C A D A M

USER'S MANUAL

VERSION 1.4.3

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By

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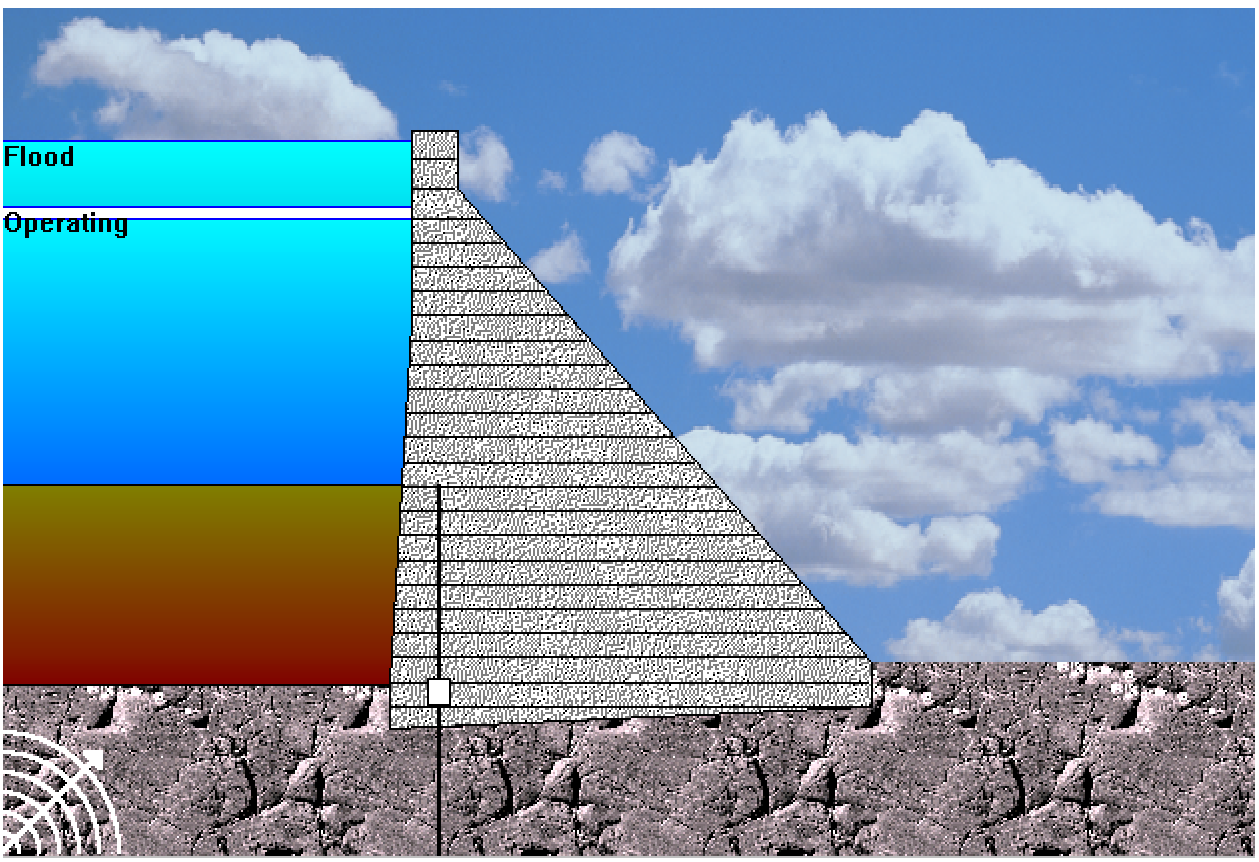

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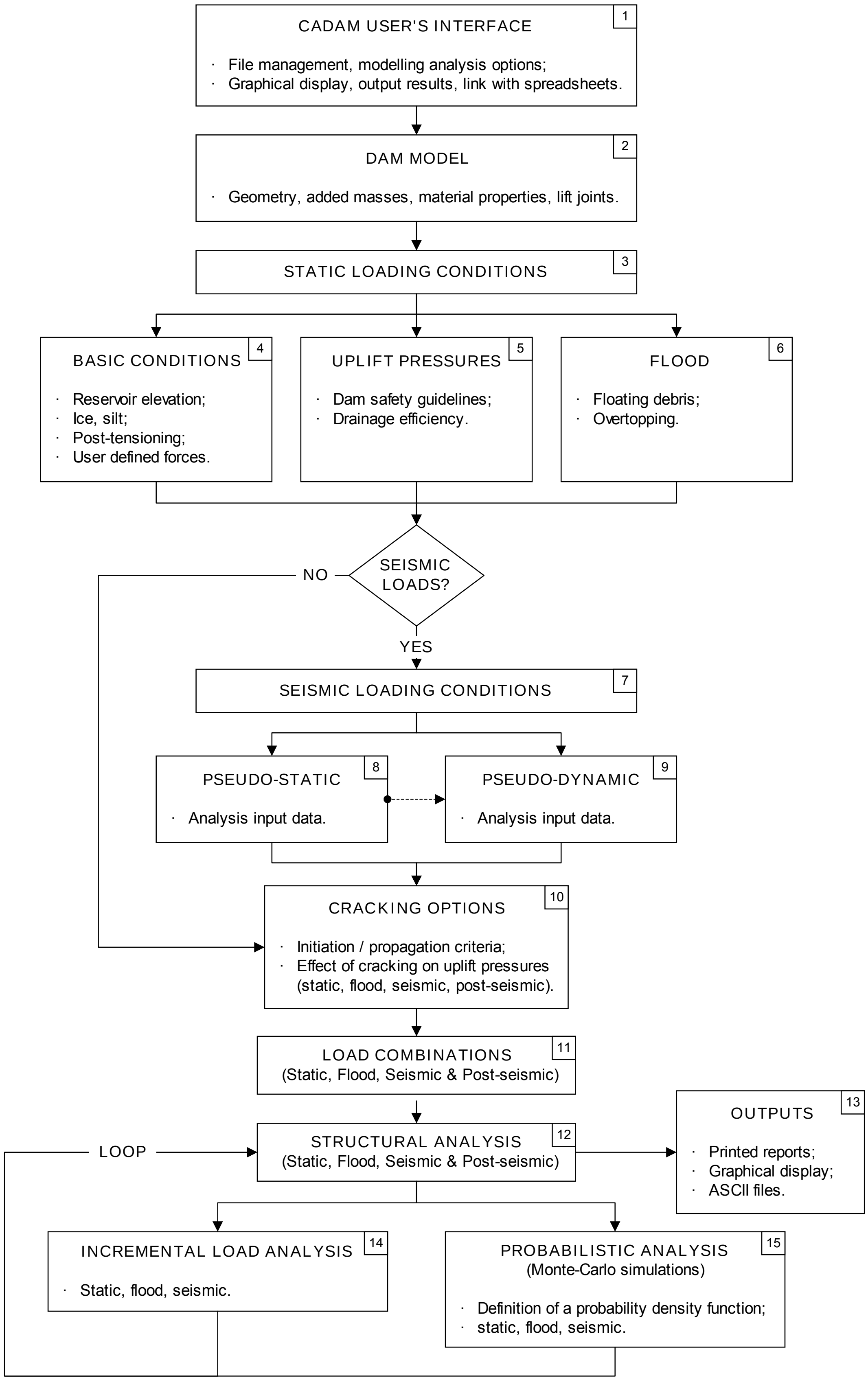
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PREFACE

The computer program CADAM was developed in the context, of the R&D activities, of the industrial chair on *Structural Safety of Existing Concrete Dams.* This chair was established in 1991 at École Polytechnique de Montréal and is funded jointly by NSERC (Natural Sciences and Engineering Research Council), Hydro-Québec and Alcan.

The support of these organisations is gratefully acknowledged. In addition, the contributions and discussions with the engineers of the industrial partners, throughout this development, as well as related research topics were most useful and stimulating. These technical contributions are also acknowledged.

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CADAM – USER'S MANUAL

PART I – GENERAL INFORMATION

1 INTRODUCTION

1.1 Objectives

CADAM is a computer program that was primarily designed to provide support for learning the principles of structural stability evaluation of concrete gravity dams. CADAM is also used to support research and development on structural behaviour and safety of concrete dams.

CADAM is based on the **gravity method** (rigid body equilibrium and beam theory). It performs stability analyses for hydrostatic loads and seismic loads. Several modelling options have been included to allow users to explore the structural behaviour of gravity dams (e.g. geometry, uplift pressures and drainage, crack initiation and propagation criteria).

Within the context of training engineering students, CADAM allows:

- To corroborate hand calculations with computer calculations to develop the understanding of the computational procedures.
- To conduct parametric analysis on the effects of geometry, strength of material and load magnitude on the structural response.
- To compare uplift pressures, crack propagation, and shear strength (peak, residual) assumptions from different dam safety guidelines (CDSA 1995, USACE 1995, FERC 1991, FERC 1999 and USBR 1987).
- To study different strengthening scenarios (post-tensioning, earth backing, buttressing).

1.2 Program Input-Output and Computing Environment

CADAM provides an interactive environment for inputting data from the keyboard and the mouse. The output consists of (a) **interactive tabular data** and plots that could be quickly reviewed to evaluate the analysis results, (b) **output file reports** that display in tabular and graphical form a synthesis of all results, (c) **exchange data files** that are exported to the spreadsheet program Microsoft Excel to allow further processing of the data and to produce further plots that could be included in other documents. **Hard copies** of interactive graphical screen plots could also be obtained.

Note: This CADAM User's Manual can be interactively displayed when using CADAM by clicking on the User's Manual option of the help menu. However, Acrobat Reader 4 must be installed on your system to activate the user's manual on-line. Acrobat Reader 4 can be downloaded for free from Adobe web site.

1.3 System Requirements

CADAM runs under Windows 95, 98, NT4, 2000 and Me. The system must have the following minimum characteristics:

- Pentium processor (Pentium 100 MHz or above recommended)
- 16 MB of available RAM (32 MB recommended)
- Super VGA display, 256 colors, 640 X 480 resolution (800 X 600 recommended)
- 10 MB of disk space
- Internet connection, CD drive or 3½" floppy drive for installation

Note: On Windows NT 4, Service Pack 3 must be applied before you install and use CADAM.

1.4 Installing / Removing CADAM

To install CADAM with the CD-ROM disk:

1. Insert CADAM CD-ROM in your CD drive,
2. The main panel of the installation wizard should appear automatically. If it doesn't, run **setup.exe** from Windows Explorer or from the Windows Run dialog.

To install CADAM with the floppy disks:

1. Insert CADAM setup disk (disk #1) in your floppy drive,
2. Run **setup.exe** from Windows Explorer or from the Windows Run dialog.

To install or update CADAM from the web site:

1. Download the compressed file **CadamCD.zip** (located in the download area of the web site) from CADAM web site http://www.struc.polymtl.ca/cadam/.
2. Decompress **CadamCD.zip** in an empty directory.
3. If a previous version of CADAM is already installed, remove it (see instructions below)
4. Run **setup.exe** from Windows Explorer or from the Windows Run dialog.

The installation wizard will guide you through the installation process. Just follow the instructions as they appear on the screen. The default installation folder for CADAM is …\Program files\CADAM. You can install the software in a different folder if you like, but if you have a previous version of CADAM, it is recommend to **remove the old version** before proceeding to the installation. Depending on your system configuration, CADAM setup program may update the library COMCTL32.dll located in your Windows\System folder. This update will not affect already installed software. CADAM setup may also install certain fonts if they are not present in your system. After the installation, you will be prompt to reboot your system in case your library COMCTL32.dll was updated. You are now ready to run CADAM!

If you need to remove CADAM for any reason, you can do so using Windows remove program.

To remove CADAM:

1. From the Windows **Start** menu, Choose **Settings** and then **Control Panel**.
2. Double-click on **Add/Remove Programs.**
3. Choose **CADAM** from the list.
4. Click on the button **Add/Remove** .

1.5 Overview of Modelling and Analysis Capabilities

Figure 1 shows the basic user interface of CADAM, while the meaning of the various buttons is shown in Figure 2.

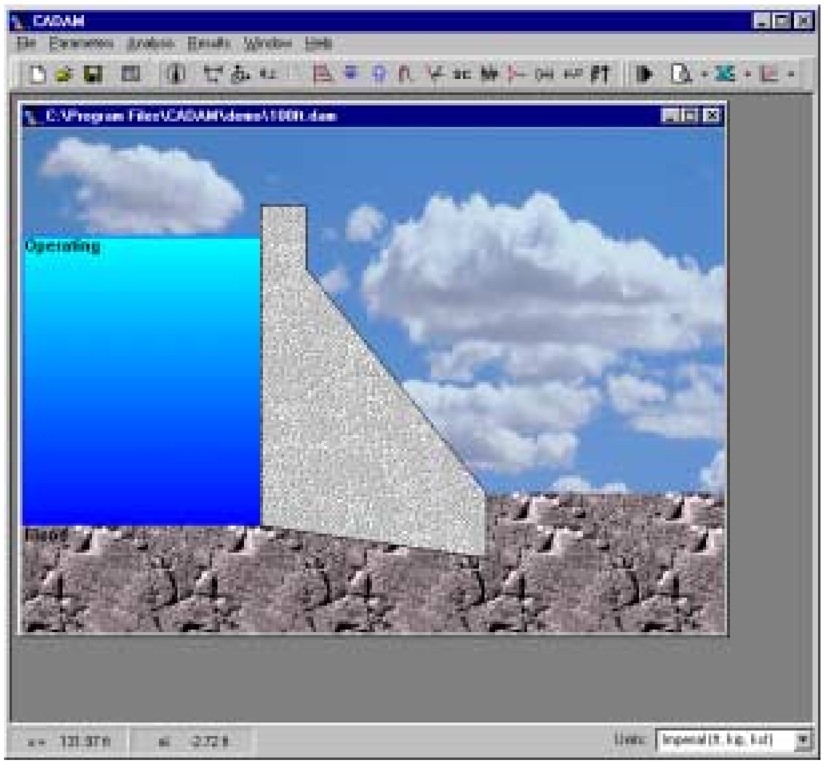


Figure 1

Create a new document	Open an existing file
Save model in use	Open MS Calculator
General information	Section Geometry
Concentrated masses	Material properties
Lift joints generation	Pre-cracked lift joints
Drainage and uplift pressures	Reservoir, ice, floating debris & silts
Post-tensioning	Applied forces
Pseudo-static method	Pseudo-dynamic method
Cracking options	Load combination
Probabilistic analyses	Incremental load analysis
Start analysis	CADAM reports
MS Excel reports	Graphical results

Figure 2

Figure 3 shows the basic loading conditions supported for static analysis.

