Assessment of Concrete Arch Dam under Possible Earthquake Loading in Sri Lanka: Case Study on Victoria Dam

Shobitha Tharmarajah and Kamal Karunananda.

Abstract—Although Sri Lanka is traditionally considered as non-seismic country, formation of new tectonic plate boundary in the Indian Ocean about 400-600km from southern shore of Sri Lanka can cause a great seismic threat to existing infrastructures in Sri Lanka. Earthquake happening near south coast of Sri Lanka will have an amplified effect on hilly land region due to faults, lineaments and other weak zones present within the central hilly area. The most critical infrastructure situated in hilly land region susceptible to earthquake is Victoria dam. Victoria Dam is the largest concrete dam in Sri Lanka which was built across the river Mahaweli at Teledeniya during 1980-84. Victoria dam is a double curvature arch dam of 122m of height consist 722million cubic meter capacity of reservoir. Numerical model of the structure is prepared according to the correct dimensions data of the dam. Linear elastic finite element analysis of maximum cross section and 3D model is performed with the computer program sap 2000 (version 19). Static analysis is carried out under self-weight and hydrostatic force. Dynamic analysis is performed based on earthquake load and hydrodynamic load. Three Earthquake records are obtained from PEER data base and Westergaard pressure method is used determine hydrodynamic effects during earthquake. Seismic evaluation process of the dam is carried out for 3D model based on demand capacity ratio and accumulated duration of over stress excursion and spatial distribution of stresses. Results of the analysis are discussed and finally structural strengthening methods of the dam from seismic hazards are proposed.

Index Terms—Demand capacity ratio, Cumulative over stressed duration, Cantilever stress, Arch stress, Time history analysis, Finite element model, Contraction.

1 Introduction

Earthquake is a natural geological event which generates vibration and earth shaking in the surface of the earth crust due to the strong elastic strain energy release by the sudden slip of faults or movement of tectonic plate. Earthquake event is categorized as intra plate earthquake and inter plate earthquake according to the location of plate tectonic.

Under ground shaking, earth surface moves rapidly and cause damages to the building. Therefore large manmade massive structures and buildings should be designed in order to withstand with the seismic effects. Dams are massive manmade hydraulic structures constructed across the reservoir and impound water in the upstream side for several purposes such as hydroelectric power, irrigation purposes, and flood control. Dams can be classified in many ways based on their function, hydraulic design, rigidity and structural action. Earthquake causes major failure of the dam structures and destruction of surrounded area. Earthquake triggers landslide rock falls and mass movement debris flow which are common in the hilly land areas. High amplitude of waves are generated from the mass movement and rock falls in to the reservoir. Previous designed massive dams should be reexamined with the computational methods and new analytical techniques. Less than 30 dam's failure has been observed all over the world due to seismicity.

Sri Lanka is an Island situated within Indo Australian tectonic plate which is far away from Plate tectonic boundaries. Sri Lanka is considered as non- seismic country since it is away from the high seismic active boundaries. Researches shows the evidence of the existing new tectonic plate boundary in the Indian Ocean which lies 400-500km from the southern shore of Sri Lanka. The new plate boundary implies a major effect to Sri Lanka. Effects of the earthquake happening near the south coast will have an amplified effect on infrastructures situated in central hilly regions due to abounded faults lineaments and other weak zones(Dissanayake 2010).There is a possibility of moderate earthquake happening in high amplitude which requires the investigation of seismic response in the existing structures in Sri Lanka to take adequate precaution to minimize the damages from the earthquake. Dams are the massive structures and they can be subjected to severe destructive impact due to earthquake since they are located in the central high land of Sri Lanka. The consequence of major dam failure in the Mahaweli River can cause major destruction to life, properties and environment.

Victoria dam is the largest concrete dam in Sri Lanka which was built under Mahawali master plan project with Rs.9.8 billion in 1980-1984 to solve several problems in Sri Lanka such as hydroelectricity for the country, insufficient water for agriculture, unemployment, less facility of fishery and flooding. The dam was constructed across the narrow and deep Maha-

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wali River which is more suitable to the arch dams. Victoria dam is a double curvature (cupola) arch dam of 122m maximum height and 520m crest length. The arch dam is constructed with the individual crown cantilevers. A large amount of water load acting on the upstream surface of the dam is transferred to the abutment by the arch action and a certain amount of water load is transfer to the foundation by cantilever action. The destruction of the Victoria dam cause flooding up to Trincomalee affecting the livelihood in the area. Crack was identified and it has been developing in the downstream face of the Victoria dam. (Sri Lanka,Head works division of Mahaweli authority, 2014).Therefore Victoria dam is investigated to identify the effect of Earthquake.

