Transactions, SMiRT-22
San Francisco, California, USA - August 18-23, 2013
Division V

SAFETY ASSESSMENT OF CRITICAL INFRASTRUCTURES FOR AIRCRAFT CRASH

Dimitar Stefanov[1], **Antoaneta Kaneva**[2]

[1] Assoc. Professor, Dept. of Earthquake Engineering, NIGGG – Bulgarian Academy of Sciences
[2] Chief Researcher, Dept. of Earthquake Engineering, NIGGG – Bulgarian Academy of Sciences

ABSTRACT

Assessment of the effects of an aircraft impact on large dams is the basic topic of the present work. An example of concrete gravity dam is analyzed for aircraft impact caused by two different airplanes – military jet and a passenger airplane. The analyses are performed using two and three dimensional finite element models of the dam. The dynamic non-linear direct transient analyses are carried out. Two basic scenarios are considered – impact at downstream and upstream side of the dam. Conclusions about the possibility of breaching are drawn based on the performed analyses.

INTRODUCTION

The Sept. 11, 2001, terrorist attack on the United States has drawn public attention to the potential for an aircraft crash into structures that are part of critical infrastructure, including nuclear power plants and large dams.

In most countries a load case of an aircraft impact has not been taken into account in the design of critical structures up to now and assessment of the effects of such load cases has been started in order the needed upgrading of the structures to be defined. In some countries the resistance of nuclear buildings against aircraft impact has been analyzed in the past predominantly for military aircrafts or civil aircrafts of small size. Special attention should be paid to the assessment of the effects of aircraft crashes of different sizes on large dams.

The methodology for assessment of dams is grounded on knowledge of the methodology used for seismic safety of dams and the methodology used for assessment of nuclear power plants to aircraft crash impact.

Airplane impact effects on concrete structures are traditionally categorized into local and global effects. Local effects are related to effects close to the target structure in the region of the impact. Global effects include overall axial, bending and shear effects in the structure between the impact region and support points, global stability and vibrations in the structure. The main part of this paper deals with the local effects.

LOADING DEFINITION AND CRASH LOCATION SCENARIOS

Aircraft of medium or small size are chosen for the analyses depending on the topography and dimensions of the chosen dam cases. Big commercial aircrafts are considered inappropriate for dam attack. Dams are usually situated in mountains, on river valleys with steep slopes where the dimensions of the valley will limit the approach of a big aircraft. It is considered easier for the aircraft to approach the dam from the upstream face because there is more space for the aircraft to flight above the lake and then lower at the necessary altitude to strike the crest zone of the dam. Though considered difficult to aim at the usually not high crest zone of the dam above the water surface, the analyses are performed assuming that the impact is accomplished hitting the crest zone. The fuselage spot is assumed located immediately above the water surface. In case the aircraft attacks the wall partly under water the speed of the aircraft will be decreased due to water friction. In this study it is assumed conservatively that the aircraft crashes in the crest zone totally above the water level at the upstream face of the dam. Also a crash of a big commercial aircraft at the downstream face of the dam is analyzed.

The aircraft loading functions are evaluated based on Riera approach. Three basic load cases are considered:

Load case 1 – Military jet “Phantom”, V=215 m/s;
Load case 2 – Passenger airplane Boeing 767, V=160 m/s;
Load case 3 – Passenger airplane Boeing 767, V=260 m/s.

There are several reasons to choose these cases. The first one is that the military jet (Figure 1) was the first load case ever considered. The load curve is derived theoretically and after that confirmed experimentally (Sandia tests) Henkel et al. (2007). The passenger airplane Boeing 767 (Figure 2) is a typical representative of the “medium size” aircrafts. The concrete gravity dam is a bigger target compared to a nuclear reactor and the approach to the dam wall can be achieved at different velocities. That is why a wide range of velocities is considered up to 260 m/s.

