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Seismic and Stability Analysis of Gravity Dams Using Staad PRO

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***Abstract*—**This paper presents the main features and organization of STAADPRO, a computer program that has been developed for the static and seismic stability evaluations of concrete gravity dams. STAADPRO is based on the gravity method using rigid body equilibrium and beam theory to perform stress analyses, compute crack lengths, and safety factors. Seismic analyses could be done using either the pseudo-static or a simplified response spectrum method. STAADPRO is primarily designed to provide support for learning the principles of structural stability evaluation of gravity dams. It could also be used for research and development on stability of gravity dams. In adopting several worldwide published dam safety guidelines, a large number of modelling options have been implemented regarding (a) crack initiation and propagation, (b) effects of drainage and cracking under static, seismic, and post-seismic uplift pressure conditions, and (c) safety evaluation formats (deterministic allowable stresses and limit states, probabilistic analyses using Monte Carlo simulations). Structural stability evaluation of a 30m dam is presented to illustrate the use of STAADPRO that is available free from the web site. . Finite element (FE) method of analysis was used by employing Lagrangian Eulerian formulation of 4node plain quadrilateral elements, with modal analysis.The loadings were determined based on codebook, while the FE model is being implemented using the staad pro software tool.

***Keywords*—**Seismic, Stability, Analysis Gravity Dams Staad Pro

I. INTRODUCTION – SPECIFICATION

1.1 Purpose

The purpose of this manual is to provide technical criteria and guidance for the planning and design of concrete gravity dams with seismic analysis for civil works projects. Specific areas covered include design considerations, load conditions, stability requirements, methods of stress analysis, seismic analysis guidance, and miscellaneous structural features. Information is provided on the evaluation of existing structures and methods for improving stability.

1.2. Scope

a. This manual present's analysis and design guidance for concrete gravity dams. Conventional concrete and roller compacted concrete (RCC) are both addressed. Curved gravity dams designed for arch action and other types of concrete gravity dams are not covered in this manual. For structures consisting of a section of concrete gravity dam within an embankment dam, the concrete section will be designed in accordance with this manual.

b. The procedures in this manual cover only dams on rock foundations. Dams on pile foundations should be designed according to Engineer Manual(EM) 111022906.

c. Except as specifically noted throughout the manual, the guidance for the design of RCC and conventional concrete dams will be the same.

1.3 Applicability

This manual applies to all HQUSACE elements, major subordinate commands, districts, laboratories, and field operating activities having responsibilities for the design of civil works projects.

II. ABOUT GRAVITY DAM

A gravity dam is a solid structure, made of concrete or masonry, constructed across a river to create a reservoir on its upstream. The section of the gravity dam is approximately triangular in shape, with its apex at its top and maximum width at bottom. The section is so proportioned that it resists the various forces acting on it by its own weight. Most of the gravity dams are solid, so that no bending stress is introduced at any point and hence, they are sometimes known as solid gravity dams to distinguish them from hollow gravity dams in those hollow spaces are kept to reduce the weight. Early gravity dams were built of masonry, but nowadays with improved methods of construction, quality control and curing, concrete is most commonly used for the construction of modern gravity dams. A gravity dam (Figure.1.) is generally straight in plan and, therefore, it is also called straight gravity dam. The upstream face is vertical or slightly inclined. The slope of the downstream face usually varies between 0.7: 1 to 0.8: 1. Gravity dams are particularly suited across gorges with very steep side slopes where earth dams might slip. Where good foundations are available, gravity dams can be built up to

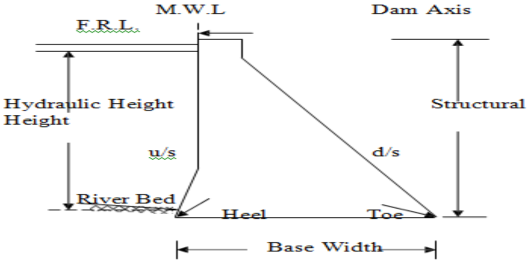


Figure.1. **GRAVITY DAM**

any height. Gravity dams are also usually cheaper than earth dams if suitable soils are not available for the construction of earth dams. This type of dam is the most permanent one, and requires little maintenance.

III. BASIC DEFINITION

3.1.Axis of the dam

The axis of the gravity dam is the line of the upstream edge of the top (or crown) of the dam. If the upstream face of the dam is vertical, the axis of the dam coincides with the plan of the upstream edge. In plan, the axis of the dam indicates the horizontal trace of the upstream edge of the top of the dam. The axis of the dam in plan is also called the base line of the dam. The axis of the dam in plan is usually straight. However, in some special cases, it may be slightly curved upstream, or it may consist of a combination of slightly curved right portions at ends and a central abutment straight portion to take the best advantages of the topography of the site.

3.2 Length of the dam

The length of the dam is the distance from one abutment to the other, measured along the axis of the dam at the level of the top of the dam. It is the usual practice to mark the distance from the left abutment to the right abutment. The left abutment is one which is to the left of the person moving along with the current of water.

3.3 Structural height of the dam:

The structural height of the dam is the difference in elevations of the top of the dam and the lowest point in the excavated foundation. It, however, does not include the depth of special geological features of foundations such as narrow fault zones below the foundation. In general, the height of the dam means its structural height.