The seismic performance of earthquake is currently manipulating based on stress analysis with some engineering judgments. This paper demonstrates the assessment of seismic stress analysis on Victoria darm under possible earthquakes using sap 2000(version 19) with the damage evaluation. The aim of the damage evaluation is carried out to prove whether the failure modes can develop or not in the dam structure under the seismic loadings. Suitable strengthening method is proposed and analysed to increase the natural frequency of the dam to withstand for the strong seismic and hydro dynamic loadings during the earthquake event.

2 LITERATURE REVIEW

In 2010 C.B Dissanayakke stated the intra plate earthquake that can strike Sri Lanka and about future earthquake hazards that can happen due to formation of new tectonic plate boundary in the Indian Ocean with the evidence of the existing of new tectonic plate boundary in Indian Ocean which situated 400-500km from the southern shore of Sri Lanka. The new plate boundary implies a major effect to Sri Lanka. Central highland of the country consists of weak zones and faults which can be able to affect by the earthquake due to developing plate split. The reservoirs in the highland of the country should be monitored regularly by installing a seismometer in the dams. (Dissanayake, 2010)

In 2010 E. Mirzaei, S.Vahnani and R. Mirghaderi were performed seismic analysis of double curvature arch dam. Hydrodynamic analysis was carried out with the generalized Westergaard method. A general formula for arch dam based on the same parabolic pressure distribution with the depth which was used by Westergaard. Normal hydrodynamic pressure at any point of the curved upstream surface was denoted. The normal hydrodynamic pressure on the dam is directly proportional to the total normal acceleration. The normal pressure at each point then converted into hydrodynamic forces by multiplying by tributary area associated with that point. The hydrodynamic force was converted to added mass matrix on each point of the upstream face node. (Mirzaei, Vahdani, Mirghaderi, 2010)

In 2004 Ghannat proposed a damage evaluation method for estimating the probable damage of the dam under static and dynamic loading for both gravity and arch dam. More than three earthquake events were selected to perform the dynamic analysis. Linear and nonlinear analysis were carried out using a computer program called GDAP and QDAP respectively. Pacoima and Marrow point dam was analyzed and the evaluation was carried out in terms of cumulative overstress duration and demand capacity ratio. An allowable target line was developed for both gravity and arch dams. The damage evaluation target line was described, if the estimation damage occur below the acceptance level, the dam can be able to withstand under applied earthquake loading. Curve of the Pacoima dam was below the acceptable target line. It was concluded that the 20% of the dam surface is overstress. Meanwhile the curve of the marrow point dam exceeded the target line. Therefore it was concluded that the applied seismic load induced severe damage and significant nonlinear response due to opening of contraction joint. Maximum joint opening point was selected and the deflection of the particular point was provided using the computer program called QDAP. (Ghanaat, 2004)

3 METHODOLOGY

3.1 Model

Modelling and analysis of the dam structure has been performed using linear finite element analysis using computer software Sap 2000 (Version 19).Modelling of foundation is neglected even though the supports are considered as fixed in the dam structure analysis. Spillway gates are not separately modelled since the spillway gates were constructed by reinforcement concrete.The structure is subdivided into smaller elements and connected with nodal points or vertices as shown in the Figure 3.1

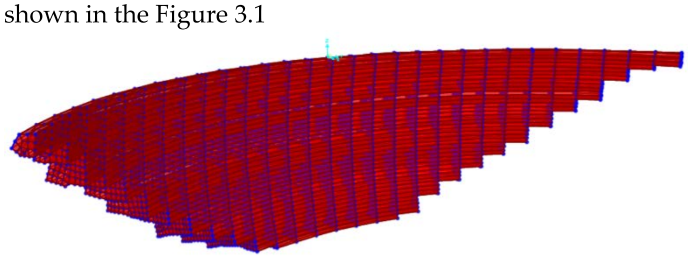

Figure: 3.1 – 3D Model of Victoria dam

3.2 Dimensional Property

Victoria dam is a double curvature arch dam separated by 35 individual cantilever section and 34 contraction joint. The dam has the maximum cross section height of 122m and crest length of 520m. The largest cross section of the structure is

ISSN 2229-5518

identified in the center of the dam. The thickness of the center cantilever cross section is decrease from 25 m at the base to 6m at the crest.