Figure 1 Load case 1, Phantom jet

Figure 2 Load case 2&3, B767 passenger airplane

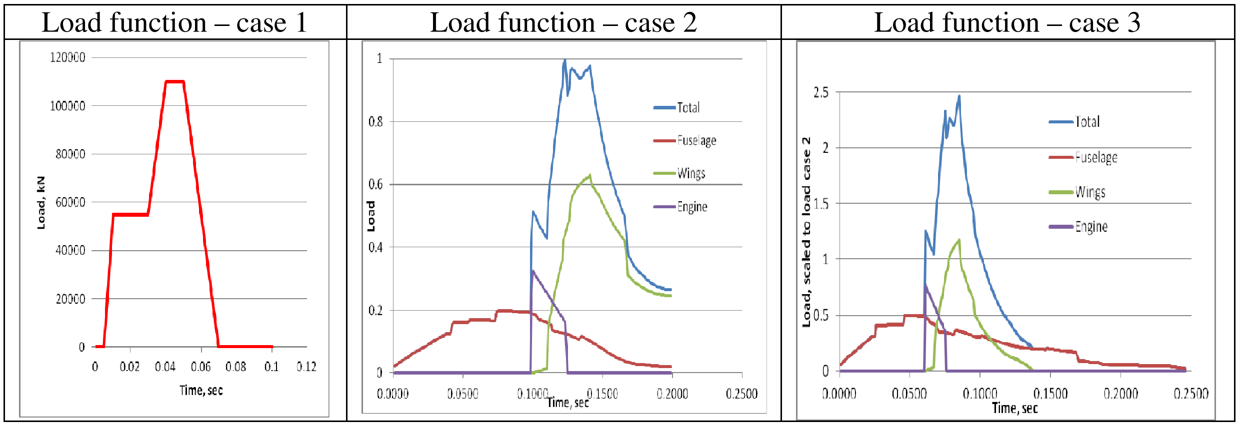

Figure 3 Load time functions for three load cases

The impact force in load case 1 is “concentrated” in a circle of 10 m^2 area assumed as the Phantom impact spot and acts during a very short interval of time compared to the duration of impact of Boeing airplane. In the 2D numerical model of the dam the Phantom impact is represented as pressure acting on the upstream face of two elements of the model while in the 3D numerical model the pressure of the Phantom impact acts on one element. The loading functions in load case 2 and 3 act on impact area which consists of several regions – a circle with area 20 m^2 for the fuselage, two regions for the wings with area 19m^2 each and two circles for the engines with area of 3m^2 each. Graphically the contact area is shown in Figure 4. The total impact load functions, represented in the graphs in Figure 3, comprise the three components, of the fuselage, of the wings and of the engines, with different time characteristics. In the analyses the pressure of the each component acts according its time function in the respective impact region. In the 3D numerical model the region of the fuselage spreads on two elements, each wing on six elements and each engine on one element. In the 2D numerical model the pressure of the fuselage crash is modeled on three elements and the pressure from the wings on one element. Here it is worth mentioning that an assumption was made to model the pressure from airplane impact on 2D plane strain model, i.e. the pressure from the impact is assumed acting uniformly on a "block" of 20 m width which length is to represent the contributing length of spatial response of the dam wall and to a certain degree to represent the concept of the block structure of the dam. This assumption is applied for all load cases of 2D numerical models of the dam. Details on the deriving of the time load functions are given in Kostov et al. (2013).

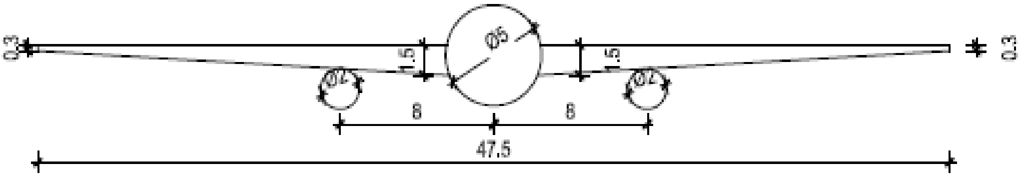

Figure 4 Dimensions of the contact area for B767

All analyses are performed considering the gravity load and the hydrostatic pressure.

DESCRIPTION OF THE STRUCTURE, NUMERICAL MODELS

The diversity in dam design layout and geometrical dimensions is well-grounded by the diversity of the topography of the dam sites. That diversity cannot be encompassed in the frames of one single study. Therefore the main objective of the study is to determine the effect of an aircraft impact on the dam behavior and possible consequences on the dam. As a first study of the effects of aircraft crash in a dam wall, the analyses are focused on concrete gravity dams, very often used in Europe.