3.4 Maximum base width of the dam:

The maximum base width of the dam is the maximum horizontal distance between the heel and the toe of the maximum section of the dam in the middle of the valley.

3.5. Toe and Heel:

The toe of the dam is the downstream edge of the base, and the heel is the upstream edge of the base. When a person moves along with water current, his toe comes first and heel comes later.

3.6. Hydraulic height of the dam

The hydraulic height of the dam is equal to the difference in elevations of the highest controlled water surface on the upstream of the dam (i. e. FRL) and the lowest point in the river bed.

IV. ABOUT NATURAL RESPONSE

The structural response of a material to different loads determines how it will be economically utilized in the design process. Earthquake is a natural disaster that has claimed so many lives and destroyed lots of property. Earthquake hazards had caused the collapse and damage to continual functioning of essential services such as communication and transportation facilities, buildings, dams, electric installations, ports, pipelines, water and waste water systems, electric and nuclear power plants with severe economic losses. Earthquake is a major source of seismic forces that impinge on structures others are Tsunami, seethe etc. Earth wall is chosen as a material for the dam since its major constituent earth is abundantly available and provides a sustainable solution. This necessitates the seismic analysis of concrete gravity dam. Finite element has been widely used in seismic analysis of concrete gravity dams (Waltz 1997, Lotfi 2003) with a defined approach as presented in this programme.Earthquakes had caused severe damages and consequently huge economic losses including losses of lives. The analytical computation of the modal approach procedure has been carried out and implemented using STAAD PRO tool. The pseudo static seismic coefficient method was adopted in computing the seismic loads on the dam. The dam used as a case study was assumed to be in seismic zone 1 with seismic coefficient ranging between 0.0 and 0.05. The dam was analysed seismically using the decoupled modal approach and the results were compared with that of the concrete gravity dam.

V. ABOUT THE SOFTWARE

STAAD or (**STAAD.Pro**) is a structural analysis and design computer program originally developed by Research Engineers International in Yorba Linda, CA. In late 2005, Research Engineer International was bought by Bentley Systems. An older version called Staad-III for windows is used by Iowa State University for educational purposes for civil and structural engineers. The commercial version STAAD.Pro is one of the most widely used structural analysis and design software. It supports several steel, concrete and timber design codes.It can make use of various forms of analysis from the traditional 1st order static analysis, 2nd order p-delta analysis, geometric non linear analysis or a buckling analysis. It can also make use of various forms of dynamic analysis from modal extraction to time history and response spectrum analysis.

VI. SEISMIC RESPONSE OF CONCRETE GRAVITY DAMS

In earth dams, seismic forces or shaking can induce destabilising deformation or outright failure if not made earthquake resistant. A permanent simplified procedure can be adopted to estimate permanent horizontal displacements of the dams using finite element method that account for nonlinear material behaviour and strength reduction due to liquefaction or strain softening. It has been shown ((Hatami, 2001) that the seismic performance of earth dams has been related to the nature and state of compaction of the fill material.

VII. FLUID STRUCTURE SYSTEM

During earthquake occurrence, the dam and reservoir body respond differently, as a result of hydrodynamic forces impinging on the fluid body and solid structure. As a result of this, interaction will occur between the fluid–solid structure interfaces as particles move relatively to the mesh points whereas, the meshes moves with the material particles (Bathe, 1996, Qixiang et al. 2000). Much research work has been carried out for the dynamic response of the fluid solid structure systems. Several methods of analysis for the fluid structure systems (Figure.2) use finite element idealization in the nonlinear dynamic response of the system (Fenves and Vargas Loli, 1988).

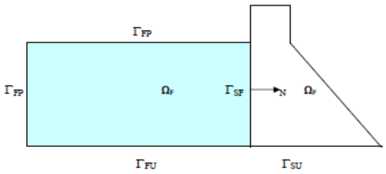


Fig. 1.(a) Domains and boundaries of the fluid-structure system

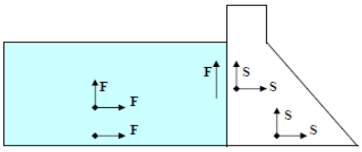


Fig. 1(b): Degrees of freedom of the fluid-structure system

In Fig.1(a, b) the following terms are defined as:

Ω_F= Fluid domain
Ω_S = Structure domain
Γ_{FP} = Fluid boundary at reservoir end
Γ_{SU} = Portion of structure boundary along an earthquake ground motion path
Γ_{FP} = Free surface of the fluid
Γ_{SF} = Fluid-structure common interface
Γ_{FU} = Portion of structure boundary along an earthquake ground motion path
N = Normal to the fluid boundary

Figure.2. **FLUID STRUCTURE SYSTEMS**

VIII. LOADINGS

8.1 STATIC LOADS.

The static loads are due to

(i) The weight of the dam: the unit weight is assumed to be 19.62kN/m^3 until an exact unit weight is determined from materials investigation.,

(ii) Hydrostatic pressure of the water in the reservoir and

(iii) The uplift forces caused by hydrostatic pressure on the foundation at the interface of the dam and the foundation. Uplift forces are usually considered in stability and stress analysis to ensure structural adequacy and are assumed to be unchanged by earthquake forces.