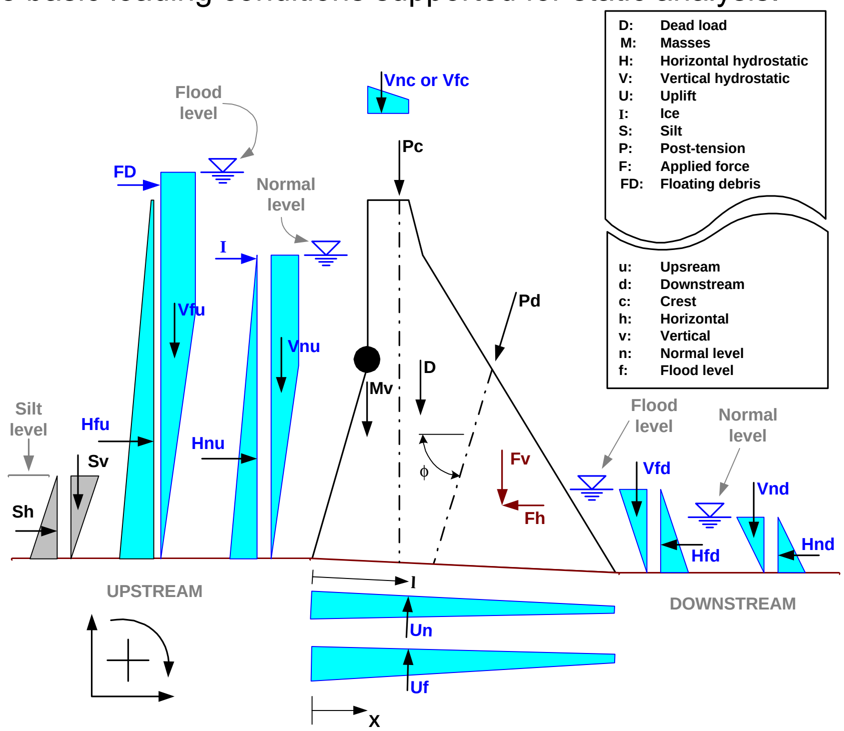


Figure 3

Figure 4 and Figure 5 show the basic loading conditions supported for the pseudo-static and pseudo-dynamic seismic analyses, respectively.

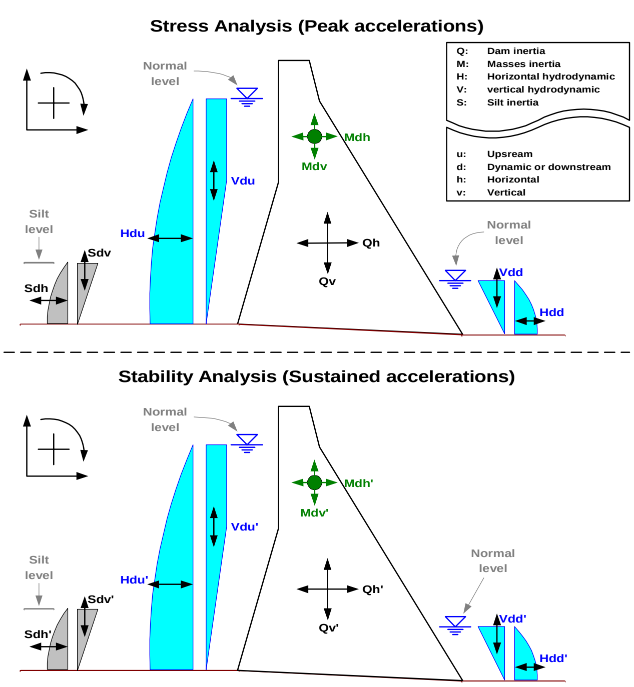


Figure 4

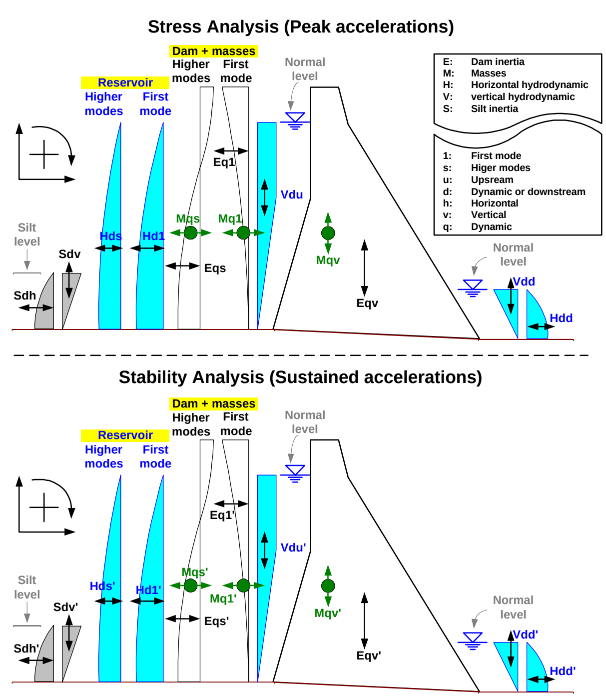


Figure 5

1.5.1 Basic Analytical Capabilities

The program supports the following analysis capabilities:

- <u>Static Analyses</u>: CADAM could perform static analyses for the normal operating reservoir elevation or the flood elevation including overtopping over the crest (Figure 3).

- <u>Seismic Analyses</u>: CADAM could perform seismic analysis using the **pseudo-static** method (Figure 4; seismic coefficient method) or the **pseudo-dynamic** method (Figure 4 and Figure 5), which corresponds to the simplified response spectra analysis described by Chopra (1988) for gravity dams.

- <u>Post-Seismic Analyses:</u> CADAM could perform post-seismic analysis. In this case the specified cohesion is not applied over the length of crack induced by the seismic event. The post-seismic uplift pressure could either (a) build-up to its full value in seismic cracks or (b) return to its initial value if the seismic crack is closed after the earthquake.

- <u>Probabilistic Safety Analysis (Monte-Carlo simulations):</u> CADAM could perform a probabilistic analysis to compute the probability of failure of a dam-foundation-reservoir system as a function of the uncertainties in loading and strength parameters that are considered as random variables with specified probability density functions. A Monte-Carlo simulations computational procedure is used. Static and seismic analysis could be considered.

- <u>Incremental Load Analysis:</u> CADAM could automatically perform sensitivity analysis by computing and plotting the evolution of typical performance indicator (ex: sliding safety factor) as a function of a progressive application in the applied loading (ex: reservoir elevation).

1.5.2 Modelling Capabilities

CADAM performs the analysis of a single 2D monolith of a gravity dam-foundation reservoir system subdivided into lift joints. A typical analysis requires the definition of the following input parameters:

- <u>Section geometry:</u> Specification of the overall dimensions of the section geometry. Inclined upstream and downstream faces as well as embedding in the foundation (passive rock wedge) are supported.

- <u>Masses:</u> Concentrated masses can be arbitrarily located within or outside the cross-section to add or subtract (hole) vertical forces in a static analysis and inertia forces in a seismic analysis.

- Materials: Definition of tensile, compressive and shear strengths (peak and residual) of lift joints, base joint, and rock joint (passive rock wedge).

- Lift joints: Assign elevation, inclination and material properties to lift joints.

- Pre-cracked lift joints: Assign upstream/downstream cracks in joint(s) as initial conditions.

- Reservoir, ice load, floating debris and silt: Specification of water density, normal operating and flood headwater and tailwater elevations, ice loads, floating debris and silt pressure (equivalent fluid, frictional material at rest, active or passive).

- Drainage system: Specification of drain location and effectiveness. The stresses computations could be performed through linearisation of effective stresses (FERC 1999, CDSA 1995, USACE 1995, USBR 1987) or superposition of total stresses with uplift pressures (FERC 1991).

- Post-tension cable: Specification of forces induced by straight or inclined post-tension cables installed along the crest and along the d/s face.

- Applied forces: User's defined horizontal and vertical forces can be located anywhere.

- Pseudo-static analysis: Specification of the peak ground horizontal and vertical accelerations as well as the sustained accelerations. Westergaard added mass is used to represent the hydrodynamic effects of the reservoir. Options are provided to account for (a) water compressibility effects, (b) inclination of the u/s face, (c) limiting the variation of hydrodynamic pressures over a certain depth of the reservoir. Hydrodynamic pressures for the silt are approximated from Westergaard formulation for a liquid of higher mass density than water.

- Pseudo-dynamic analysis: Specification of the input data required to perform a pseudo-dynamic analysis using the simplified method proposed by Chopra (1988): (a) peak ground and spectral acceleration data, (b) dam and foundation stiffness and damping properties, (c) reservoir bottom damping properties and velocity of an impulsive pressure wave in water, (d) modal summation rules.

- Cracking options: Specification of (a) tensile strengths for crack initiation and propagation, (b) dynamic amplification factor for the tensile strength, (c) the incidence of cracking on static uplift pressure distributions (drain effectiveness), (d) the effect of cracking on the transient evolution of uplift pressures during earthquakes (full pressure, no change from static values, zero pressures in seismic cracks), (e) the evolution of uplift pressures in the post-seismic conditions (return to initial uplift pressures or build-up full uplift pressures in seismically induced cracks).

- Load combinations: Specification of user defined multiplication factors of basic load conditions to form load combinations. Five load combinations are supported: (a) normal operating, (b) flood, (c) seismic 1, (d) seismic 2, and (e) post-seismic.

- <u>Probabilistic Analyses:</u> Estimation of the probability of failure of a dam-foundation-reservoir system, using the Monte-Carlo simulation, as a function of uncertainties (PDF) in loading and strength parameters that are considered as random variables.

- <u>Incremental Analysis:</u> Automatically compute the evolution of safety factors and other performance indicators as a function of a user specified stepping increment applied to a single load condition.

1.5.3 Output Results

Output results are presented in three distinct formats:

1 CADAM reports:
- Input parameters
- loads
- load combinations
- stability drawings

2 MS Excel reports:
- Input parameters
- loads
- load combinations

3 Graphical plots:
- Joint cracking, stresses and resultants
- Probabilistic analyses results (CDF / PDF)
- Incremental analyses results (SF vs. Load)

Those options are presented in details in section 21.2.

1.6 Organisation of the User's Manual

CADAM User's manual has been divided in four parts providing:

- General information about the program (Chapters 1 and 2),
- Information explaining the key features of the user interface, menu items, and button bar for inputting data (Chapters 3-19),
- A summary of the equations used to perform the stress and stability analyses (Chapter 20),
- A description of the output data (Chapter 21).

Appendix A presents the pseudo-dynamic analysis of Pine Flat Dam, previously analysed by Chopra (1988). Appendix B presents additional CADAM input files related to a 52m high dam and a 100ft dam with an inclined base. Flowcharts relevant to modelling of basic loading conditions and structural stability evaluation of gravity dams have been included in Appendix C as complementary information. Finally, Appendix D presents uplift distributions proposed in different guidelines (CDSA, USACE, FERC & USBR) that are in use in CADAM.

2 BASIC MODELLING INFORMATION

2.1 Units

The dam and the loads could be defined either in metric units using kN for forces and metres for length or alternatively imperial units could be used (kip, feet). The program could automatically switch from one set of unit to the other by selecting the appropriate option on the status bar of the main window.

2.2 Two-Dimensional Modelling of Gravity Dams

Considering unit thickness for input data: CADAM performs the analysis of a 2D monolith of unit thickness (1m in metric system, or 1ft in imperial system). All input data regarding forces (masses) should therefore be specified as kN/m or Kips/ft, (post-tension forces, user-defined forces, concentrated masses etc…).

2.3 Basic Assumptions of the Gravity Method

The evaluation of the structural stability of the dam against sliding, overturning and uplifting is performed considering two distinct analyses:

1. A stress analysis to determine eventual crack length and compressive stresses,
2. A stability analysis to determine the (i) safety margins against sliding along the joint considered, and (ii) the position of the resultant of all forces acting on the joint.

The gravity method is based (a) on rigid body equilibrium to determine the internal forces acting on the potential failure plane (joints and concrete-rock interface), and (b) on beam theory to compute stresses. The use of the gravity method requires several simplifying assumptions regarding the structural behaviour of the dam and the application of the loads:

- The dam body is divided into lift joints of homogeneous properties along their length, the mass concrete and lift joints are uniformly elastic,
- All applied loads are transferred to the foundation by the cantilever action of the dam without interactions with adjacent monoliths,
- There is no interaction between the joints, that is each joint is analysed independently from the others,
- Normal stresses are linearly distributed along horizontal planes,
- Shear stresses follow a parabolic distribution along horizontal plane in the uncracked condition (Corns et al. 1988, USBR 1976).

A special attention must be given to the interpretation of the computed magnitude and distribution of stresses along the dam-foundation interface while using the gravity method. The stresses and base crack likely to occur could be affected by the deformability of the foundation rock that is not taken into account while using the gravity method. The effect of the displacement compatibility at the dam-foundation interface is likely to be more important for large dams than for smaller dams. Simplified formulas to correct the maximum compressive stress computed at the interface from the gravity method while considering deformability of the foundation have been presented by Herzog (1999).

2.4 Sign Convention

- Global system of axis: The origin of the global axis system is located at the heel of the dam. The global axis system allows to locate the coordinate of any point of the dam body along the horizontal "x =" direction, and the vertical "el.=" direction.
- Local Joint axis system: The dam base joint and each lift joint are assigned a local one-dimensional coordinate system, "l=" along their lengths (horizontal or inclined). The origin of this local coordinate system is at the u/s face of the dam at the u/s elevation of the joint considered.
- Positive directions of forces and stresses: The sign convention shown in Figure 6 is used to define positive forces and moments acting in the global coordinate system.

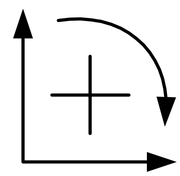


Figure 6

The sign convention shown in Figure 7 is used to define stresses acting on concrete (joints) elements.

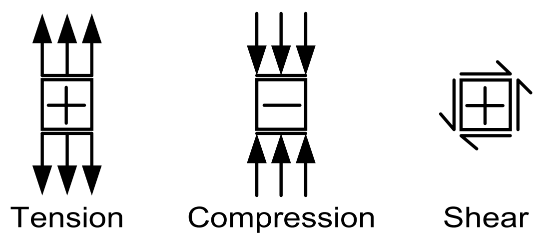


Figure 7

Positive direction of inertia forces: According to d'Alembert principle, the inertia forces induced by an earthquake are in the opposite direction of the applied base acceleration (Figure 8).

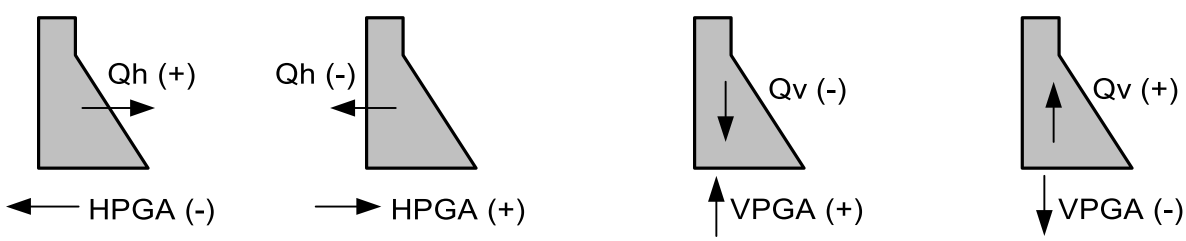


Figure 8

PART II – INPUTTING DATA

3 DESCRIPTION OF THE USER INTERFACE

When CADAM program is started the main window will look like Figure 9.

