (i) formulation of uplift pressure in cracks gives closer result, (ii) generated CMOD rate function on reduced time scale is a good representation of creep effect in FPZ, (iii) LEFM assumption is valid, (iv) there is a likelihood of existence of four effective crack located on upstream face of the dam, (v) crack lengths at each of these locations change annually which are likely to pass through the dam section after some year and (vi) crack length change may also increase the sliding instability.

The factor of safety against sliding (FSS) at slope changing point by present model is very high in comparison to FSS value calculated using USACE

uplift criteria in the cracks. The reason of this difference may be attributed to the fact that in present model calculated uplift pressures are effective only in saturated portion of the crack with peak values almost closer to the crack mouth pressure. But in USACE criteria rectangular uplift pressure occupies the whole crack length for any given reservoir level. This difference in uplift pressure calculation in crack at slope changing point makes a large difference in the FSS values. This result gives a very important insight that safety of the dam at slope-changing point is more conservative by present method than used by USACE. At dam foundation interface USACE criteria of FSS value changes very slowly in each year. But uplift values in cracks in present study makes the trend of FSS value to decrease faster and at end of each cycle (eleventh month) it tries to go even below the FSS value calculated by USACE. The reason of this may be: (i) the crack lying at or closer to the bottom have greater stagnation pressure during closing phase than uplift pressure as suggested by USACE (always rectangular or triangular with maximum pressure equal to the crack mouth pressure) and (ii) during closing phase (reservoir level decreases) total uplift force decreases by USACE criteria while in present model total uplift force increases. This fact makes the FSS values calculated by USACE criteria to increase while FSS values calculated for present model of uplift pressure decreases over a year.