8.2 DYNAMIC LOADS

Earthquake or seismic loads are the major dynamic loads (Major 1980, Schoeber 1981,Polyakov 1985, Wyatt (1989) being considered in the analysis and design of dams especially in earthquake prone areas. The seismic coefficient method is used in determining the resultant location and sliding stability of dams. Seismic analysis of dams is performed for the most unfavourable direction, despite the fact that earthquake acceleration might take place in any direction. Fig. 2 shows the dynamic loads on a gravity dam. There are different ways of computing earthquake loads on dams. The deterministic approach will be employed where the ground acceleration in terms of **g** (acceleration due to gravity) is specified for the region where the dam will be constructed. Hence, the exciting force on the structure is,

$P_{(t)} = Ma_X$ (1)
and
$a_X = \alpha g$ (2)
where $\mathbf{a_X}$, $\boldsymbol{\alpha}$, $\mathbf{g}$ are the ground acceleration, seismic coefficient and acceleration due to gravity respectively.

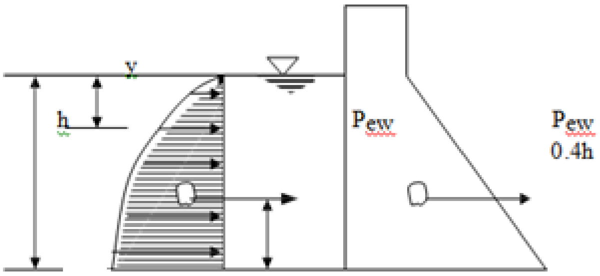


Figure.3. **SEISMICALLY LOADED GRAVITY DAM**

From Fig.3 and equation (1) therefore, the equilibrium system is expressed as:
$Pe_X = Ma_X = W\alpha g/g = W\alpha$ (3a)
In which $a_X = \alpha g$ and $W = Mg$ (3b)
along vertical direction
$Pe_W = (2 * C_e * \alpha * y * \sqrt{(h * y)}) / 3$ (4a)
and
$C_e = 51 / \sqrt{(1 - 0.72 * (h / (1000t_e))^2)}$ (4b)
where Pe_X, M, a_X, W, α, g are the horizontal earthquake force on the dam, mass horizontal earthquake acceleration, weight, acceleration due to gravity and seismic coefficient respectively. Also Pe_W, h, t_e are the additional total water load down to depth y, total height of reservoir, and period of vibration respectively.

IX. ANALYSIS

9.1 STRESS ANALYSIS

a. General.

(1) A stress analysis of gravity dams is performed to determine the magnitude and distribution of stresses throughout the structure for static and dynamic load conditions and to investigate the structural adequacy of the substructure and foundation.

(2) Gravity dam stresses are analyzed by either approximate simplified methods or the finite element method depending on the refinement required for the particular level of design and the type and configuration of the dam. For preliminary designs, simplified methods using cantilever beam models for two-dimensional analysis or the trial load twist method for three-dimensional analysis are appropriate as described in the US Bureau of Reclamation (USBR), "Design of Gravity Dams" (1976).The finite element method is ordinarily used for the feature and final design stages if a more exact stress investigation is required.

b. Finite element analysis.

(1) Finite element models are used for linear elastic static and dynamic analyses and for nonlinear analyses that account for interaction of the dam and foundation. The finite element method provides the capability ofmodeling complex geometries and wide variations in material properties. The stresses at corners, around openings, and in tension zones can be approximated with a finite element model. It can model concrete thermalbehavior and couple thermal stresses with other loads. An important advantage of this method is that complicated foundations involving various materials, weak joint son seams, and fracturing can be readily modelled. Special purpose computer programs designed specifically for analysis of concrete gravity dams are CG-DAMS (Anatech1993), which performs static, dynamic, and nonlinear analyses and includes a smeared crack model, and MERLIN(Saouma 1994), which includes a discrete cracking fracture mechanics model.

(2) Two-dimensional, finite element analysis is generally appropriate for concrete gravity dams. The designer should be aware that actual structure response is three dimensions a land should review the analytical and realistic results to assure that the two-dimension approximation is acceptable and realistic. For long conventional concrete dams with transverse contraction joints and without keyed joints, a two-dimensional analysis should be reasonably correct. Structures located in narrow valleys between steep abutments and dams with varying rock module which vary across the valley are conditions that necessitate three-dimensional modelling.

9.2. DYNAMIC ANALYSIS

The structural analysis for earthquake loadings consists of two parts: an approximate resultant location and sliding stability analysis using an appropriate seismic coefficient and a dynamic internal stress analysis using site-dependent earthquake ground motions if the following conditions exist:

a. The dam is 100 feet or more in height and the peak ground acceleration (PGA) at the site is greater than 0.2 g for the maximum credible earthquake.
b. The dam is less than 100 feet high and the PGA at the site is greater than 0.4 g for the maximum credible earthquake.
c. There are gated spillway monoliths, wide roadways, intake structures, or other monoliths of unusual shape or geometry.
d. The dam is in a weakened condition because of accident, aging, or deterioration. The requirements for a dynamic stress analysis in this case will be decided on a project-by-project basis in consultant and approved by CECW-ED.