3.2 Material Property

Grade 30 concrete was used with 150mm maximum aggregate size, low heat alkali cement and ice were used to reduce the crack occurring. 35 individual cantilever blocks were constructed which were bonded with grout. Reinforcement was laid only in the spillway gates. Foundation of the dam is impounded with fractured gneiss rock around 8- 17ft in weathered rock.
Static compressive strength is 30 N/mm^2
Static tensile strength is 3 N/mm^2
Dynamic compressive strength is 36 N/mm^2
Dynamic tensile strength is 4.5 N/mm^2

Table 3.1 – Material property of Victoria dam

Material properties	Victoria dam
Modulus of elasticity in GPa	24
Poisson's ratio	0.2
Specified concrete compressive strength MPa	30
Unit weight of concrete	$23kNm^{-3}$

3.3 Loading

3.3.1 Determination of Static Loads

Arch dam subjected to various static loads such as dead load, hydrostatic acting both upstream and downstream sides of the dam, uplift, sediment load, ice loads. Dead load and hydro static loads are dominant in the stress analysis. Dead load acting on dam consist of entire structure of the dam with gates and abutment. Weight of the abutment is negligible when compared to the weight of the structure in the stress analysis. Unit weight of the mass concrete is taken as $23kNm^{-3}$ for entire structure of the dam since the spill way was constructed with reinforced concrete.Hydrostatic forces are acting on the dam due to hydrostatic pressure exerted by the upstream reservoir and downstream tail water under normal condition. The tail water and head water pressure increase linearly with the depth and it acting perpendicular to the curved surface. Specific gravity of the reservoir water is considered as 10 kNm^{-3}. This paper considered the reservoir water in the upstream side is completely filled to its maximum height. The tail water force acting opposite to the head water force where the tail water depth is comparatively lesser than the height of the dam. Therefore the effect of the tail water is negligible in the stress analysis.

3.3.2 Determination of Dynamic Loads

Dynamic loads are changed with the time. Seismic loads and hydrodynamic loads are considered in the analysis.Strong ground motions of Manjil_Iran, Denali_Alaska, Chi_Chi Taiwan accelerogram records are input in SAP 2000 as generic function.

Table 3.2 – Earthquake data

Earthquake event	Magnitude (Ritchter)	Peak horizontal ground acceleration(g)	Peak vertical ground acceleration (g)
Manjil_Iran	7.37	0.65	0.52
Denali_Alaska	7.9	0.33	0.29
Chi Chi_Taiwan	7.62	0.19	0.12

A parabolic distribution of hydro dynamic pressure was determined by Westeergaard for incompressible reservoir. A certain amount of water is moving back and forth with the dam body during the earthquake which was determined by inertia force of the water body. Westergaard was authenticated the inertia force exerted by the water is equivalent to the pressure exerted by the water during ground acceleration. The body of water attached with the dam is defined as added mass.
The generalized Westergaard method was developed to compute the hydrodynamic pressure in any point of the upstream face of the dam due to total acceleration normal to the dam. Hydrodynamic pressure exerted by the normal acceleration is equal to the inertia force produced in unit cross section with length$\frac{7}{8}\sqrt{H(H-Z)}$, where H is depth of water above the base of the dam and Z is distance from the base of the dam.
Normal hydro dynamic pressure is defined as;
$P_n = \alpha \ddot{u}_n^t$
$\alpha = \frac{7}{8} \rho w \sqrt{H(H-Z)}$
P_n = normal hydro hydrodynamic pressure
$\ddot{u}_n^t$ = normal acceleration
ρ_w = density of water
α = Westergaard pressure coefficient

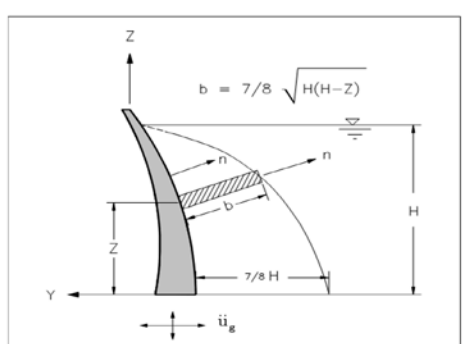

Figure 3:2Generalized Westergaard added hydrody-

namic mass model for arch

The normal pressure at each point then converted into hydrodynamic forces by multiplying by tributary area associated with that point. (Mirzaei, Vahdani, Mirghaderi, 2010). Finally, the normal hydrodynamic force is resolved to its Cartesian components, from which a full 3x3 added-mass matrix at each nodal point on the upstream face of the dam is obtained (Kuo, 1982)

3.3 Damage Evaluation of Earthquake load for arch dams

The evaluation of earthquake stress analysis is performed in terms of demand capacity ratio and cumulative overstress duration. Developed target line is used to measure the level of damage during seismic event. Ultimate dynamic load combination is applied to evaluate the response of dam. Tensile stress is more critical in arch dams.