The characteristics of the basic concrete material are accepted based on averaged data of several concrete dams, and on experimental studies, and are as follow:

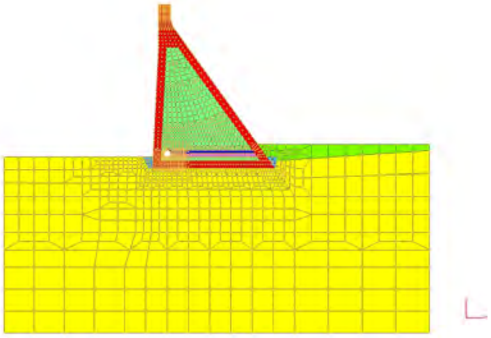

Figure 5. 2D numerical model

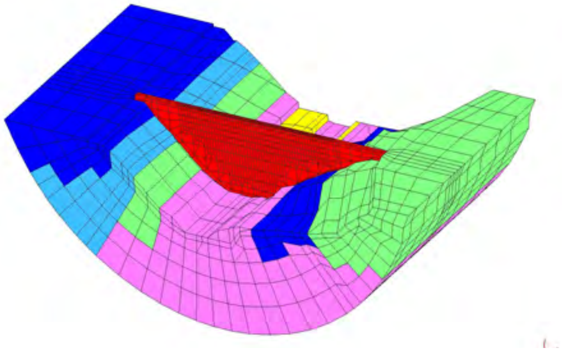

Figure 6. 3D numerical model

Young's modulus (dynamic), E = 3.6E+7 kN/m^2;
Poison's ration, $\nu = 1.5$;

Concrete density ρ= 2.46 kN/m^3;
Cohesion, C = 4330 kN/m^2;
Angle of internal friction, φ = 61.5^o;
Tensile strength of concrete, R_t = 2200 kN/m^2.

The 2D numerical model (Figure 5) is comprised of 2D plain strain elements and the 3D numerical model (Figure 6) – of solid elements. The rock foundation is modeled to take into account the soil-structure interaction. The dimensions of the modeled rock foundation are reasonably chosen so that to minimize the effect of the boundary conditions on the behavior of the dam wall.

In this study it is assumed the assessment of dam's behavior under impact of aircraft to be grounded on knowledge of the methodology used for seismic safety of dams and methodology used for assessment of nuclear power plants to aircraft crash impact. The parameter that is controlled are the depth (length) of the tension zone in the horizontal cross-sections of the concrete dam body and damaged part of the cross section as per cent of the cross section (dimension of plastic zone).

The failure criteria are breaching of dam wall and uncontrolled release of water. These are possible in the following cases:

- Destruction of the dam crest;
- Crossing through the section of plastic zone;

TWO-DIMENSIONAL ANALYSIS

In the first step of this study the analyses are performed with the 2D model. The aim is to have an idea of the response of the structure. The materials of the dam wall are modeled as elastic-plastic using the Mohr-Coulomb formulation. The dynamic non-linear direct transient analyses are carried out based on Newmark's method.

The results from load case 1 (impact at upstream site) are shown in Figure 7 to Figure 12. These figures represent the distribution of principal stresses, vertical SYY stresses and equivalent plastic strain at two moments – the first one corresponds to maximum value of the time load function (t=0.472 s.) and the second one corresponds to decreasing branch of the load function (t=0.686 s.), near the time when impact load ends.