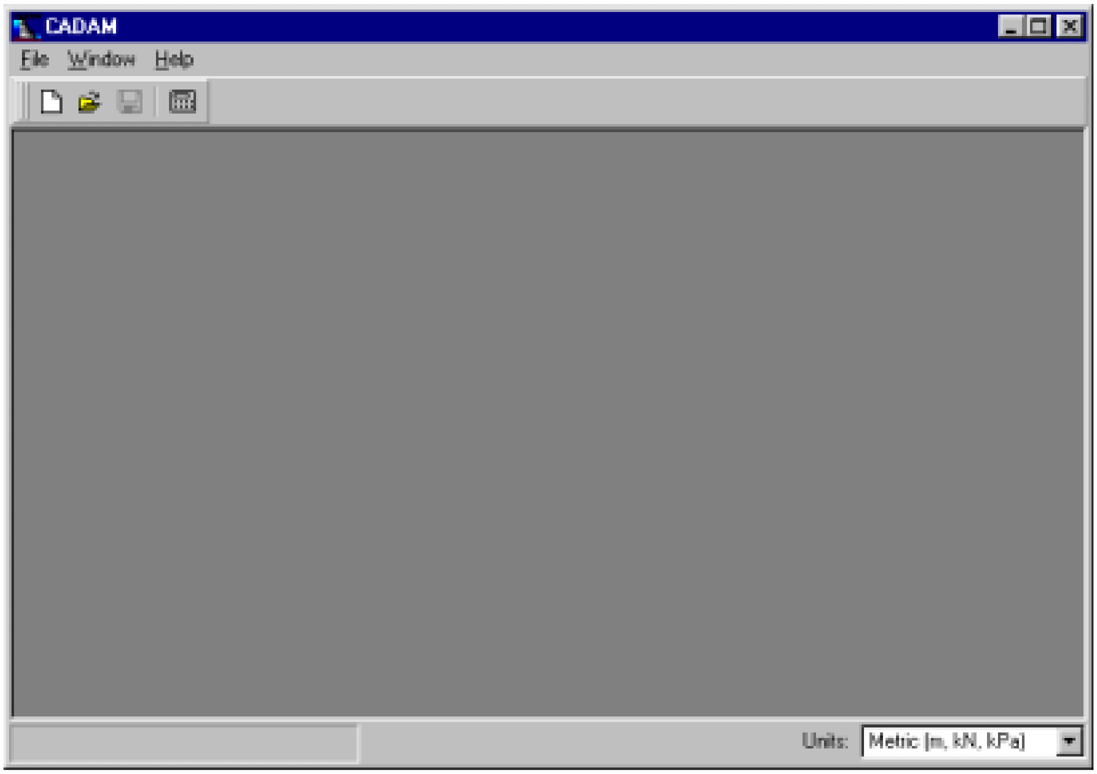


Figure 9

CADAM is a Multi Document Interface (MDI). This means that the user may open many files in CADAM and switch easily from one to the other. In a MDI program, child windows represent open files or new models.

When a child window is opened (new document or opened file), a graphical display of the system analysed is shown as well as the current position of the mouse pointer given in the global coordinate system (x=, el.=) on the status bar. For a new document, there is no graphical display at first because the geometry is still undefined. The CADAM window is always open and will host the other child windows used by the program. Closing CADAM terminates the program and closes all child windows.

FILE MENU: The following menu items are displayed from the File menu (Figure 10):

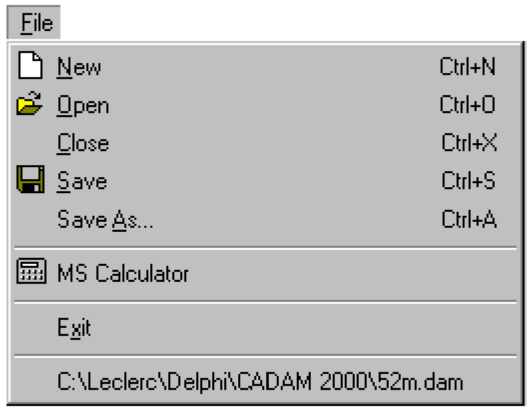


Figure 10

- New: To start a new problem, activate the new file. The filename is given as noname1 until you save the file using the name of your choice. This will become the current problem filename with the .DAM extension.
- Open: You could also load a previous problem from an input file saved on disk.
- Close: Close the active child window.
- Save: You could save the current problem.
- Save As: You could save the current problem and assign it a new name.
- MS Calculator: Start Microsoft Calculator.
- Exit: Exit CADAM.

PARAMETERS MENU: The following menu items are displayed from the Parameters Menu:

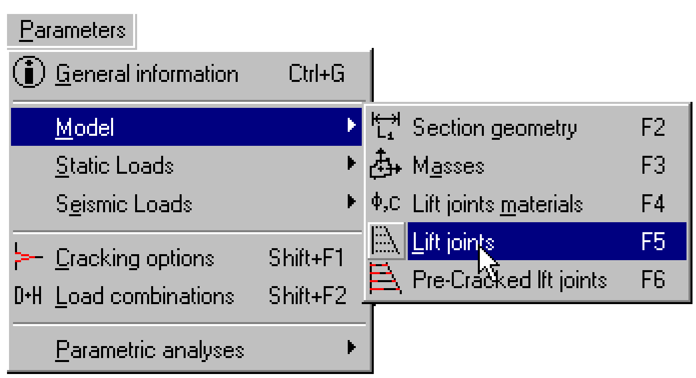
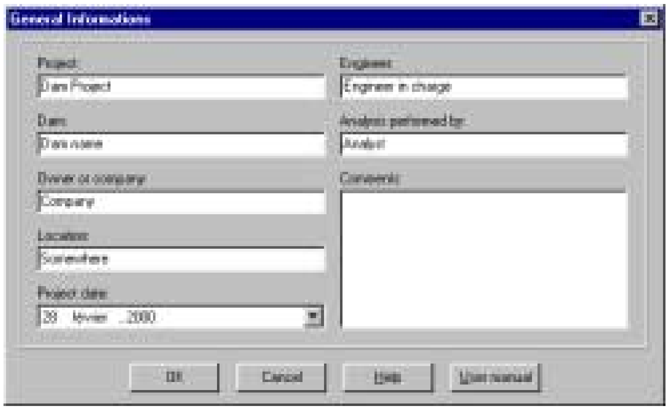


Figure 11

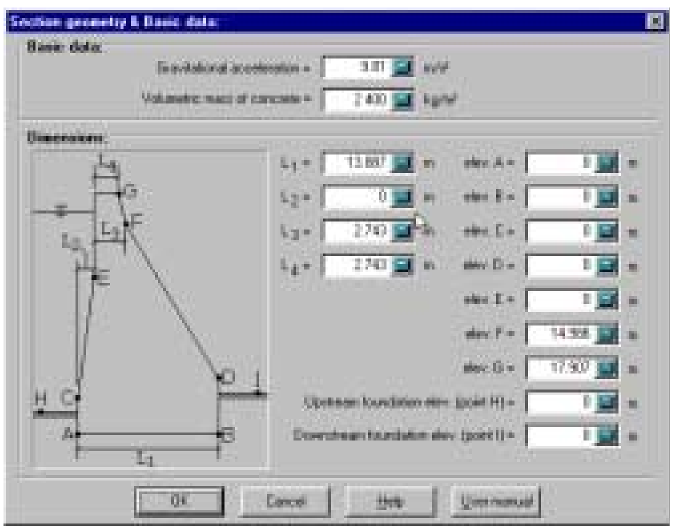
The items appearing in this Menu are directly available from the shortcut bar located on top of the program window.

4 GENERAL INFORMATION



This window is to input general information about the dam analysed. This information appears in the reports, except for the comment part. The comments are associated with a particular problem and allow the user to leave notes that will be accessible while reloading the problem.

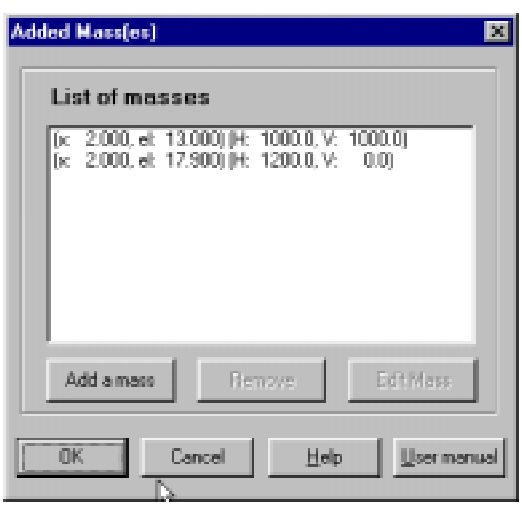
5 SECTION GEOMETRY AND BASIC DATA



This window is to input the key points and basic geometrical dimensions to define the dam cross-section. The system of units, gravitational acceleration and volumetric mass of concrete are specified. By changing any dimension value, the user must be aware that a new model will be created while the old one will be erased.

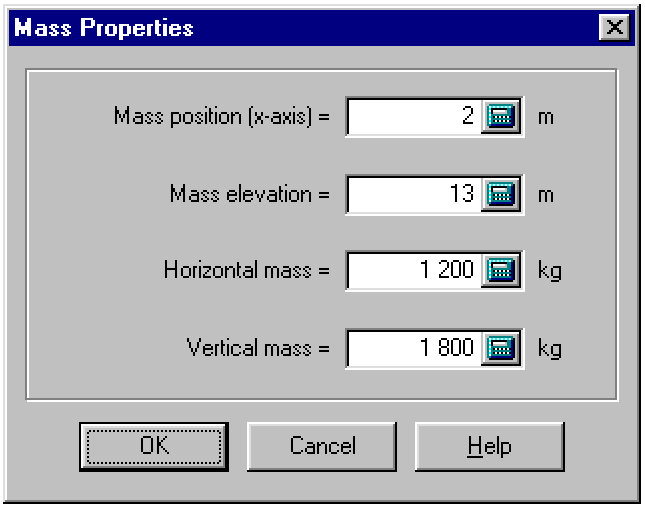
It is not required to fill all input data boxes to create a model. Elevation points may overlap. Higher Elevation points are automatically corrected by CADAM when a point elevation, located bellow and on the same side, is modified.

6 CONCENTRATED MASSES



This window is used to add or subtract vertical and/or horizontal concentrated masses located arbitrarily within or outside of the dam cross-section. The masses could be used to represent fixed equipment located on the crest, or to introduce corrections to the basic cross section to represent holes or a non-uniform mass distribution along the length of the dam. Concentrated masses could also be used to modify the hydrodynamic forces used in seismic analysis.

Vertical added masses are considered identical to the dam body self-weight in the computation of the overturning safety factor, even for negative masses.



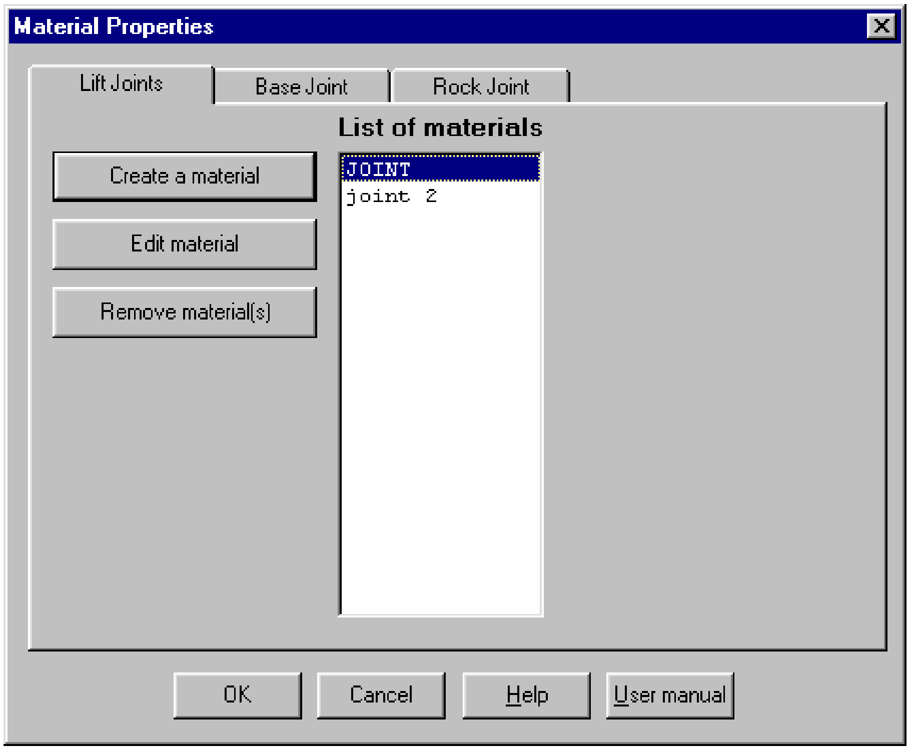
Static analysis: in static analysis, concentrated masses are producing vertical forces computed as the product of the vertical mass and the gravitational acceleration.

Pseudo-static seismic analysis: The inertia forces induced by concentrated masses are computed as the product of the mass and the specified seismic acceleration (either the peak ground acceleration or the sustained acceleration according to the analysis performed).

Pseudo-dynamic seismic analysis: The inertia forces induced by the concentrated masses are computed as the product of the computed modal acceleration at the elevation of the mass and the mass itself (floor spectra concept). The total added concentrated mass to the model is considered small with respect to the mass of the dam. Therefore, it is assumed that the first period of vibration of the dam and the related mode shape are not affected by concentrated masses.