Demand capacity ratio (DCR) of the arch dam is referred as ratio of arch or cantilever stress to tensile strength of the concrete. Maximum allowable DCR is 2 where it is defined as apparent dynamic tensile strength. Stress excursions are obtained from the stress analysis graph. Both cantilever and arch stresses are used to evaluate damage criteria of arch dam.

Cumulative inelastic duration is number of cycle of an arch or cantilever stress. Higher cumulative duration tends to higher possibility of damages. Cumulative value for DCR value 2 is assumed as zero in target line and maximum allowable cumulative overstress duration is 0.4Seconds for arch dams.Time step of the earthquake is defined as 0.02 through-out the analysis. Cumulative inelastic duration is calculated approximately by multiplying number of stress excursion exceeding a certain DCR value by analytical time step.

- If the DCR is less than 1, the performance of the dam is considered to be within the elastic region since there is no damages for the structure
- If the DCR is equal to 1, there is no significant damages in the dam since the contraction joint is still opened.
- If the DCR is greater than 1 and less than 2, there is acceptable occurrence of damages with the contraction joint opening and possible tensile cracking in the lift lines. Overstressing is ranged to 20% of the dam surface area.
- If the analysis stress result is above the limit line, severe damage will be occurred.(Ghanaat, 2004)

4 RESULTS

Figure 4:1 shows the performance curve of arch stress due to Denali_Alaska, Chi Chi_Taiwan earthquakes are below the target line which demonstrate that the acceptable damages are occurred in both upstream and downstream side, contractions joints openings are significant with horizontal lift line cracking and over stressed region is defined as 20% of the total surface area. The performance curve due to Manjil_Iran earthquake is above the target line which demonstrate that the severe damages are occurred during Manjil_Iran earthquake event.

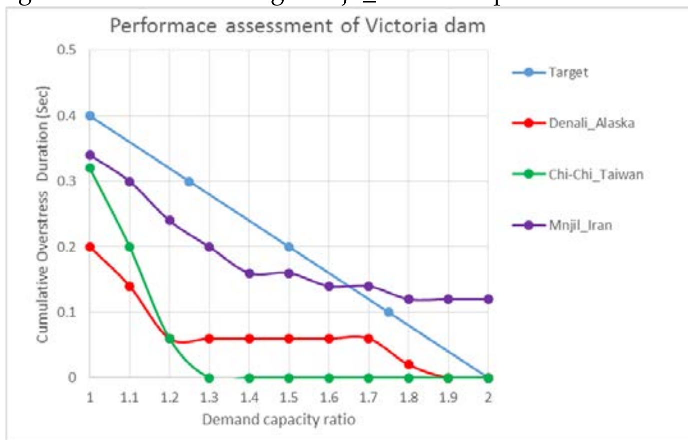

Figure 4:1 Performance assessment of Victoria dam for arch stress

The Figure 4:2 shows the performace curve of cantilever stress due to all three earthquake records are above the target line which demonstrate that the severe damages are occurred due to cantilever stress.

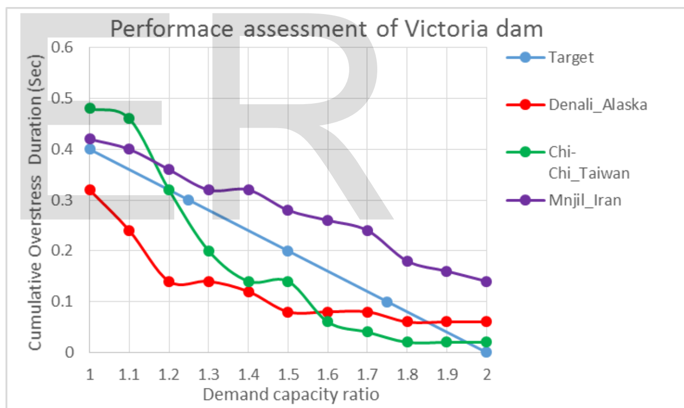

Figure 4:2Performance assessment of Victoria dam for cantilever stress

Table 4.1 Maximum displacement

Earthquake event	Maximum displacement (mm)
Manjil_Iran earthquake	27.5
Denali _Alaska	13
ChiChi_Taiwan	9