Dynamic Analysis Process

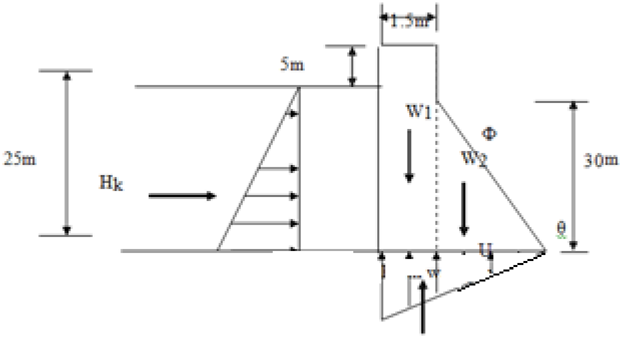
The procedure for performing a dynamic analysis includes the following:

a. Review the geology, seismology, and contemporary tectonic setting.
b. Determine the earthquake sources.
c. Select the candidate maximum credible and operating basis earthquake magnitudes and locations.
d. Select the attenuation relationships for the candidate earthquakes.
e. Select the controlling maximum credible and operating basis earthquakes from the candidate earthquakes based on the most severe ground motions at the site.
f. Select the design response spectra for the controlling earthquakes.
g. Select the appropriate acceleration-time records that are compatible with the design response spectra if acceleration-time history analyses are needed.
h. Select the dynamic material properties for the concrete and foundation.
i. Select the dynamic methods of analysis to be used.
j. Perform the dynamic analysis.
k. Evaluate the stresses from the dynamic analysis.

X. STABILITY AND STRESS ANALYSES

The following assumptions are made for the Earth wall gravity dam

Freeboard = 30% of the reservoir height. Crest width = 0.23 times dam's height. This is used to allow the passage of small vehicles, Base width = 0.87 times dam's height. This is used to avoid tension in the base. Using similar triangles, $\theta = 48.8^0$ and $\varphi = 41.2^0$.



See Figure.4

Figure.4. **STABILITY AND STRESS ANALYSES**

Vertical force:

Vertical force = W_1 (=γhl) + W_2 (= 0.5γhl) + uplift (U = 0.5γhl) = 583.16kN Horizontal force P_W : P_W (= $0.5\gamma h^2$) = 313.92kN

$$\text{Sliding Criteria:} \quad \text{F.S.} = \frac{\text{Net vertical force}}{\text{horizontal force}} = 1.86$$

1.86 > 1.6. Hence, sliding criteria is favourably satisfied.

Overturning Criteria

Sum of Overturning moment = 3051.16kNm
Sum of stabilizing moment = 5883.02kNm
So that F.S.= 1.93 > 1.6. Hence, overturning criteria is favourably satisfied.

Stress Analysis

Normal Stress at the toe considering the limiting case at e = 9.2/6 = 1.53m, Then, $P_n = 0.127 N/mm^2$

Principal Stress at the toe, $\sigma_1 = 0.072 N/mm^2$
The stresses obtained are less than the allowable values, therefore safe against overstressing.

XI. SYSTEM ANALYZED

The 30m (100ft) high gravity dam to illustrate some of STAADPRO potentials. This dam that was used in USACE (2000) to evaluate and compare stability analysis and uplifting criteria for gravity dams by three US Federal agencies.The usual upstream and downstream reservoir elevations are set to 27.432m (90ft) and 1.524m (5ft), respectively. Lift joints are spaced at every 3.048m (10ft) in elevation from the base. The drainage system is initially considered according to USACE (1995) guideline, the drain position, efficiency and the elevation of the drainage gallery

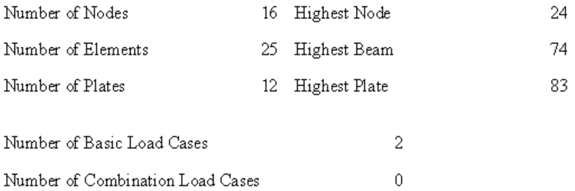
11.2 STAAD INPUT AND OUTPUT

The analyses are done by using STAADPRO and the calculation results and diagrams are shown in the Figure.,5,6,7,8,9 & 10

Job Information

	Engineer	**Checked**	**Approved**
Name:			
Date:	28-Apr-12		

Structure Type SPACE FRAME



Number of Nodes	16	Highest Node	24
Number of Elements	25	Highest Beam	74
Number of Plates	12	Highest Plate	83

Number of Basic Load Cases	2
Number of Combination Load Cases	0

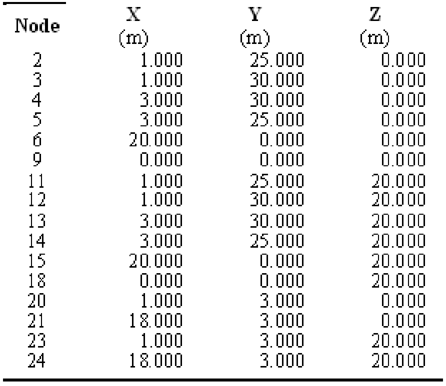
Included in this printout are data for:

All The Whole Structure

Included in this printout are results for load cases:

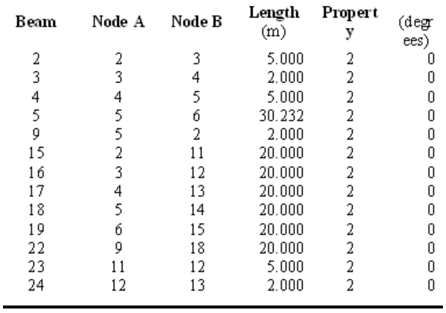
Type	**L/C**	**Name**
Primary	1	LOAD CASE 1
Primary	2	LOAD CASE 2

Nodes



Node	X (m)	Y (m)	Z (m)
2	1.000	25.000	0.000
3	1.000	30.000	0.000
4	3.000	30.000	0.000
5	3.000	25.000	0.000
6	20.000	0.000	0.000
9	0.000	0.000	0.000
11	1.000	25.000	20.000
12	1.000	30.000	20.000
13	3.000	30.000	20.000
14	3.000	25.000	20.000
15	20.000	0.000	20.000
18	0.000	0.000	20.000
20	1.000	3.000	0.000
21	18.000	3.000	0.000
23	1.000	3.000	20.000
24	18.000	3.000	20.000

Beams



Beam	Node A	Node B	Length (m)	Property	(degrees)
2	2	3	5.000	2	0
3	3	4	2.000	2	0
4	4	5	5.000	2	0
5	5	6	30.232	2	0
9	5	2	2.000	2	0
15	2	11	20.000	2	0
16	3	12	20.000	2	0
17	4	13	20.000	2	0
18	5	14	20.000	2	0
19	6	15	20.000	2	0
22	9	18	20.000	2	0
23	11	12	5.000	2	0
24	12	13	2.000	2	0

Plates

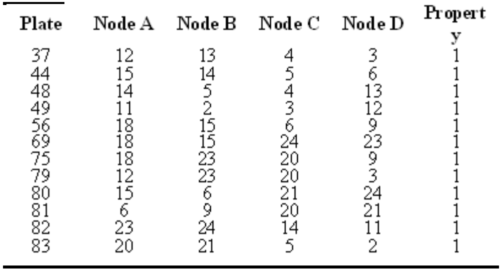
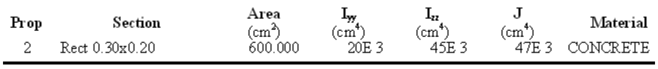


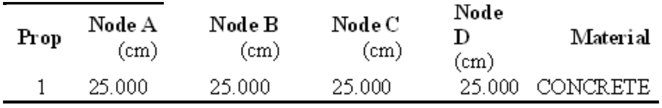
Plate	Node A	Node B	Node C	Node D	Property
37	12	13	4	3	1
44	15	14	5	6	1
48	14	5	4	13	1
49	11	2	3	12	1
56	18	15	6	9	1
69	18	15	24	23	1
75	18	23	20	9	1
79	12	23	20	3	1
80	15	6	21	24	1
81	6	9	20	21	1
82	23	24	14	11	1
83	20	21	5	2	1

Section Properties



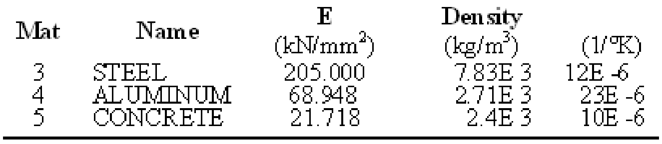
Prop	Section	Area (cm^2)	I_{yy} (cm^4)	I_{zz} (cm^4)	J (cm^4)	Material
2	Rect 0.30x0.20	600.000	20E 3	45E 3	47E 3	CONCRETE

Plate Thickness



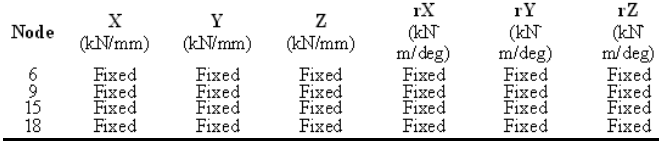
Prop	Node A (cm)	Node B (cm)	Node C (cm)	Node D (cm)	Material
1	25.000	25.000	25.000	25.000	CONCRETE

Materials



Mat	Name	E (kN/mm^2)	Density (kg/m^3)	(1/°K)
3	STEEL	205.000	7.83E 3	12E -6
4	ALUMINUM	68.948	2.71E 3	23E -6
5	CONCRETE	21.718	2.4E 3	10E -6

Supports



Node	X (kN/mm)	Y (kN/mm)	Z (kN/mm)	rX (kN m/deg)	rY (kN m/deg)	rZ (kN m/deg)
6	Fixed	Fixed	Fixed	Fixed	Fixed	Fixed
9	Fixed	Fixed	Fixed	Fixed	Fixed	Fixed
15	Fixed	Fixed	Fixed	Fixed	Fixed	Fixed
18	Fixed	Fixed	Fixed	Fixed	Fixed	Fixed