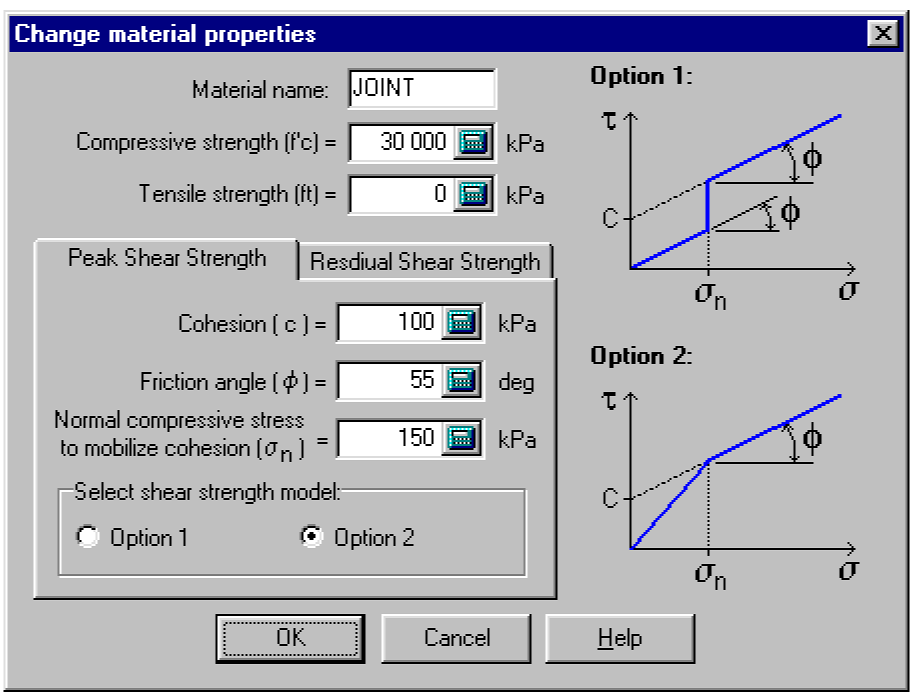
7 MATERIAL PROPERTIES

7.1 Lift Joints



<u>Specifying material strength properties:</u> This window is used to create a list of lift joint material properties. You could define as many materials as needed to describe variations of strength properties along the height of the dam. You may modify at will any created material. Moreover, you may remove a material from the list but only if it is not assigned to a joint.

A lift joint is a concrete-concrete joint located above the concrete-rock interface where the base joint is located.

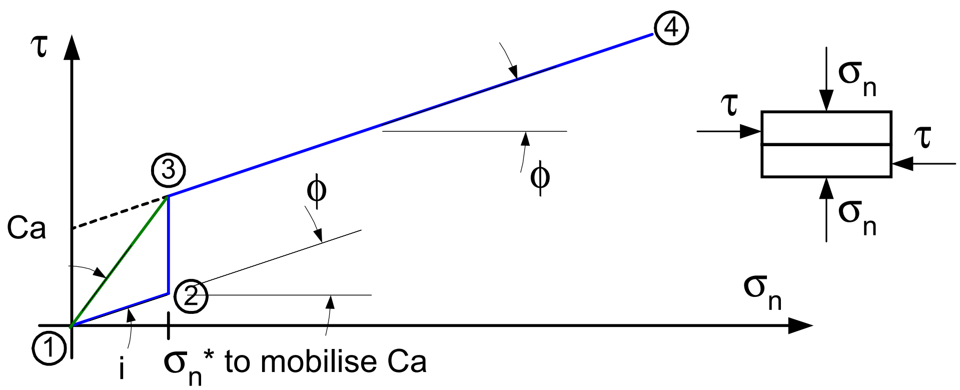


<u>Minimal normal compressive stresses to mobilise cohesion:</u> Apparent cohesion, Ca, is sometime specified for an unbonded rough joint (with zero tensile strength) due to the presence of surface asperities. The apparent cohesion is often derived as the shear strength for zero normal stress from the straight-line regression of a series of shear tests carried out at different normal stress intensities. However, for unbonded joint, it is obvious that the shear strength should be zero if there is no applied normal stress. A minimal value of normal compressive stresses could therefore be specified to

mobilise Ca along a joint (Figure 12). For normal compressive stresses below the minimal compressive stress (σ_n*), two options are offered to the user:

Option 1: The shear resistance is equal to the normal compressive stress times the friction coefficient, which is tanϕ. The cohesion Ca (real or apparent) is only used if $\sigma_n \geq \sigma_n$*.

Option 2: The shear resistance is equal to the normal compressive stress times the friction coefficient, which is tan(ϕ+i). There is no cohesion for $\sigma_n < \sigma_n$*, but a larger friction angle is used (ϕ+I). For $\sigma_n \geq \sigma_n$*, the friction angle ϕ is used with the cohesion (Ca).



Option 1: ① — ② $\tau = \sigma_n \cdot \tan(\phi)$

Option 2: ① — ③ $\tau = \sigma_n \cdot \tan(\phi + i)$

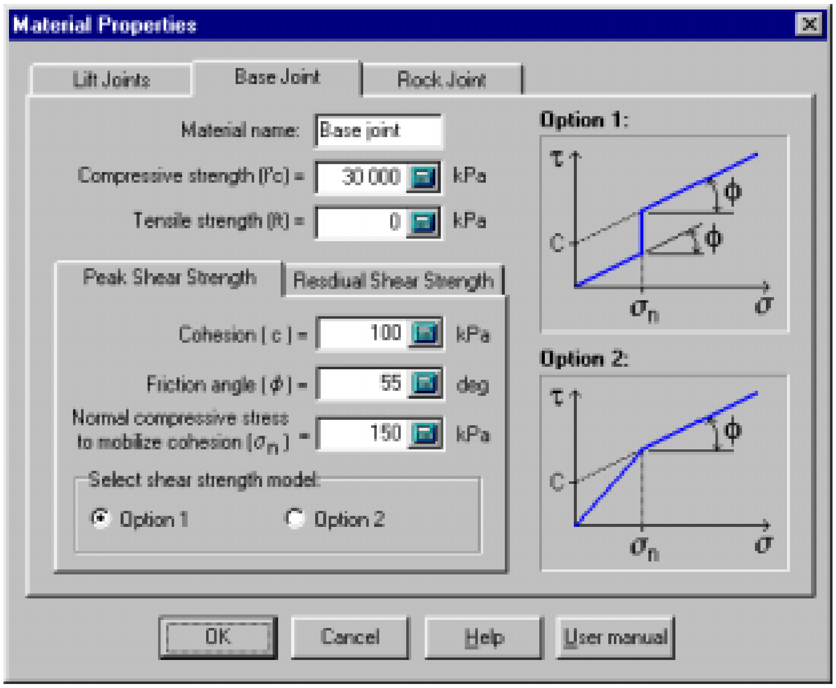
$\Big\}$ $\sigma_n < \sigma_n^*$

Options 1 & 2: ③ — ④ $\tau = \sigma_n \cdot \tan(\phi) + Ca$ $\quad \sigma_n \geq \sigma_n^*$

Figure 12

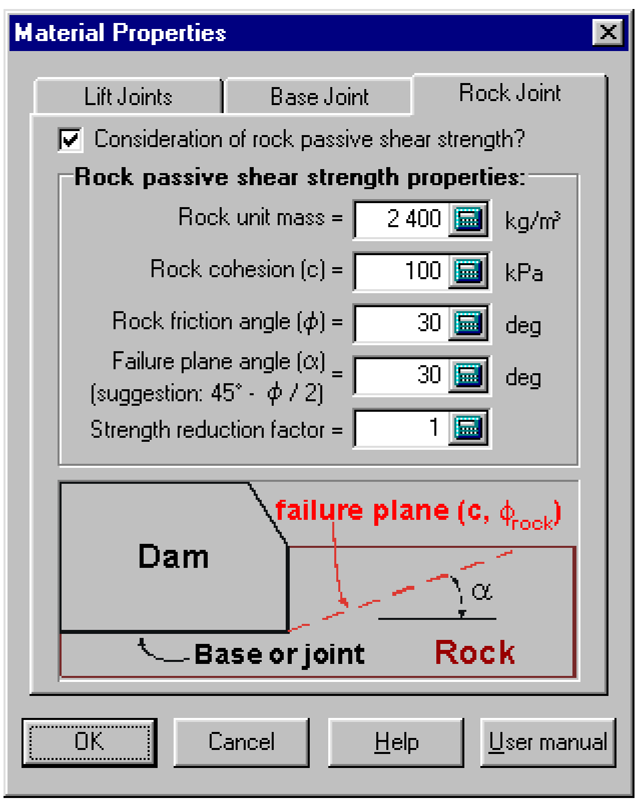
Note that options 1 and 2 will give the same results for σ_n* = 0 or Ca = 0, where the usual two parameters Mohr failure envelope is obtained.

7.2 Base Joint



The material strength properties at the concrete-rock interface are specified, using same models (options) as those for lift joints (see section 7.1)

7.3 Rock Joint



In the case where the dam is embedded in the foundation, this window allows the definition of parameters including the contribution of a passive wedge resistance to the sliding resistance of the dam. If the tailwater elevation is above the rock failure plane, CADAM computes automatically the uplift pressure acting on the failure plane. Note that a careful interpretation of the resulting sliding resistance is required as the peak strengths from the passive wedge and dam joint may not be additive since deformations required to reach the peak values are often unequal (Underwood 1976, Corns et al. 1988). The strength reduction factor (S_{RF}) affects both rock cohesion and friction angle as:

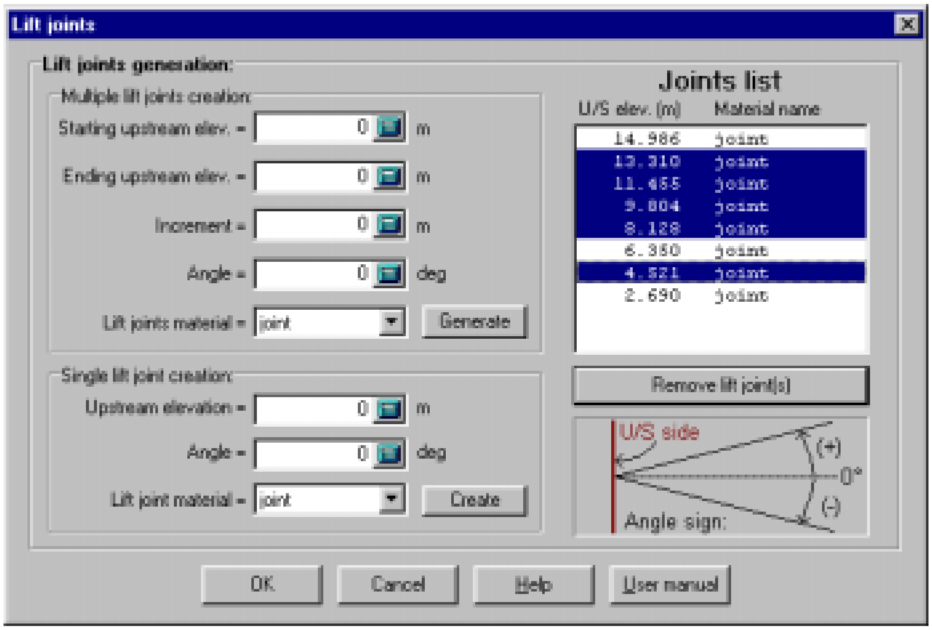
$$\phi' = \tan^{-1}(S_{RF} \tan\phi)$$

$$c' = S_{RF}\ c$$

ϕ' : Reduced rock friction angle;
c' : Reduced rock cohesion.

The sliding safety factor for a dam-foundation system including a passive wedge resistance should be computed by the shear-friction method as explained in section 20.3.

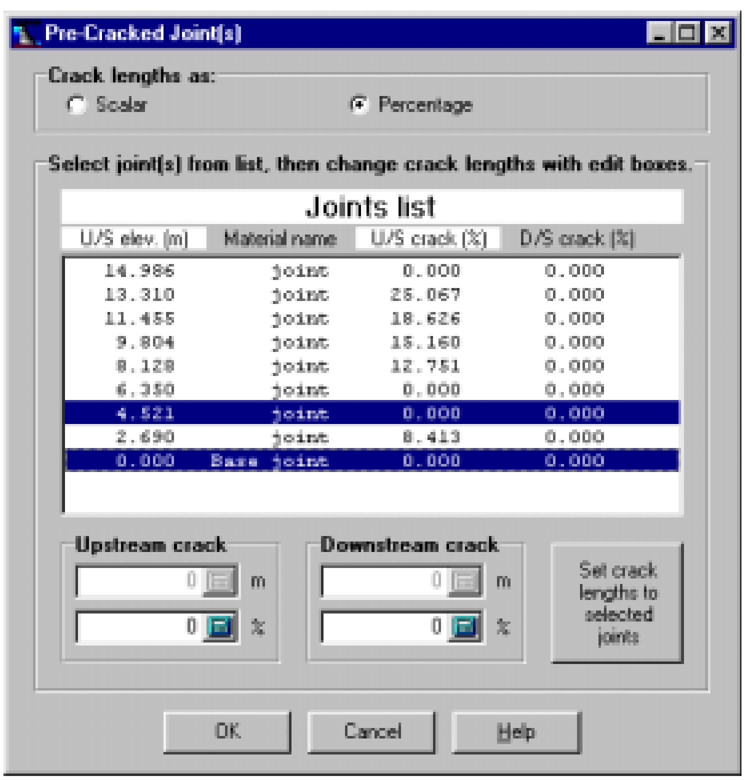
8 LIFT JOINT – GENERATION AND GEOMETRY



This window allows the automatic generation of lift joints along the height of the dam. The inclination angle of the joint could be specified.

Material properties could be assigned to group of lift joints. Material properties must be defined prior to create lift joints. Single lift joints could be added to the list of joints.

9 PRE-CRACKED LIFT JOINTS

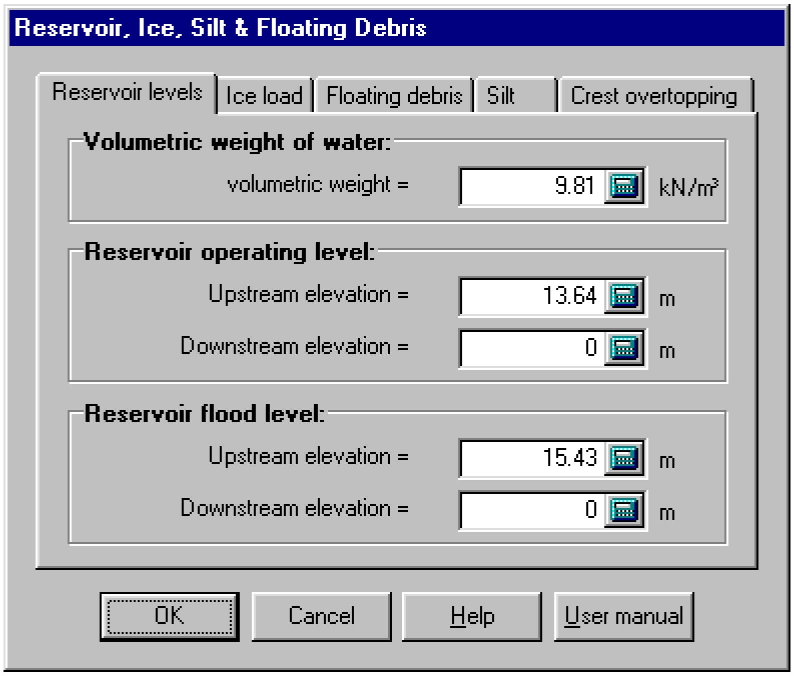


This window allows the user to assign existing cracks to lift joints along the height of the dam. These cracks and related uplift pressures are considered as initial conditions and will always be considered in all load combinations. Cohesion is set to zero along a crack. Moreover, these cracks will be taken into account for linear analyses (no further cracking).