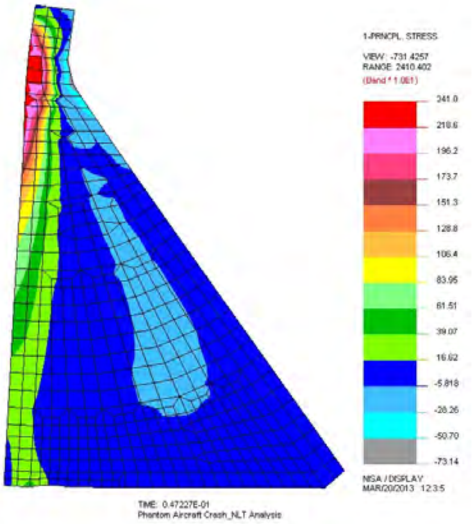

Figure 7 2D, Load 1, principal stresses

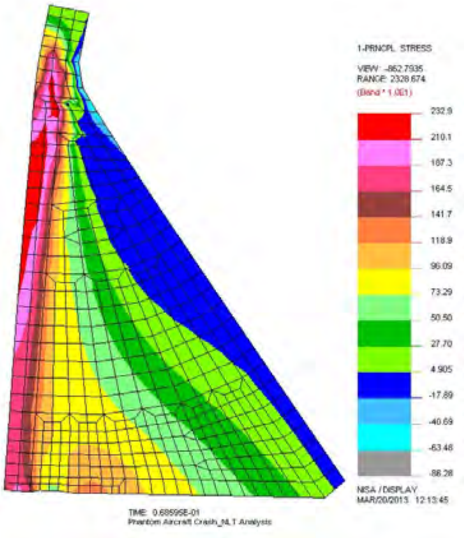

Figure 8 2D, Load 1, principal stresses

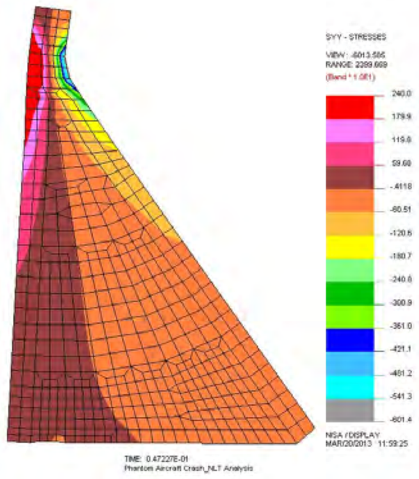

Figure 9 2D, Load 1, SYY stresses

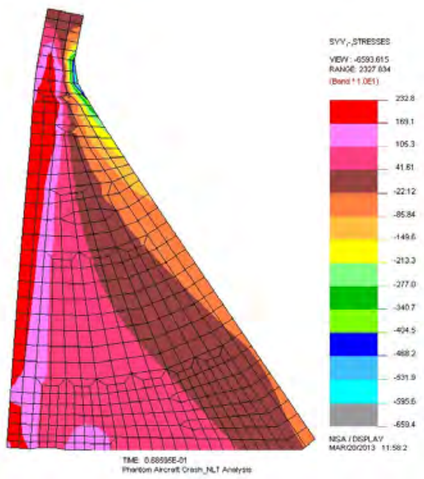

Figure 10 2D, Load 1, SYY stresses

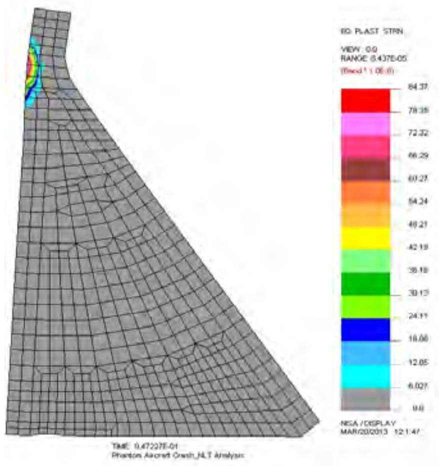

Figure 11 2D, Load 1, equivalent plastic strain

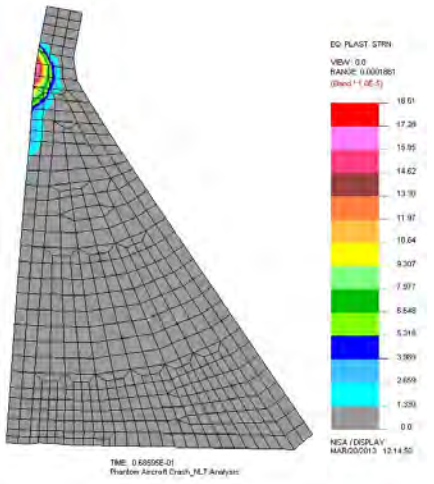

Figure 12 2D, Load 1, equivalent plastic strain

Considering the distribution of the principal stresses and equivalent plastic strains it is possible to conclude that surface destructions are expected. The part of the dam with highest values of the stresses is at the change of the cross section of the wall in the crest zone. The tensile strength of the concrete is reached only at the surface of the wall at crest zone at upstream face of the dam. This gives us grounds to conclude that only surface damages are expected under this loading function and break of the wall that could lead to water overflow is not expected.