Plate Loads : 2 LOAD CASE 2

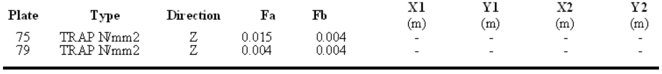
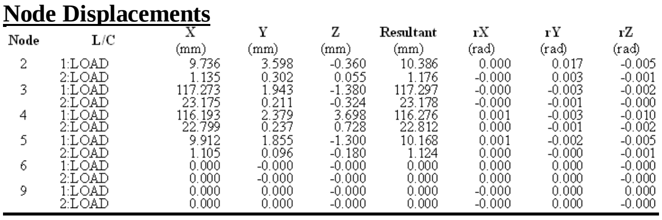


Plate	Type	Direction	Fa	Fb	X1 (m)	Y1 (m)	X2 (m)	Y2 (m)
75	TRAP N/mm2	Z	0.015	0.004	-	-	-	-
79	TRAP N/mm2	Z	0.004	0.004	-	-	-	-

Node Displacements



Node	L/C	X (mm)	Y (mm)	Z (mm)	Resultant (mm)	rX (rad)	rY (rad)	rZ (rad)
2	1:LOAD	9.736	3.598	-0.360	10.386	0.000	0.017	-0.005
	2:LOAD	1.135	0.302	0.055	1.176	-0.000	0.003	-0.001
3	1:LOAD	117.273	1.943	-1.380	117.297	-0.000	-0.003	-0.002
	2:LOAD	23.175	0.211	-0.324	23.178	-0.000	-0.001	-0.000
4	1:LOAD	116.193	2.379	3.698	116.276	0.001	-0.003	-0.010
	2:LOAD	22.799	0.237	0.728	22.812	0.000	-0.001	-0.002
5	1:LOAD	9.912	1.855	-1.300	10.168	0.001	-0.002	-0.005
	2:LOAD	1.105	0.096	-0.180	1.124	0.000	-0.000	-0.001
6	1:LOAD	0.000	-0.000	-0.000	0.000	0.000	0.000	-0.000
	2:LOAD	0.000	-0.000	-0.000	0.000	0.000	0.000	-0.000
9	1:LOAD	0.000	0.000	-0.000	0.000	-0.000	0.000	0.000
	2:LOAD	0.000	0.000	-0.000	0.000	-0.000	0.000	-0.000

Node Displacement Summary

	Node	L/C	X (mm)	Y (mm)	Z (mm)	Resultant (mm)	rX (rad)	rY (rad)	rZ (rad)
Max X	3	1:LOAD	**117.273**	1.943	-1.380	117.297	-0.000	-0.003	-0.002
Min X	18	1:LOAD	**0.000**	0.000	0.000	0.000	0.000	-0.000	0.000
Max Y	2	1:LOAD	9.736	**3.598**	-0.360	10.386	0.000	0.017	-0.005
Min Y	6	1:LOAD	0.000	**-0.000**	-0.000	0.000	0.000	0.000	-0.000
Max Z	4	1:LOAD	116.193	2.379	**3.698**	116.276	0.001	-0.003	-0.010
	13	1:LOAD	116.193	2.379	**-3.698**	116.276	-0.001	0.003	-0.010
Max rX	4	1:LOAD	116.193	2.379	3.698	116.276	**0.001**	-0.003	-0.010
Min rX	13	1:LOAD	116.193	2.379	-3.698	116.276	**-0.001**	0.003	-0.010
Max rY	2	1:LOAD	9.736	3.598	-0.360	10.386	0.000	**0.017**	-0.005
Min rY	11	1:LOAD	9.736	3.598	0.360	10.386	-0.000	**-0.017**	-0.005
Max rZ	9	1:LOAD	0.000	0.000	-0.000	0.000	-0.000	0.000	**0.000**
Min rZ	4	1:LOAD	116.193	2.379	3.698	116.276	0.001	-0.003	**-0.010**
Max Rst	3	1:LOAD	117.273	1.943	-1.380	**117.297**	-0.000	-0.003	-0.002

Plate Centre Stresses

Plate Centre Stress Summary

			Shear		Membrane			Bending		
	Plate	L/C	Qx (N/mm²)	Qy (N/mm²)	Sx (N/mm²)	Sy (N/mm²)	Sxy (N/mm²)	Mx (kNm/m)	My (kNm/m)	Mxy (kNm/m)
Max	37	1:LOAD	**1.266**	0.000	-0.293	-2.686	-0.000		18.564	0.000
Min Qx	82	1:LOAD	**-0.084**	-0.002	-0.600	0.169	0.584	16.195	10.923	-1.453
Max	48	1:LOAD	-0.000	**0.753**	-2.638	-1.388	0.000	-11.982	-32.242	0.000
Min Qy	80	1:LOAD	-0.000	**-0.098**	0.057	0.210	0.000	-3.794	-27.189	0.000
Max Sx	79	1:LOAD	-0.003	-0.000	**1.880**	0.170	0.000	1.232	-4.951	-0.000
Min Sx	48	1:LOAD	-0.000	0.753	**-2.638**	-1.388	0.000	-11.982	-32.242	0.000
Max Sy	69	1:LOAD	-0.003	-0.070	0.368	**0.407**	2.275	-1.045	-1.948	-0.418
Min Sy	37	1:LOAD	1.266	0.000	-0.293	**-2.686**	-0.000		18.564	0.000
Max	69	1:LOAD	-0.003	-0.070	0.368	0.407	**2.275**	-1.045	-1.948	-0.418
Min	81	1:LOAD	0.003	-0.070	0.368	0.407	**-2.275**	-1.045	-1.948	0.418
Max	37	1:LOAD	1.266	0.000	-0.293	-2.686	-0.000		18.564	0.000
Min	83	1:LOAD	0.084	0.002	-0.600	0.169	0.584	**-16.195**	-10.923	1.453
Max	49	1:LOAD	0.000	0.256	1.415	-0.374	-0.000	22.304	**19.977**	0.000
Min	48	1:LOAD	-0.000	0.753	-2.638	-1.388	0.000	-11.982	**-32.242**	0.000
Max	83	1:LOAD	0.084	0.002	-0.600	0.169	0.584	-16.195	-10.923	**1.453**
Min	82	1:LOAD	-0.084	-0.002	-0.600	0.169	0.584	16.195	10.923	**-1.453**