The user may set crack lengths as a scalar (m or ft) or as a percentage of the joint length. To assign a crack length, simply select one or many joints in the joint list. Then set the upstream crack and downstream crack to desired length. Finally, click on the button <Set crack lengths to selected joints>. Repeat this process for different crack length definitions and then press Ok.

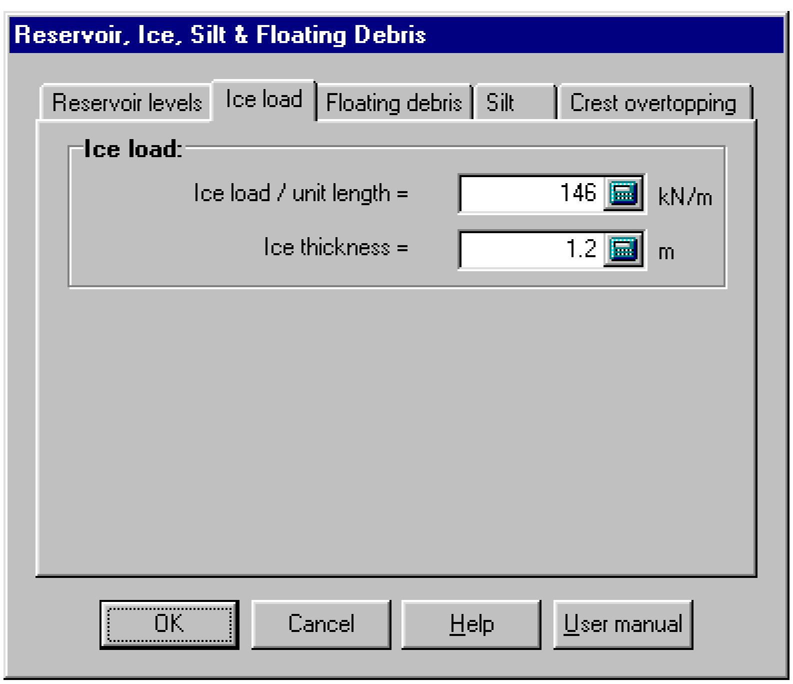
10 RESERVOIR, ICE, SILT & FLOATING DEBRIS – STATIC LOAD CONDITIONS

10.1 Reservoir Levels



This window allows the specification of the volumetric weight of water, as well as the normal and flood headwater and tailwater elevations. CADAM handles water levels located within the rock. However, CADAM sets any unassigned elevation of reservoirs at the rock level.

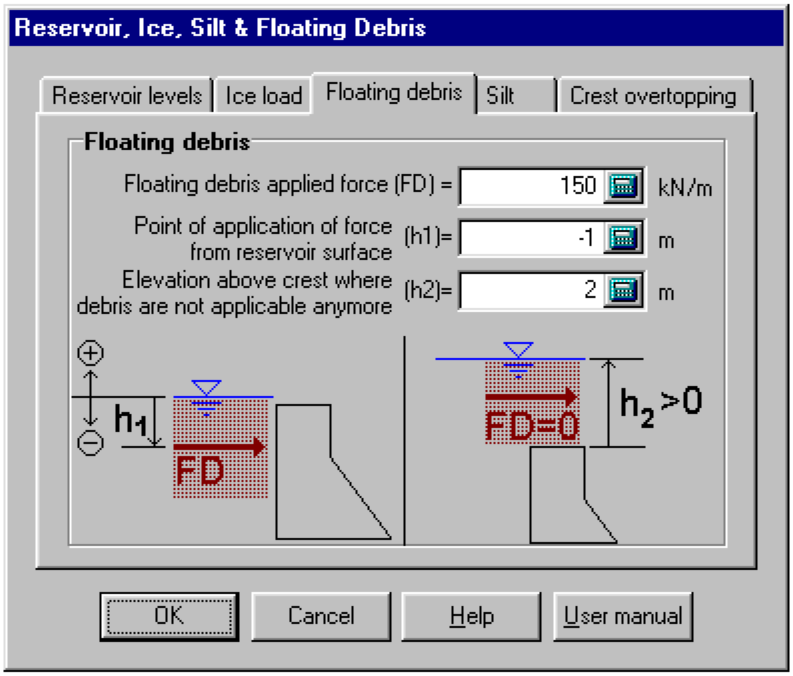
10.2 Ice Loads



This window allows the specification of the ice loads and the ice thickness. The point of application of the ice load is computed as the normal operating reservoir elevation minus half the thickness of the ice sheet.

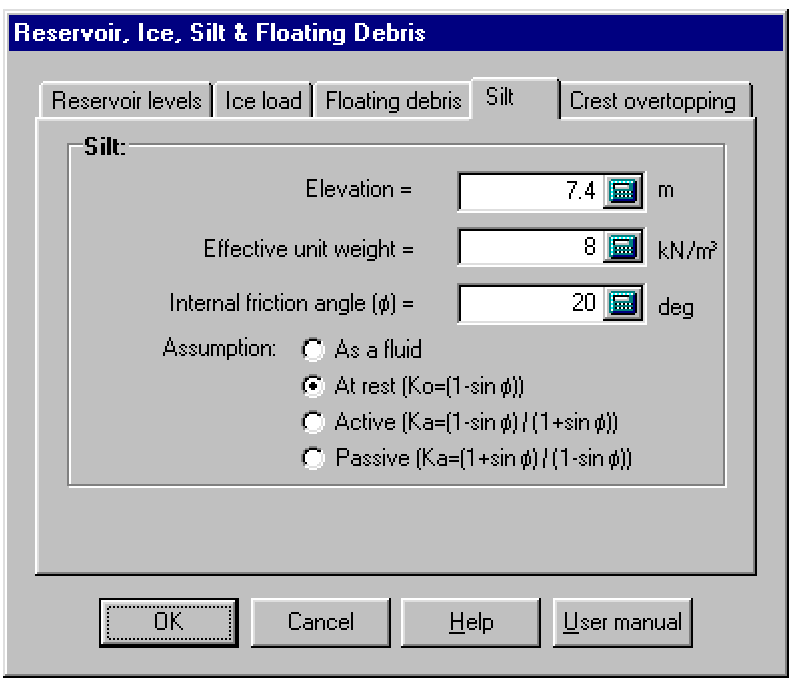
Note: Ice load will be ignored upon an overtopping of the reservoir greater than the ice thickness.

10.3 Floating Debris



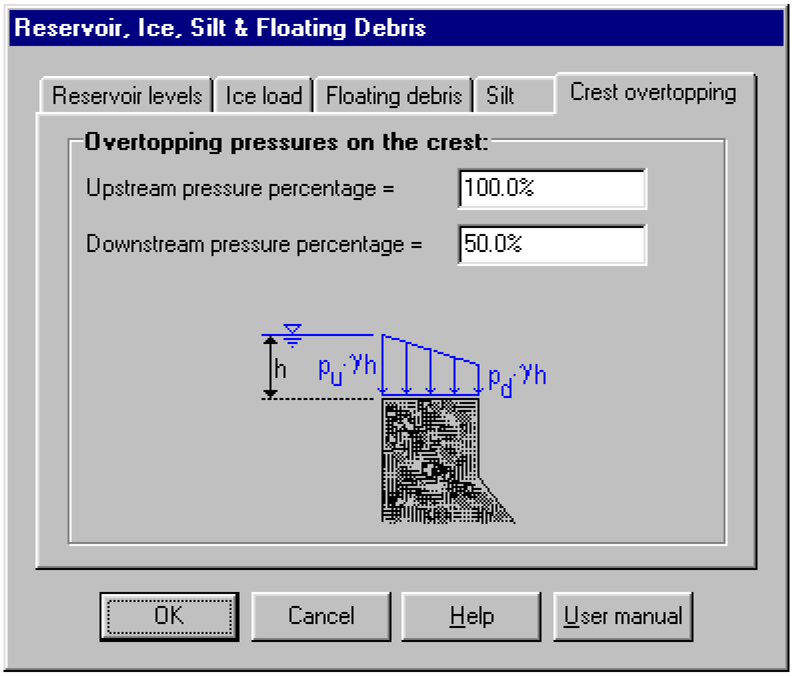
This window allows the specification of the properties of floating debris accumulated on top of the upstream reservoir. Floating debris are considered only in the flood case. The point of application of the force is taken from the reservoir surface. Moreover, upon overtopping of the reservoir, a maximum elevation above the crest is set to consider a possible discharge of the debris. This last option is more likely to be activated in probabilistic or in incremental load analyses.

10.4 Silt



This window allows the specification of the properties of silt accumulated along the u/s face of the dam. If the silt is considered "as a fluid", the internal friction angle is not used to establish the thrust exerted on the dam. While considering the internal silt friction angle ϕ, the "at rest" or "active" silt pressure could be selected. Normally the "passive" pressure is not used but has been added as an option for illustrative purposes.

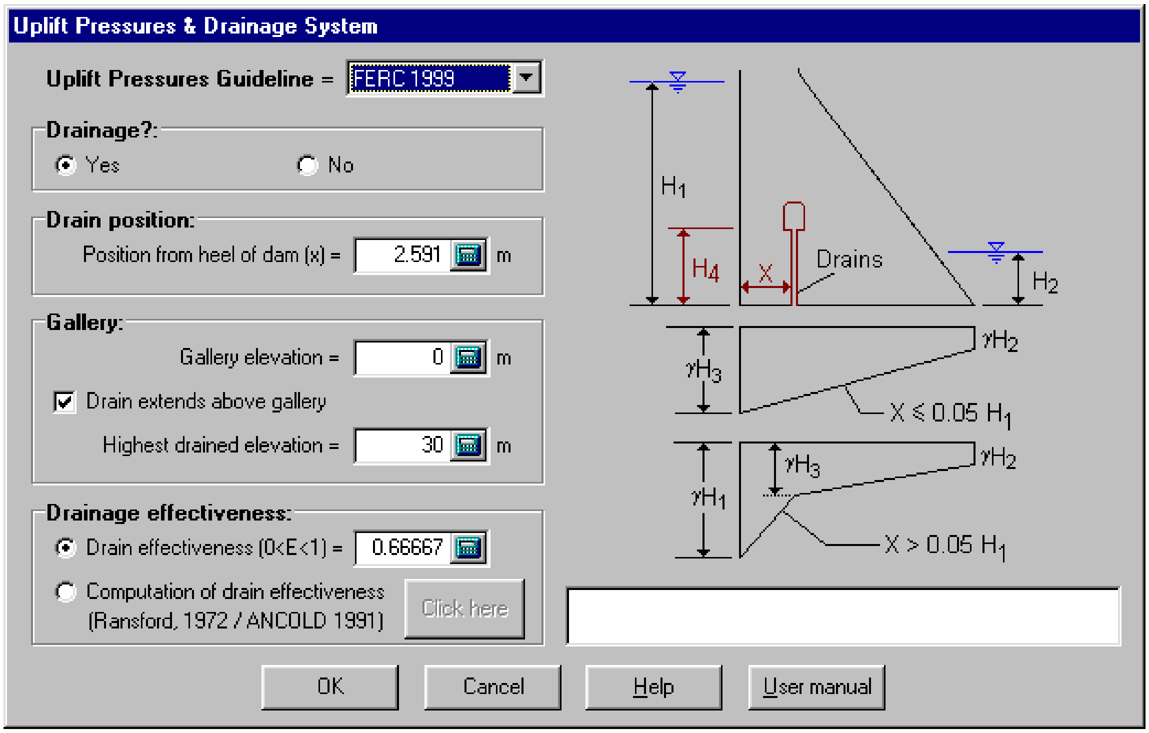
10.5 Crest Overtopping



During a severe flood it is possible that non-overflow section of the dam be overtopped. This window allows a user's definition of linear pressure distribution acting on the horizontal crest of the dam. The u/s, d/s pressures are defined in terms of a percentage of the overtopping depth, h using the parameters p_u and p_d, respectively. Negative crest pressures are allowed if subatmospheric pressures could be developed.

11 UPLIFT PRESSURES & DRAINAGE SYSTEM

11.1 Uplift Pressures – Computation of "Effective Stresses"



To perform the computation of effective stresses and related crack length, uplift pressures could be considered:

- <u>As an external load acting on the surface of the joint (FERC 1999, USACE 1995, CDSA 1995, USBR 1987 (crack propagation)):</u> In this case, normal stresses are computed using beam theory considering all loads acting on the free-body considered (including the uplift pressure resultant). The computed "effective" normal stresses then follow a linear distribution along the joint even in the presence of a drainage system that produces a non-linear distribution of uplift pressures along the joint. The effective tensile stress at the crack tip is compared to the allowable tensile strength to initiate or propagate tensile cracks.

- <u>As an internal load along the joint (FERC 1991):</u> In this case, normal stresses are computed considering all loads acting on the free-body considered but excluding uplift pressure. The computed "total stresses" are then added along the joint to the uplift pressures. "Effective stresses" computed using this procedure follow a non-linear distribution along the joint in the presence of a drainage system. For example, in the case of a no-tension material, crack initiation or propagation is taking place when the uplift pressure is larger than the total stress acting at the crack tip.

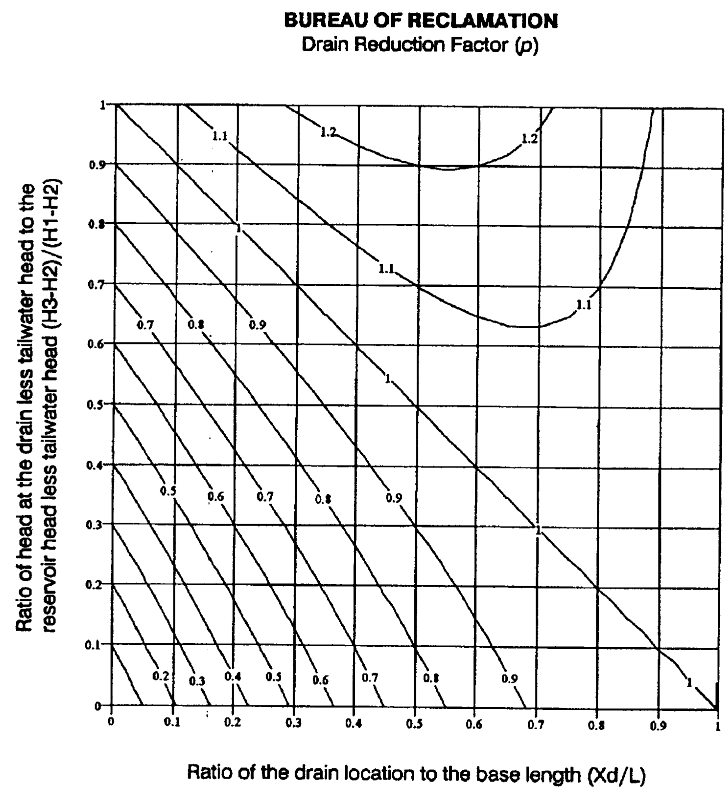
APPENDIX D presents uplift pressure distributions adopted in North-American dam safety guidelines as well as the computational procedure for the evolution of the uplift pressure upon cracking.