In this analysis the spatial action of the loading is partially included by the assumption of distributing the load at an accepted width of the dam wall and too much uncertainty is included in the results. Only the analyses of the 3D model can give reasonable results for the local effects of the impact load that is concentrated at a very small part of the dam wall.

THREE-DIMENSIONAL ANALYSIS

The results from load case 1 (impact at upstream site) are shown in Figure 13 to Figure 17.

The results show that the principal stresses hardly reach the tensile strength of concrete at the moment of maximum impact loading (Figure 13) only at the surface of the downstream face of the wall the principal stress at small spot reaches the tensile strength of the concrete. The expansion deformations at the impact region cause the maximum SYY and SZZ stresses (Figures 14 and 15) to contribute to the maximum of the principal stress. The maximum tensile SYY and maximum tensile SZZ values do not exceed the concrete tensile strength.

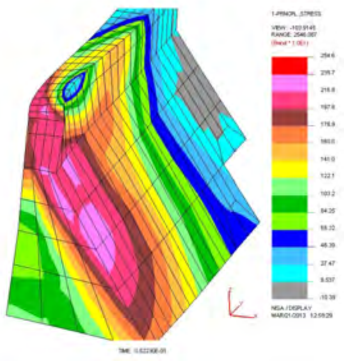

Figure 13 3D, Load 1, principle stresses

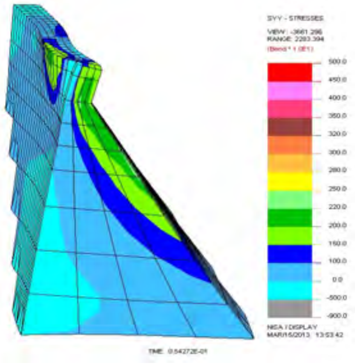

Figure 14 3D, Load 1, SYY stresses

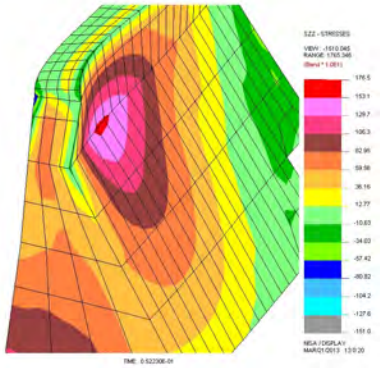

Figure 15 3D, Load 1, SZZ stresses

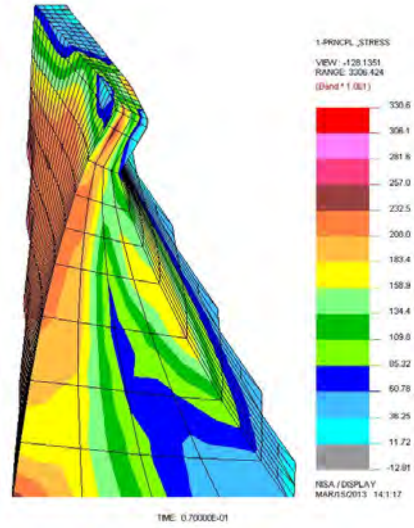

Figure 16 3D, Load 1, principle stresses

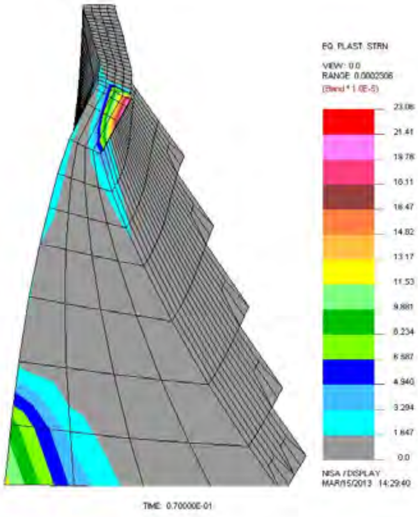

Figure 17 3D, Load 1, plastic strain

Figures 16 and 17 illustrate the principal stresses and distribution of plastic strain at end of the impact load 1. The principal stresses at crest zone are below the tensile strength and the values of plastic deformations are relatively small.