Plate Centre Principal Stresses

		Principal		Von Mis		Tresca	
Plate	L/C	Top (N/mm²)	Bottom (N/mm²)	Top (N/mm²)	Bottom (N/mm²)	Top (N/mm²)	Bottom (N/mm²)
37	1:LOAD CASE	10.865	-0.903	11.344	9.996	11.769	11.450
	2:LOAD CASE	2.218	-0.123	2.282	2.047	2.341	2.336
44	1:LOAD CASE	1.952	-1.952	2.034	2.659	2.107	2.879
	2:LOAD CASE	0.242	-0.242	0.281	0.398	0.308	0.420
48	1:LOAD CASE	4.483	-4.483	4.179	2.770	4.483	3.196
	2:LOAD CASE	0.938	-0.938	0.885	0.640	0.938	0.740
49	1:LOAD CASE	3.557	1.543	3.089	2.029	3.557	2.292
	2:LOAD CASE	0.697	0.325	0.604	0.382	0.697	0.437
56	1:LOAD CASE	0.027	-0.026	0.046	0.044	0.053	0.050
	2:LOAD CASE	0.004	-0.004	0.007	0.007	0.008	0.008
69	1:LOAD CASE	2.479	-1.992	3.880	4.047	4.471	4.633
	2:LOAD CASE	0.619	-0.619	1.019	1.115	1.176	1.286
75	1:LOAD CASE	4.449	0.947	4.059	2.243	4.449	2.383
	2:LOAD CASE	0.899	0.203	0.817	0.534	0.899	0.558

Reactions

		Horizonta	Vertical	Horizonta		Moment	
Node	L/C	FX (kN)	FY (kN)	FZ (kN)	MX (kNm)	MY (kNm)	MZ (kNm)
6	1:LOAD CASE	-4.08E 3	5.99E 3	2.48E 3	-15.9E 3	-9.52E 3	5.19E 3
	2:LOAD CASE	-685.253	879.426	232.841	-2.46E 3	-1.43E 3	385.627
9	1:LOAD CASE	-325.370	-5.99E 3	516.500	9.87E 3	-80.639	-2.59E 3
	2:LOAD CASE	-695.164	-879.426	120.421	1.7E 3	-1.789	209.202
15	1:LOAD CASE	-4.08E 3	5.99E 3	-2.48E 3	15.9E 3	9.52E 3	5.19E 3
	2:LOAD CASE	-685.253	879.426	-232.841	2.46E 3	1.43E 3	385.628
18	1:LOAD CASE	-325.370	-5.99E 3	-516.500	-9.87E 3	80.643	-2.59E 3
	2:LOAD CASE	-695.164	-879.426	-120.421	-1.7E 3	1.790	209.203

Base Pressure

Node	L/C	FX (N/mm²)	FY (N/mm²)	FZ (N/mm²)
6	1:LOAD CASE 1	0.000	0.000	0.000
	2:LOAD CASE 2	0.000	0.000	0.000
9	1:LOAD CASE 1	0.000	0.000	0.000
	2:LOAD CASE 2	0.000	0.000	0.000
15	1:LOAD CASE 1	0.000	0.000	0.000
	2:LOAD CASE 2	0.000	0.000	0.000
18	1:LOAD CASE 1	0.000	0.000	0.000
	2:LOAD CASE 2	0.000	0.000	0.000