11.2 USBR guidance on crack initiation

USBR (1987) uses the following simplified equation for the minimum allowable compressive (normal) stress at the upstream face (σ_{zu}) from uplift forces to determine crack initiation (not propagation):

$$\sigma_{zu} = pwh - \frac{f_t}{s}$$

where σ_{zu} is equal to the absolute value of the stress at the upstream face induced from uplift forces minus the allowable tensile stress. f_t is the tensile strength of the material and s is the safety factor. The term *pwh* represents the transformed uplift pressure at the heel of the dam considering the effect of a drain reduction factor *(p)*. Cracking initiates at the heel of the dam when the compressive stress σ_z does not achieve the minimum compressive stress σ_{zu} value. CADAM computes automatically the drain reduction factor *p* when the USBR guideline is selected. The graph below may also be used to obtain the drain reduction factor (*p*).



Procedure:

1. Calculate ratios (Xd/L) and (H3-H2)/(H1-H2)
2. Obtain value of *p* from graph
3. Correct *p* for tailwater using equation [*p*(H1-H2)+H2]/H1

Where:

p	=	drain reduction factor
H1	=	reservoir pressure head on the upstream face
H2	=	tailwater pressure head on the downstream face
H3	=	pressure head at the line of the drains
Xd	=	distance of the drain from the upstream face
L	=	horizontal length from upstream to downstream face.

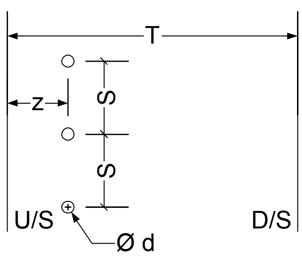
(Source: USACE 2000)

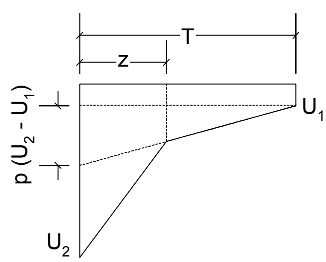
11.3 Drain Effectiveness - User's specified value

A series of windows could be activated to specify the position of the drains, the drain effectiveness and the elevation of the drainage gallery according to particular versions of Dam Safety Guidelines (USACE 1995, USBR 1987 for uplift pressures considered as external loads, FERC 1991 for uplift pressures considered as internal loads). When the elevation of the drainage gallery is above the tailwater elevation, the reference elevation to determine the pressure head at the drain line becomes the elevation of the gallery (FERC 1999, USBR1987, USACE 1995, FERC 1991).

11.4 Drain Effectiveness – Simplified seepage analysis

ANCOLD (1991) and Ransford (1972) present a simplified approach to estimate the pressure distribution developed by water seepage through or under a porous dam. In CADAM, a percolation plane corresponds to lift joints or to the base. CADAM allows the automatic evaluation of the drain effectiveness using a simplified seepage analysis presented by ANCOLD (1991). This method is based on the percolation plane geometry and on drains diameter and location as shown in figures below:

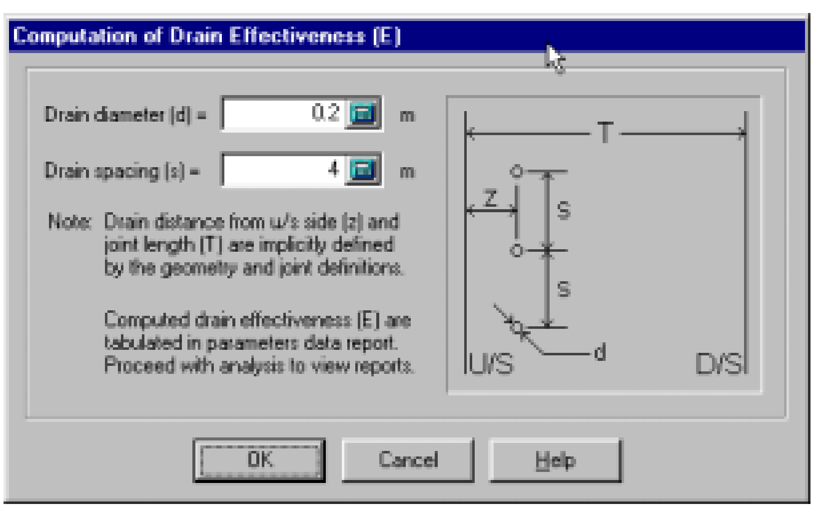




$$D^1 = \frac{1}{2\pi}\ln\left(\frac{\sinh 2\pi \frac{z}{s}}{\sinh 2\pi \frac{d}{s}}\right)$$

$$p = \frac{D^1 - \frac{z}{s}}{D^1 - \frac{z^2}{s \cdot T}}$$

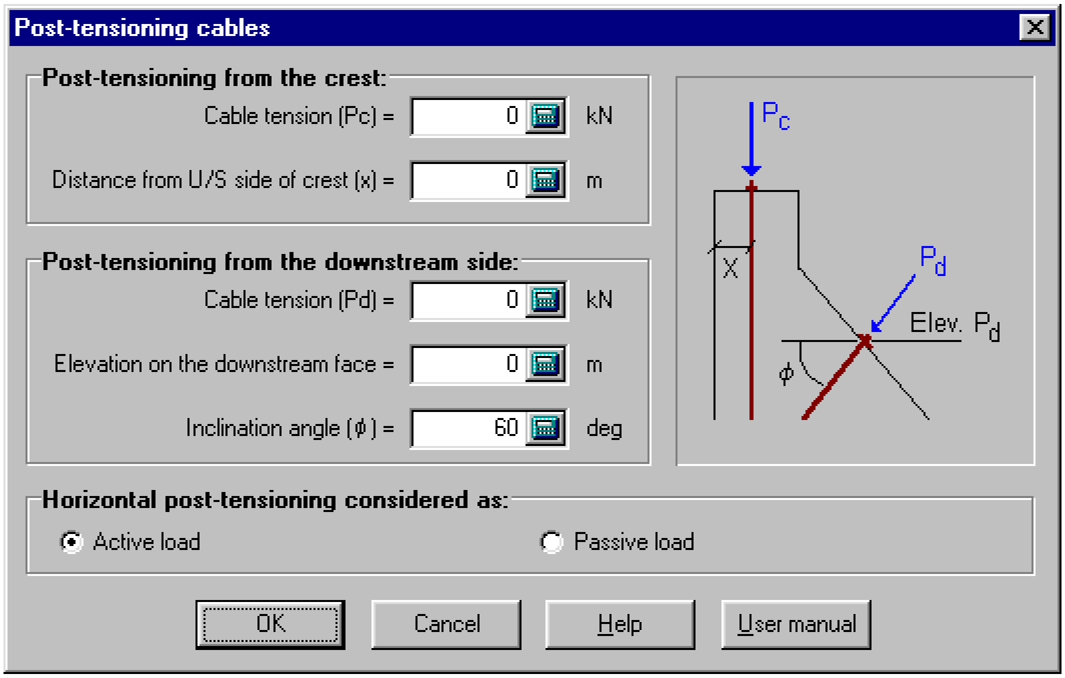
This simplified seepage analysis is applicable for a wide section where numerous drains, evenly spaced, having the same diameter. Moreover, the simplified seepage analysis is computed under no cracking and the resulting drain effectiveness will be used as initial conditions for all subsequent calculations. For more details on drain effectiveness subjected to cracking, reference should be made to section 16.3: Drainage System (drain effectiveness).



This window allows the definition of drains diameter (d) and spacing (s). The drain effectiveness is computed using the above equations. Joint length (T) and drain distance from u/s side (z) are computed implicitly by CADAM.

Computed drain effectiveness (E) are tabulated in input parameters report. Proceed with analysis to view reports.

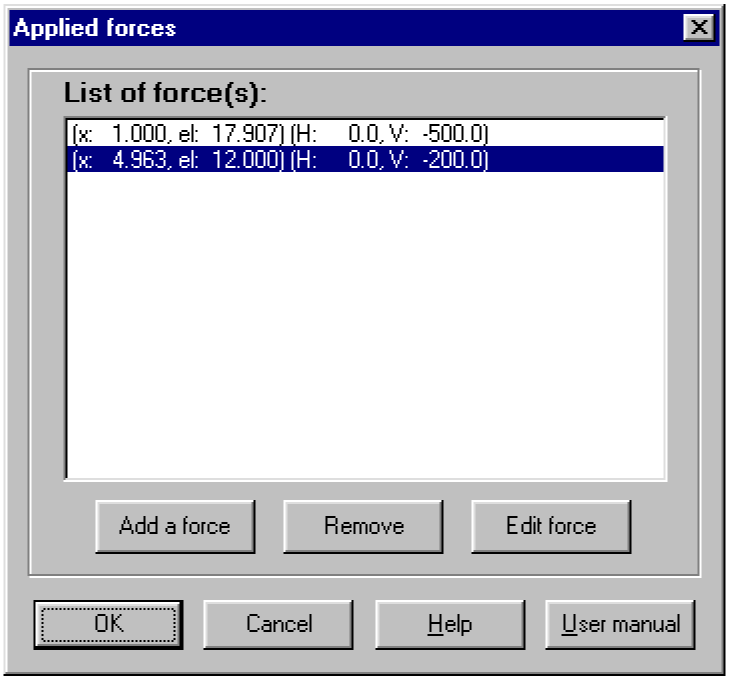
12 POST-TENSION CABLES



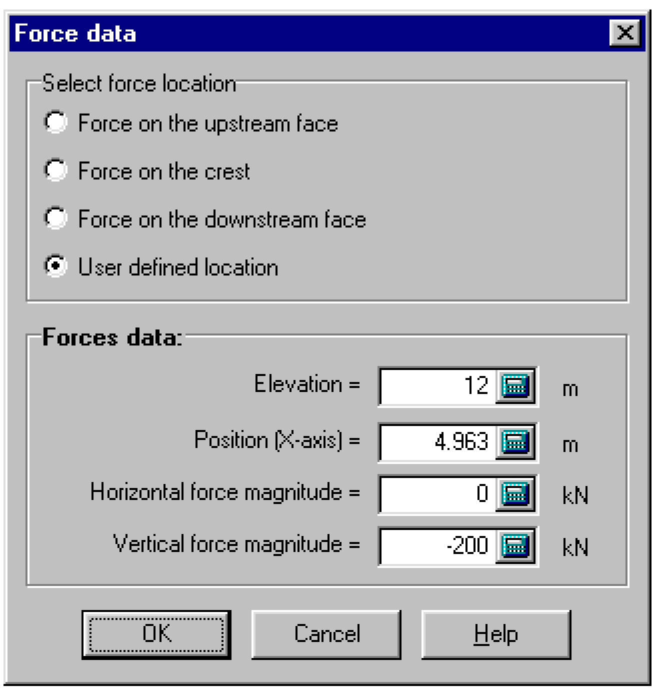
This window allows the specification of post-tension anchor forces applied either from the crest or from the d/s face. The horizontal force components induced by inclined post-tensioned cables are treated as active forces being deducted from other applied horizontal forces such as the u/s reservoir thrust.

By default, post-tensioning are considered as active loads, appearing in the denominator of the sliding safety factor equation. It is also possible to consider the horizontal component induced by inclined post-tensioning as a passive load being added to the resisting forces to sliding appearing in the numerator of the sliding safety factor equation (see section 20.3 for detailed equations).

13 APPLIED FORCES



This window allows the consideration of arbitrarily defined active external forces acting within or outside the dam body. To add a force, just click the button Add a force. To edit an existing force, click on the force description in the list and then click the button Edit force. The window below (Force data) helps adding or editing a force. In the case a force has to be located on the dam peripheral, the user should therefore select the force location and let CADAM compute the position or the elevation of the force. There is no limit in the number of forces that can be created.



14 PSEUDO-STATIC SEISMIC

14.1 Basic Assumption - Rigid Body Behaviour

In a pseudo-static seismic analysis the inertia forces induced by the earthquake are computed from the product of the mass and the acceleration. The dynamic amplification of inertia forces along the height of the dam due to its flexibility is neglected. The dam-foundation-reservoir system is thus considered as a rigid system with a period of vibration equal to zero.

- Initial state before the earthquake: Each seismic analysis begins by a static analysis to determine the initial condition before applying the seismically induced inertia forces. If cracking is taking place under the static load conditions, the crack length and updated uplift pressures (if selected by the user) are considered as initial conditions for the seismic analysis.

14.2 Seismic Accelerations

This window allows the specification of acceleration data to perform the pseudo-static seismic safety analysis. The peak and sustained values of the rock acceleration need to be specified. The seismic analysis is performed in two phases considering successively a stress analysis and then a stability analysis according to the procedure outlined in Figure 13.

Stress and stability analyses: The basic objective of the stress analysis is to determine the tensile crack length that will be induced by the inertia forces applied to the dam. Specifying peak ground acceleration values performs the stress analysis. This approach assumes that an acceleration spike is able to induce cracking in the dam. However, since the spike is likely to be applied for a very short period of time, there will not be enough time to develop significant displacements along the crack plane. If no significant displacement is taking place, the dynamic stability is maintained. However, if cohesion has been specified along the joint analysed, it is likely to be destroyed by the opening-closing action of the crack. The stress analysis is therefore used to determine the length over which cohesion will be applied in the stability analysis.

The basic objective of the stability analysis is to determine the sliding and overturning response of the dam. The pseudo-static method does not recognise the oscillatory nature of seismic loads. It is therefore generally accepted to perform the stability calculation using sustained acceleration values taken as 0.67 to 0.5 of the peak acceleration values. In this case, the sliding safety factors are computed considering crack lengths determined from the stress analysis.