In summary this load case cannot cause breaching the dam wall and uncontrolled release of water.

The results from load case 2 (impact from upstream site) are shown in Figure 18 to Figure 21. The figures are snapshots at the moment of maximum values of the total impact load. The maximum values of the principal stress are below the tensile strength of the concrete except for a very small part of the section but the tensile stresses SYY and SZZ do not exceed the tensile strength. The plastic deformations are of the same order as those for load case 1. Damages only at surface can be expected. Breaching of the dam wall and uncontrolled release of water do not occur.

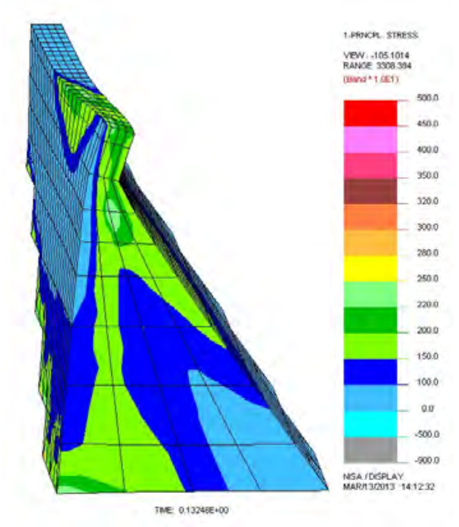

Figure 18 3D, Load 2, principal stresses

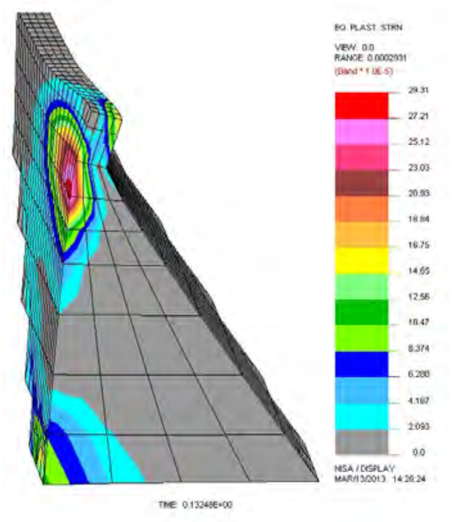

Figure 19 3D, Load 2, equivalent plastic strain

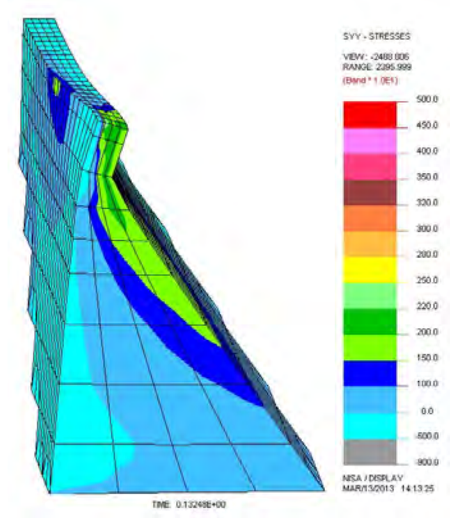

Figure 20 3D, Load 2, SYY stresses

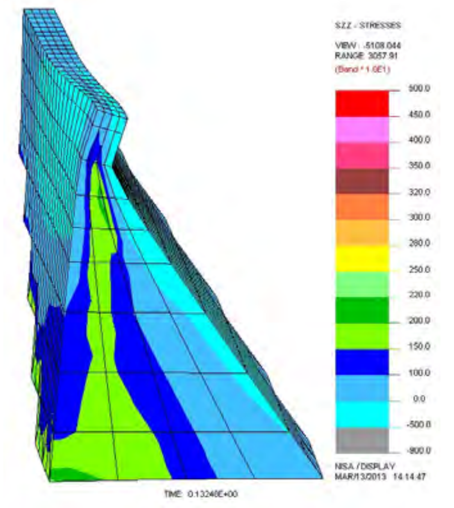

Figure 21 3D, Load 2, SZZ stresses

The results from load case 3 (impact at upstream site) are shown in Figures 22 to Figure 25.