Central upper portion of the dam is significantly weakened due to rapidly open and close process of contraction joint.Displacement is largest at the central crest level and it gradualy reduce to mid height of the dam. Therefore the largest contraction joint opening is visible in the crest level along upatream- downstream direction (perpendicular to the horizontal axis of the dam). The contraction joints are repeatedly open and close even though the opening condition is not stayed more than 0.02 seconds.

5 Selected strengthening solutions for Victoria Dam

It is observed that the arch and cantilever stresses were caused damages during earthquake event. However cantilever stress shows more critical at the base of the structure. Therefore the cantilever blocks are thickening at the bottom to reduce the concentration of load in the bottom part and increase the rigidity of the structure. Natural frequency of the structure raise with the thickening of dam. The maximum thickening width is 20m at the base and gradually reduce to 5m at 86m above the bottom of the dam. Reinforcements are anchored in existing structure in the construction.

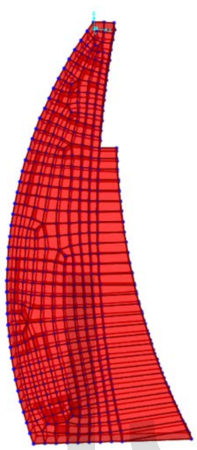

Figure 5:1 Thickening of Victoria dam

Arch stresses and cantilever stresses during Denali_Alaska and Chi Chi_Taiwan earthquakes are below the dynamic tensile strength of concrete after strengthening. Figure 5:1 shows the seismic performance assessment of the strengthen dam duringManjil_Iran earthquake.

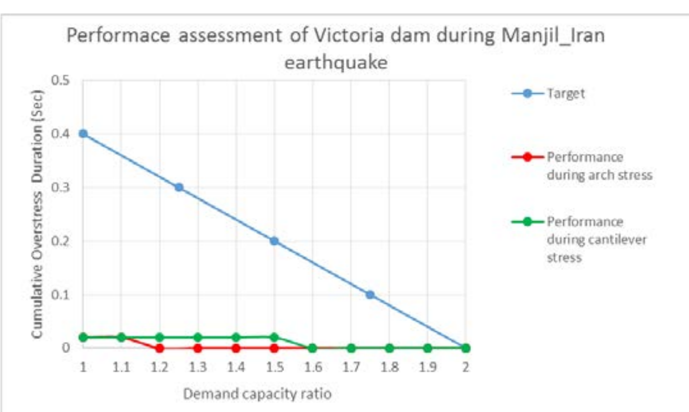

Figure 5:2 Performance assessment of Victoria dam during Manjil_Iran earthquake

Performance of dam during Manjil_Iran earthquake is under target line which demonstrate that the acceptable damages are occurred in both upstream and downstream side, contractions joints openings are significant with horizontal lift line cracking and the over stressed region is defined as 20% of the total surface area.

5 Conclusion

Seismic performance of the concrete dam was presented under case study on Victoria dam which was situated in central hilly land of Sri Lanka. 3D finite element was modelled and static and dynamic analysis were carried out using computer software sap 2000(version 19).

Table 5.1 Performance of Victoria Dam during earthquakes

Earthquake events	Performance of existing Victoria dam	Performance of strengthen dam
Manjil_Iran	Severe damages were occurred	20% of the dam surface were damaged
Denali_Alaska	20% of the surface were damage due to arch stress Severe damages were occurred due to cantilever stress	No damages
Chi Chi_Taiwan	20% of the surface were damage due to arch stress Severe damages were occurred due to cantilever stress	No damages

There are about 30 large dams in Sri Lanka all of which are vulnerable to be affected by earthquakes being originated from this new plate boundary. The proposed methodology can also be used to assess other dams in Sri Lanka to check for their vulnerability to damage due to earthquake and further the methodology can also be used to identify the amount of strengthening required to limit the damage due to the earthquake. It can be concluded that the proposed failure modes approach provides a systematic methodology for assessment of the seismic performance and probable level of damage in the damage control range of behavior.

Acknowledgment

The valuable thanks goes toFaculty of Environment and Technology, University of the West of England, UK and Mahaweli authority of Sri Lanka.

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