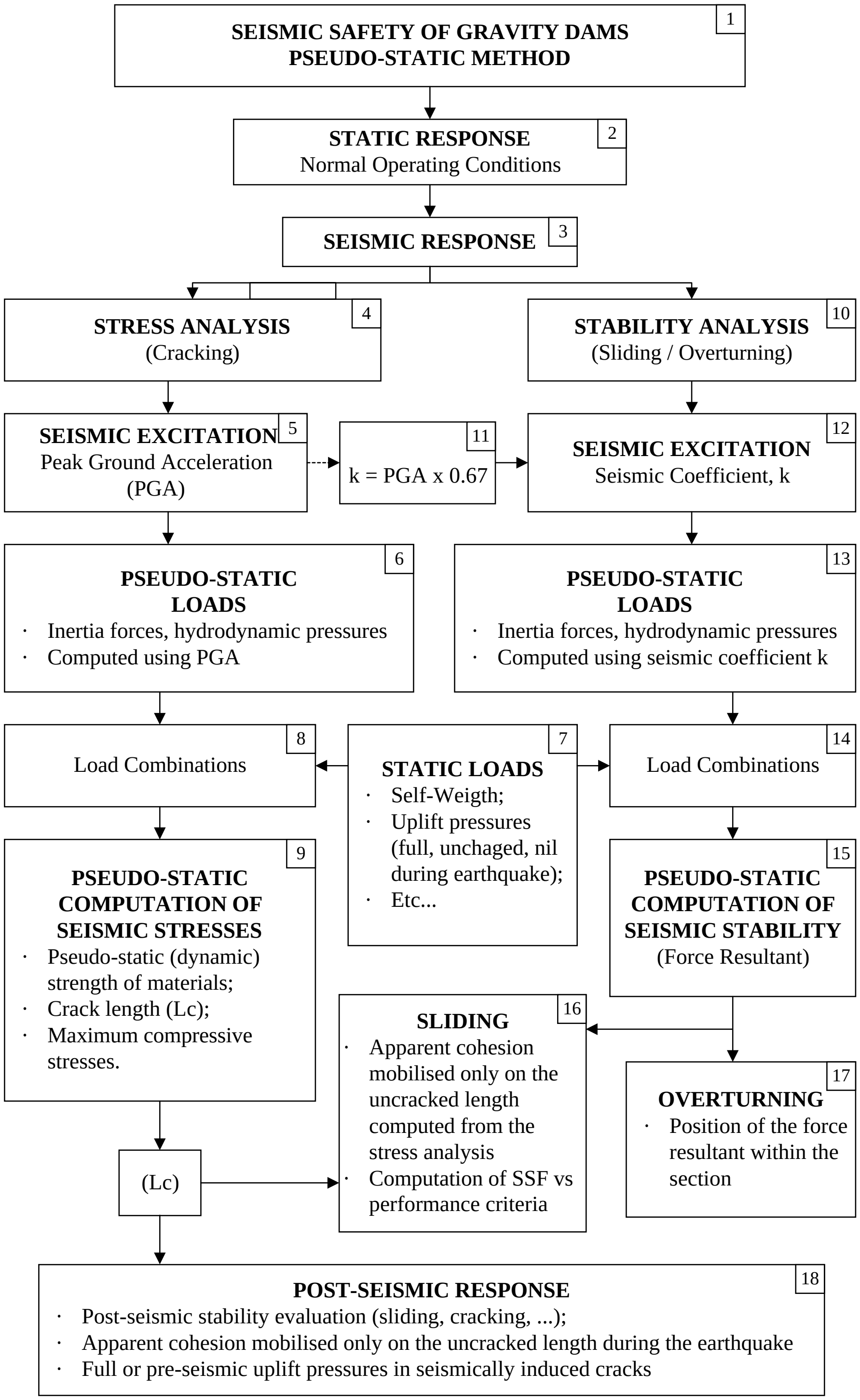
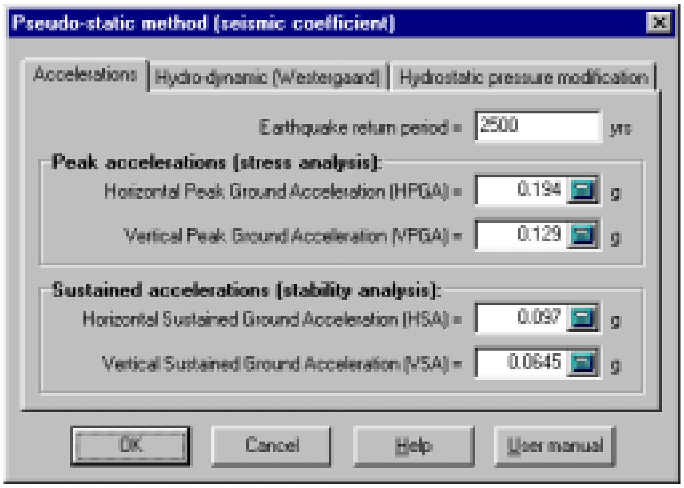


Figure 13 Pseudo-static analysis

Specific considerations for stress and stability analyses allow maintaining consistent assumptions while applying a progressive approach to perform the seismic safety evaluation ranging from (a) the pseudo-static method, to (b) the pseudo-dynamic method, and to (c) transient methods. Note that it is always possible to specify the same numerical values for peak and sustained accelerations if it is not desired to make a distinction between the two types of seismic analysis.



Earthquake return period: The earthquake return period is specified. This value is not used in the computational algorithm of the program. It will be reported in the output results as complementary information.

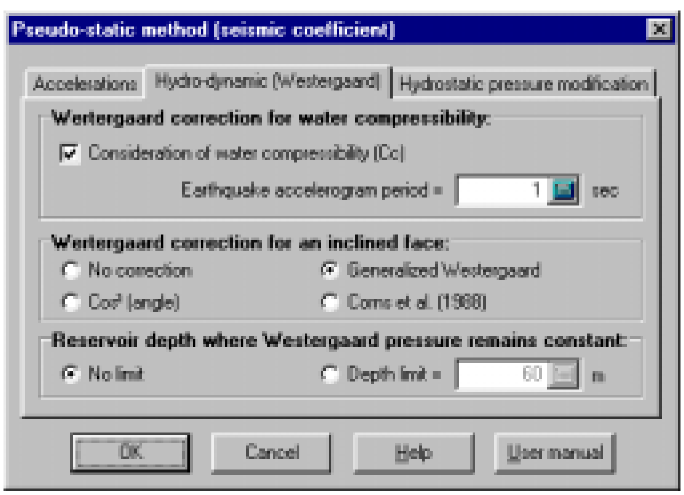
Peak accelerations (stress analysis): The acceleration values for the stress analysis are specified.

Sustained accelerations (stability analysis): The acceleration values for the stability analysis are specified.

Direction of accelerations: The seismic safety of the dam could be investigated by directing the horizontal ground acceleration either in the u/s or the d/s direction. Similarly the vertical accelerations could be oriented either in the upward or the downward direction. Cracking could be initiated and propagated either from the u/s face or the d/s face. Existing cracks issued from the initial static conditions may close according to the intensity and orientation of the seismically induced earthquake forces.

14.3 Hydrodynamic Pressures (Westergaard added masses)

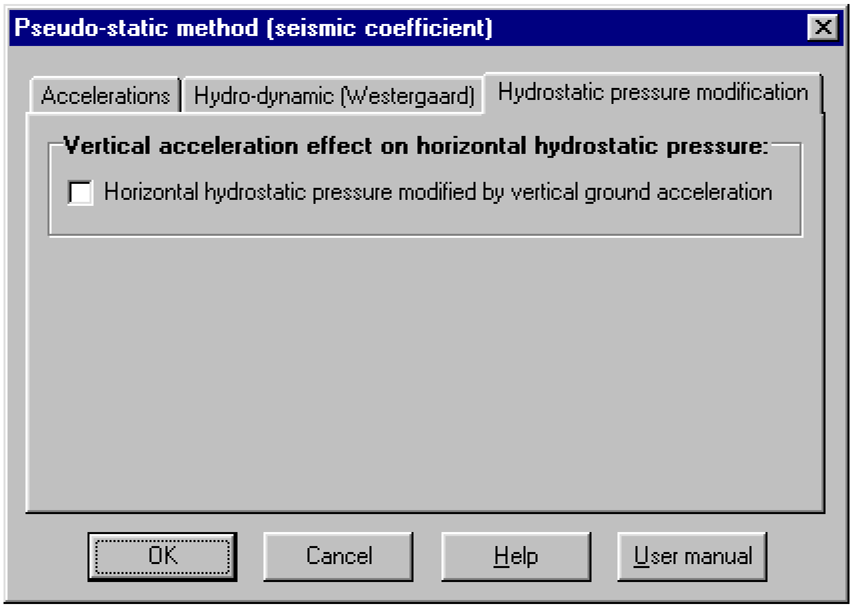
The hydrodynamic pressures acting on the dam are modelled as added mass (added inertia forces) according to the Westergaard formulation. Options have been provided for:



- Correction for water compressibility: According to the predominant period of the base rock acceleration, a correction factor is applied to the Westergaard formulation (USACE 1995, Corns et al. 1988).
- Inclination of the u/s face: The hydrodynamic pressures are acting in a direction normal to the surface that is accelerated against the reservoir. To transform these pressures to the global coordinate system two options have been provided using either the cosine square of the angle of the u/s face about the vertical (Priscu et al. 1985) or the function derived from USBR (1987) as given by Corns et al. 1988 (see Figure 24 in section 17.7).
- A reservoir depth beyond which Westergaard added pressure remains constant: This option allows to experiment with some dam safety guideline requirements indicating, for example,

that beyond a depth of 60m there is no more significant variation of hydrodynamic pressure with depth. The value computed at a depth of 60m is then maintained constant from that point to the bottom of the reservoir.

14.4 Hydrostatic pressure modification



Vertical accelerations may reduce or enlarge the effective water volumetric weight thus affecting the horizontal hydrostatic pressure acting on the dam faces. By default the hydrostatic pressure will not be affected by vertical accelerations. However, the user may activate this option by checking the appropriate box.

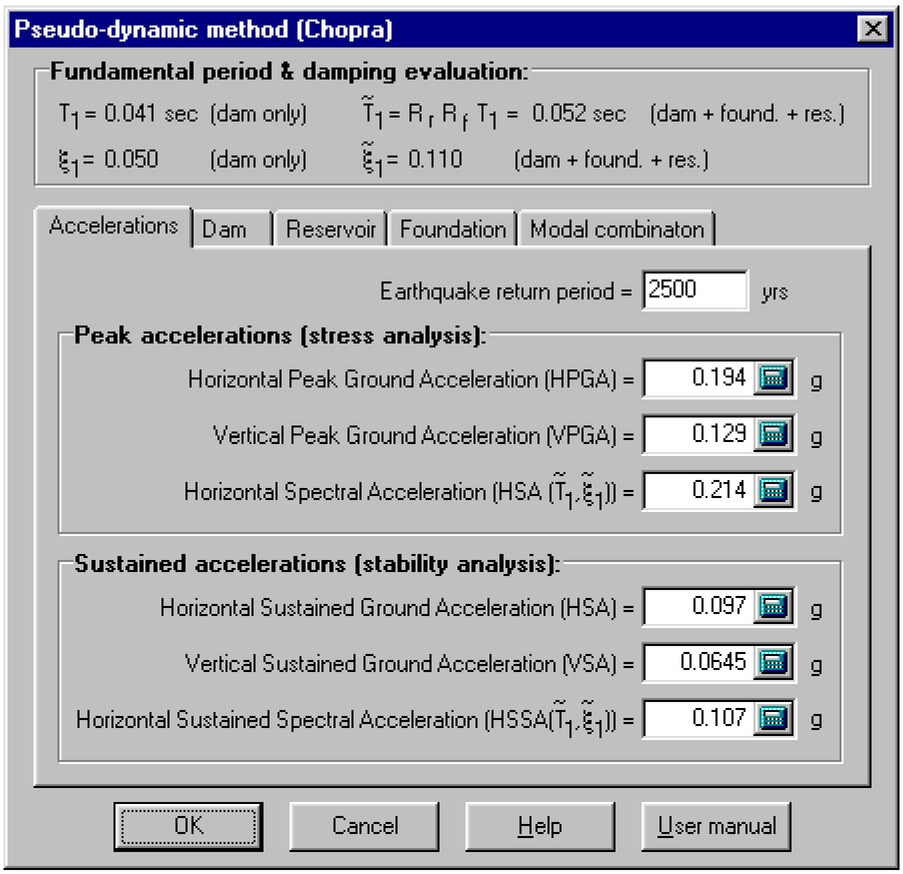
15 PSEUDO-DYNAMIC SEISMIC ANALYSIS

15.1 Basic Assumption – Dynamic Amplification

The pseudo-dynamic analysis is based on the simplified response spectra method as described by Chopra (1988). The user should consult this reference for a complete description of the input variables presented in the various windows of CADAM.

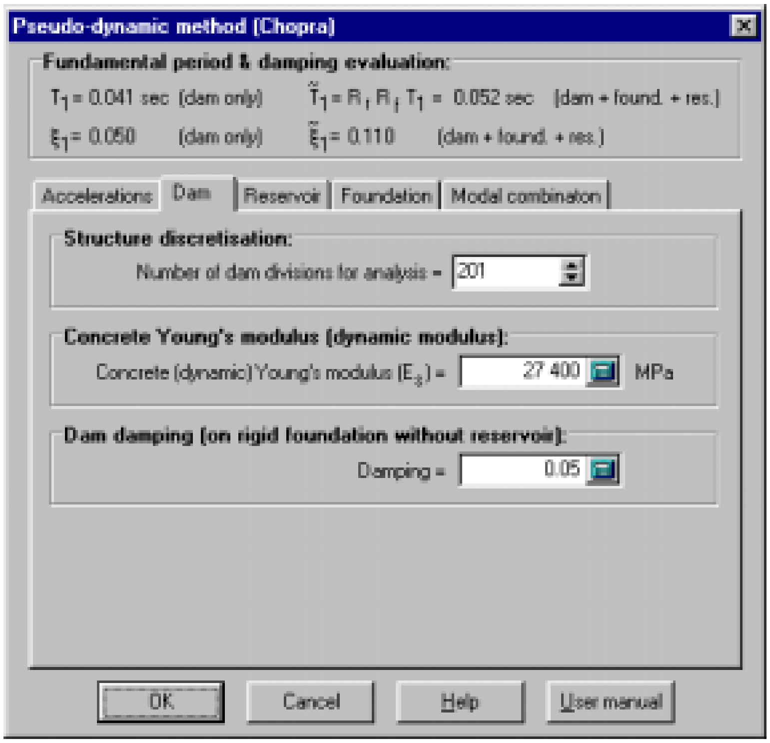
A pseudo-dynamic seismic analysis is based on the response spectra method. A pseudo-dynamic analysis is conceptually similar to a pseudo-static analysis except that it recognises the dynamic amplification of the inertia forces along the height of the dam. However, the oscillatory nature of the amplified inertia forces is not considered. That is the stress and stability analyses are performed with the inertia forces continuously applied in the same direction.

15.2 Seismic Accelerations



Since the pseudo-dynamic method does not recognise the oscillatory nature of earthquake loads it is also appropriate to perform the safety evaluation in two phases: (a) <u>the stress analysis</u> using peak spectral acceleration values, and (b) <u>the stability analysis</u> using sustained spectral acceleration values. It is assumed in these analyses that the dynamic amplification applies only to the horizontal rock acceleration. The period of vibration of the dam in the vertical direction is considered sufficiently small to neglect the amplification of vertical ground motions along the height of the dam.