The principle stresses and plastic strains are illustrated at two different moments, one when the total impact load is decreasing after its maximum value and the other one – when the impact load of the wings of the Boeing reaches maximum values. In Figure 22 and 24 are visualized the stresses (cross section of the wall) and plastic strains, respectively, at decreasing stage of the impact load. The values of the equivalent plastic strains are one order higher than those in lode cases 1 and 2 and are of the order of 1.6‰. The area of the equivalent plastic strain passes through the whole length of the crest zone. Considering the distribution of the principal stresses and equivalent plastic strains it is possible to conclude that considerable destructions and damage of the crest zone can be expected which could lead to flooding (uncontrolled flowing water) with heavy consequences. Figures 23 and 25 represent the influence of the wings (the shape of the stresses) at the moment when the load from wings reaches maximum value.

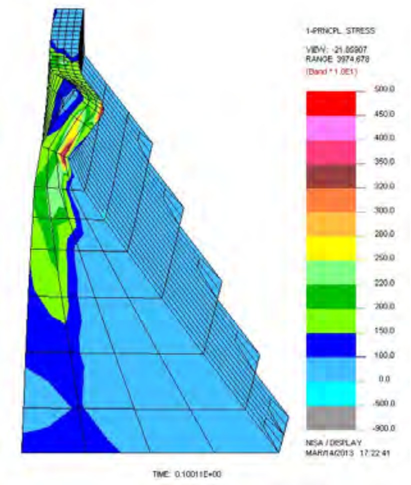

Figure 22 3D, Load 3, principal stresses, upstream site

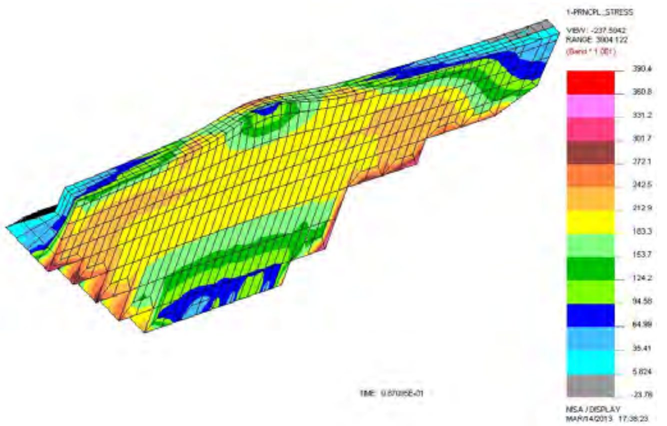

Figure 23 3D, Load 3, principal stresses, upstream site

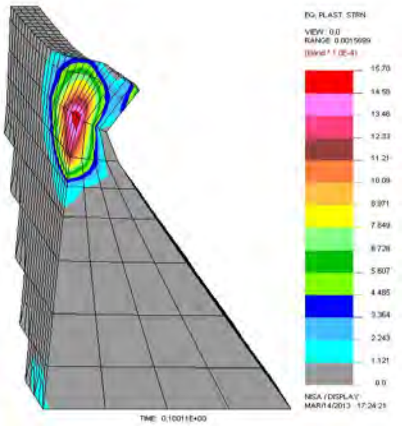

Figure 24 3D, Load 3, plastic strain, upstream site

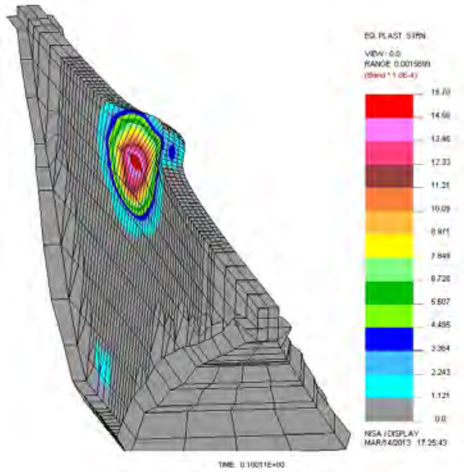

Figure 25 3D, Load 3, plastic strain, upstream site

The possibility of Boeing 767 to crash at the downstream face of the dam is studied too. Though usually the topography of the surrounding supporting blocks makes it very difficult to approach the dam with high velocity (260 m/sec) at this side this scenario is chosen as it is the heaviest load case for the structure.