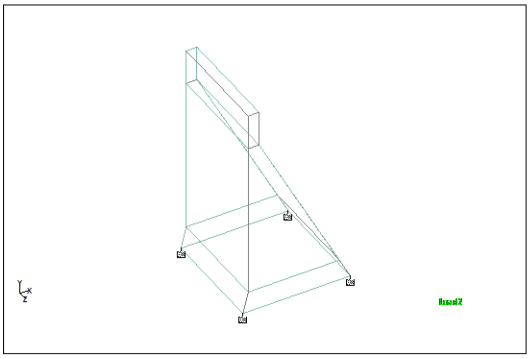


Figure.5 **MODEL STRUCTURE**

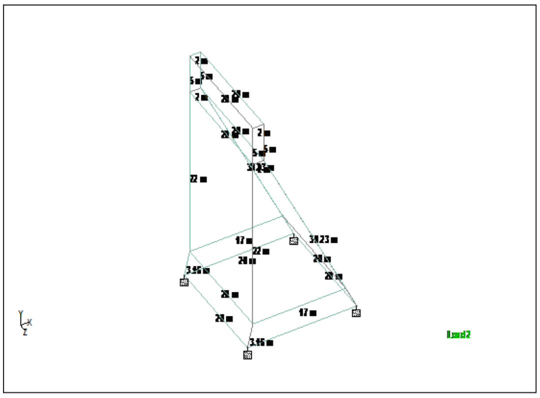


Figure.6. **STRUCTURE WITH DIMENSION**

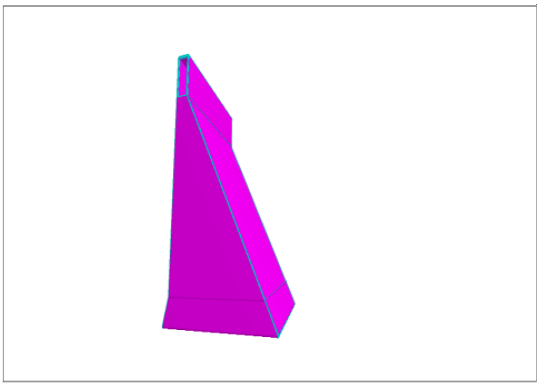


Figure.7. **STRUCTURE WITH 3D VIEW**

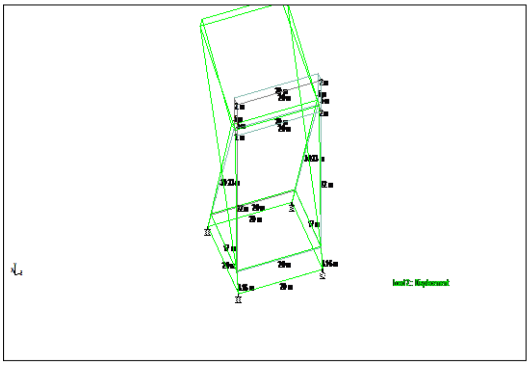


Figure.8. **STRUCTURE WITH DISPLACEMENT**

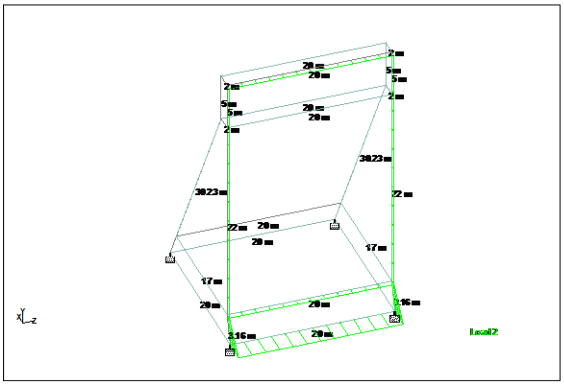


Figure.9 **STRUCTURE WITH LOADING**

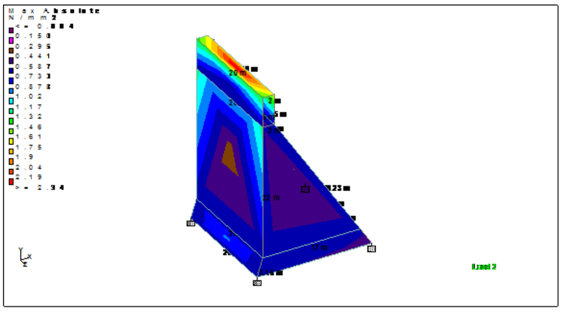


Figure.9 **STRUCTURE WITH STRESS**

XII. PERSPECTIVES FOR FUTURE DEVELOPMENTS

There are almost endless possibilities for further developments of a computer program like STAADPRO for structural safety assessment of gravity dams. Currently, the plan is to add the following features:

From pseudo-static or a pseudo-dynamic seismic analysis, the lift joint most susceptible to cracking can be easily obtained using STAADPRO. Calculation of seismic sliding displacements and rocking response of cracked dam components using transient dynamic analysis of rigid body is envisaged. Computation of displacements using beam theory for the dams and Bossiness coefficients for the semi-infinite elastic foundation. Thermal analysis will be performed along lift joints using finite differences to evaluate the thermal field required for thermal displacement and stress computations. The displacement response of a 2D model could be calibrated against that of a preliminary 3D finite element model to determine the fraction of the hydrostatic load that is resisted in a pure cantilever mode. Unit thermal loads could also be used for calibration purposes.

XIII. CONCLUSION

STAADPRO provides a very versatile computing environment to learn or investigate modelling assumptions and computational processes related to the static and seismic structural stability of gravity dams based on the gravity method. It has been shown in this paper that several assumptions related to load conditions, cracking criteria, uplift pressures intensities and analysis procedure could be used for static, seismic, and post-seismic safety assessments In general, the computations are complex to perform due to the coupling between the uplift pressure and crack length. In an actual situation, parametric analyses are most often performed to cover uncertainties in strength and loading parameters to take appropriate decision concerning a particular structure.

The authors have successfully used STAADPRO as a computational laboratory in seminars, to engineers from practice, involved in dam safety evaluation STAADPRO is also used for industrial applications and R&D in dam engineering and has been extensively validated during the past years. The organisation of the program and the particular features that have been presented herein are useful for those interested in the development and application of computer aided stability analysis of gravity dams.

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