The results from load case 3 (impact from downstream site) are shown in Figure 26 and Figure 27. The equivalent plastic strains are less than those obtain with the same load function 3 at upstream face of the dam. The principal stresses are above the tensile strength of the concrete in a limited part of the cross section. Damages could be expected under this load case though conclusions about breaching of the wall cannot be drawn. A more detailed net of the finite elements would be better to describe the problem.

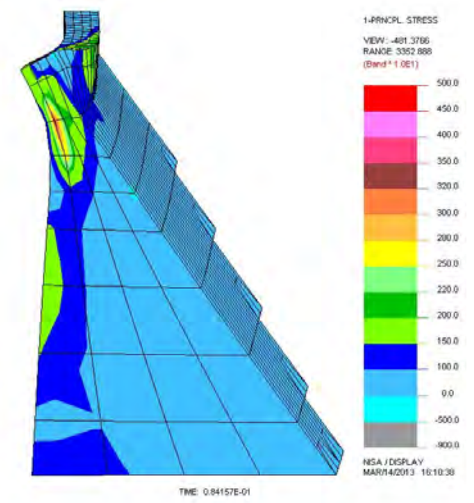

Figure 26 3D, Load 3, principal stresses, downstream site

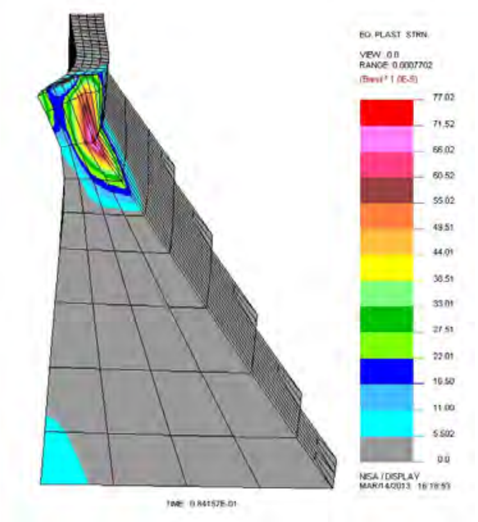

Figure 27 3D, Load 3, equivalent plastic strain, downstream site

CONCLUSIONS

The two-dimensional models are useful for preliminary assessment and evaluation of a given dam, because save time and computer resources. In the 2D analysis the spatial action of the loading is partially included by the assumption of distributing the load at an accepted width of the dam wall and final decisions about the possibility of failure cannot be made.

Three-dimensional models are needed for precise investigation of the dam behavior. Generally the maximum principle stresses are in different places and time moments for fuselage and the wings.

From the studied load cases the following conclusions about the effect of different impact loading on the dam wall can be drawn. Military jet cause only surface destruction on the dam wall and the safety of the wall is ensured. The passenger airliner causes bigger damages compared to military jet and at velocity of 260 m/s (which is really high velocity) can provoke a big destruction at crest zone combined with flooding from the running water though the wall.

The performed nonlinear dynamic analyses show a remarkable potential of concrete gravity dams to withstand also the impact of military and civil aircrafts for which they basically have not been designed.

ACKNOWLEDGEMENTS

This study is financially supported by European Commission and is a part from the project “Risk Assessment and Development of Protection Capacity for Critical Infrastructures due to Aircraft Attack”.

REFERENCES

EMRC-NISA software version 14, User manuals, (2005).

Henkel F., Klein D. (2007). "Variants of Analysis of the Load Case Airplane Crash", Transactions of the 19th SMiRT, paper J03-2, Toronto.

Kostov M., Iliev A., Andonov A. (2013). “Load time function definition for large commercial aircraft impact. Parametric study”, SMIRT-22, San Francisco, USA.