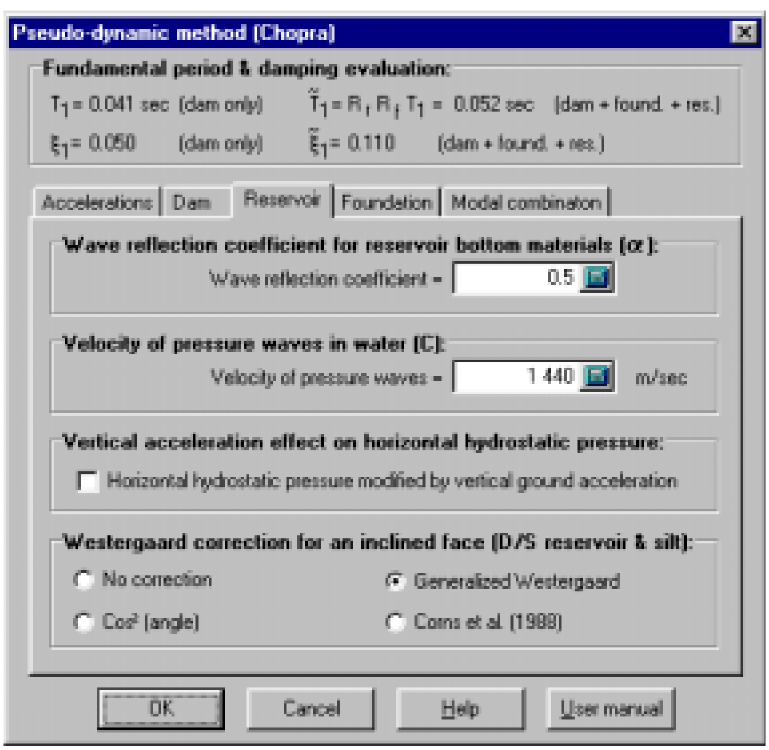
15.3 Dam Properties



To ensure the accuracy of the pseudo-dynamic method, the structure has to be divided in thin layers to perform numerical integrations. The user may specify a number of divisions up to 301. The dynamic flexibility of the structure is modelled with the dynamic concrete Young's modulus (E_s). The dam damping (ξ_1) on rigid foundation without reservoir interaction is necessary to compute the dam foundation reservoir damping ($\tilde{\xi}_1$).

Any change to these basic parameters affect the fundamental period of vibration and the damping of the dam-foundation-reservoir system computed in this dialog window. This way, the user is able to evaluate right away the spectral accelerations.

15.4 Reservoir Properties

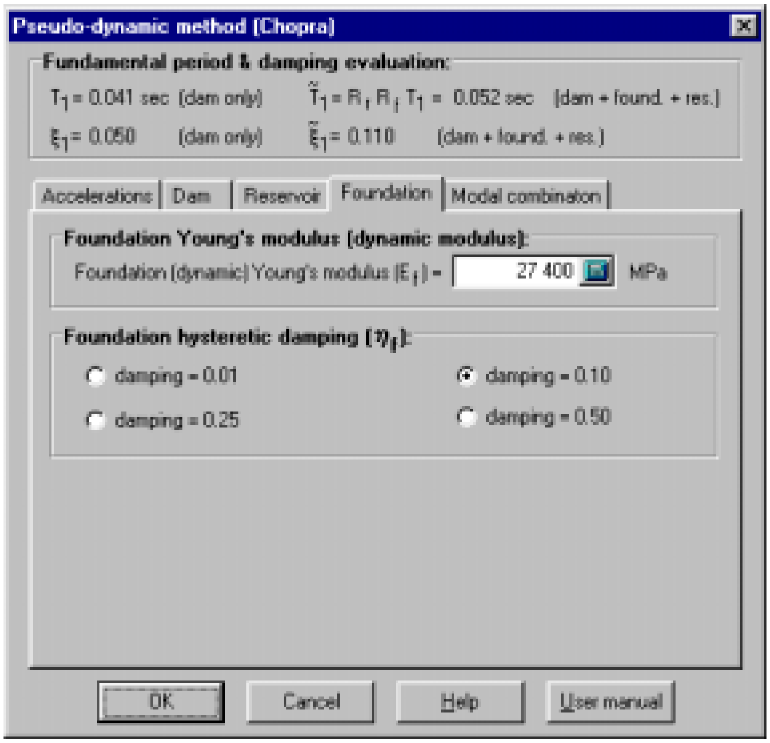


The wave reflection coefficient (α) is the ratio of the amplitude of the reflected hydrodynamic pressure wave to the amplitude of a vertical propagating pressure wave incident on the reservoir bottom. A value of α = 1 indicates that pressure waves are completely reflected, and smaller values of α indicate increasingly absorptive materials.

The velocity of pressure waves in water is in fact the speed of sound in water. Generally it is assumed at 1440 m/sec (4720 ft/sec).

Westergaard added mass procedure, with possibility of a correction for an inclined face, is used for the downstream reservoir and the silt.

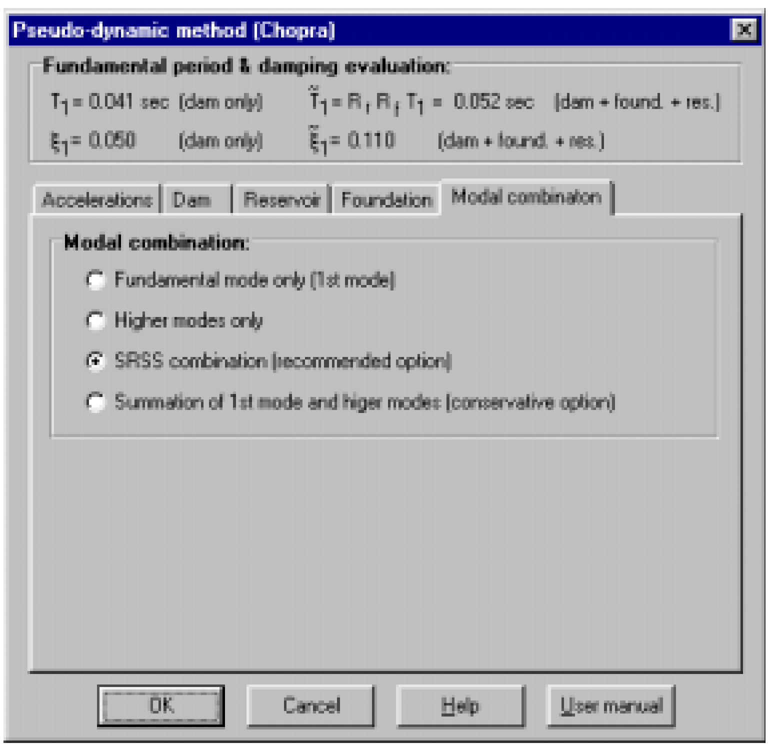
15.5 Foundation Properties



Dam-foundation rock interaction modifies the fundamental period of vibration and added damping ratio of the equivalent SDF system representing the fundamental vibration mode response of the dam.

The foundation hysteretic damping (η_f) will affect the damping ratio of the dam foundation reservoir system.

15.6 Modal Combination

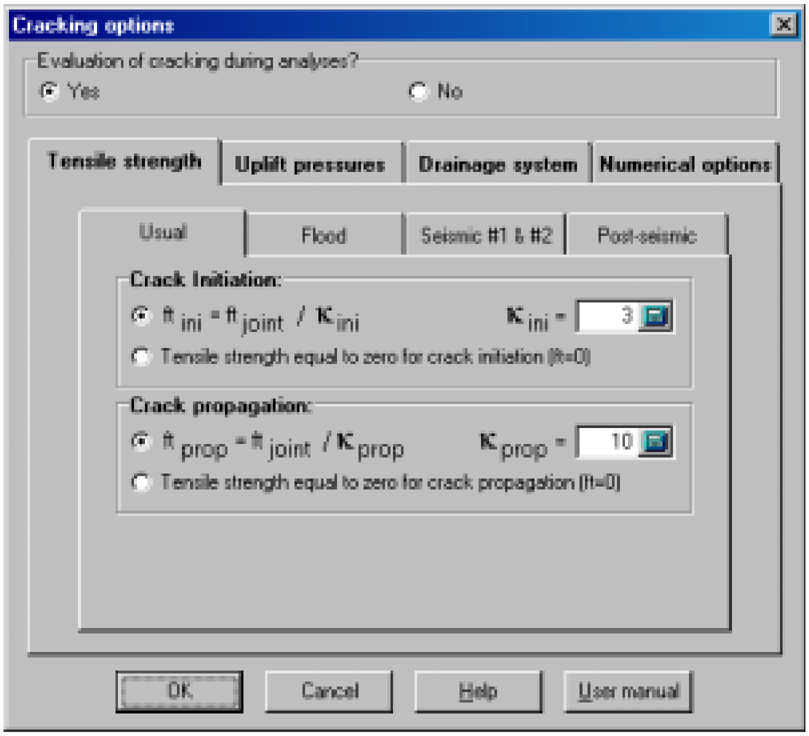


Because the maximum response in the natural vibration mode and in higher modes doesn't occur at the same time, a modal combination has to be considered. Four options are offered to the user: (i) Only the first mode; (ii) Only the static correction computed for higher modes; (iii) SRSS (square-root-of-the-sum-of-squares of the first mode and static correction for higher modes); or the (iv) Sum of absolute values which provides always conservative results.

The SRSS combination is often considered to be preferable.

16 CRACKING OPTIONS

16.1 Tensile Strength – Crack Initiation and Propagation Criteria



This window allows the specification of tensile strength to be used to determine the cracking response along the joints. The user should first indicate if cracking is allowed to take place during the analysis.

<u>No cracking possible:</u> The analysis could be performed assuming linear elastic properties without any possibility for concrete cracking by specifying "No" in the upper box (Evaluation of cracking during analyses?).

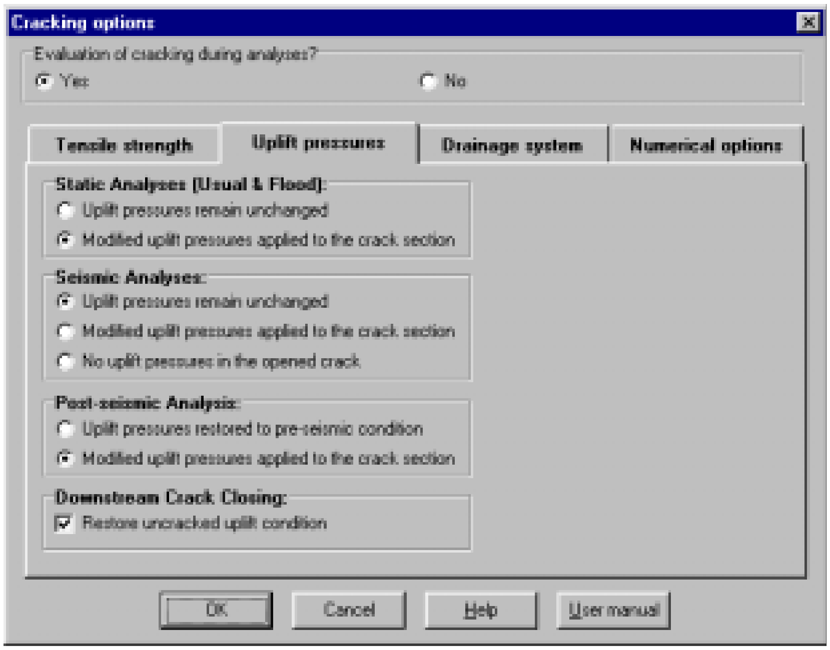
When cracking is allowed, a distinction is made between the criteria for <u>crack initiation</u> and <u>crack propagation</u> (Figure 18). After crack initiation, say at the u/s end of a joint where stress concentration is minimal, it is likely that stress concentration will occur near the tip of the propagating crack (ANCOLD 1991). For example the crack initiation criterion could be set to a tensile strength of 1000 kPa but once the crack is initiated it should be propagated to a length sufficient to develop compression at the crack tip (no-tension condition for crack propagation). The allowable tensile strengths for crack initiation and propagation are specified for different load combinations: (a) usual normal operating, (b) flood, (c) seismic (1 and 2), and (d) post-seismic.

<u>Crack initiation:</u> The allowable tensile strength for crack initiation is specified as the tensile strength divided by the user defined coefficient. Once a crack has been initiated, its length is computed by applying the specified crack propagation criterion.

<u>Crack propagation:</u> The allowable tensile strength for crack propagation is specified as the tensile strength divided by the user defined coefficient. This value should be equal to or lower than the tensile strength specified for crack initiation.

<u>Dynamic magnification of tensile strength:</u> Under rapid loading during a seismic event the tensile strength of concrete is larger that under static loading. A dynamic magnification factor could be specified to increase the tensile strength used for seismic crack initiation and propagation criteria.

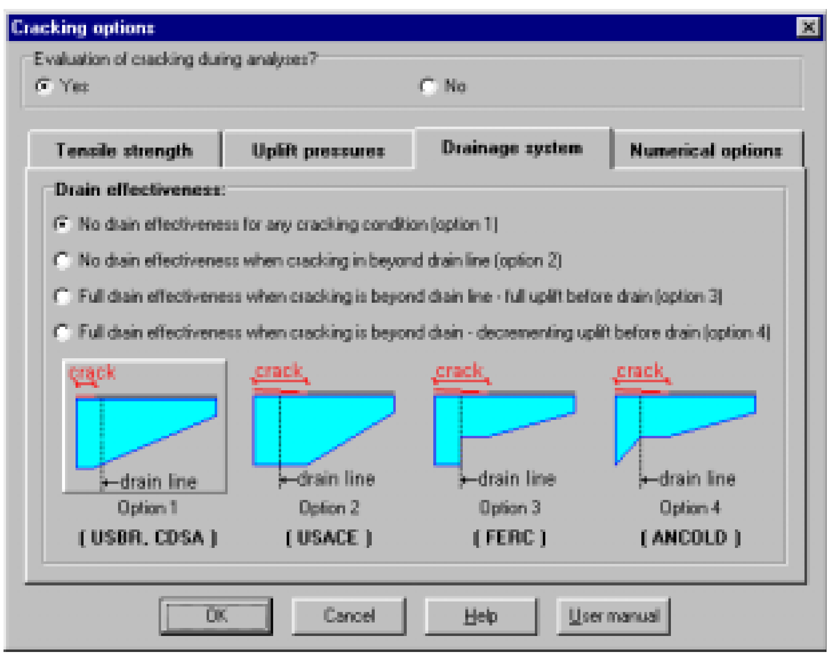
16.2 Uplift Pressures in Cracks



Different options are available to consider the evolution of the uplift pressure along a joint where cracking is taking place during (a) a static analysis (usual and flood combinations), (b) seismic analysis, and (c) post-seismic analysis. In the case a downstream crack is closing, CADAM may restore the uncracked uplift condition. Simply by checking the appropriate box activates this option.

Refer to Figure 29 in section 20.7 for uplift pressures evolution in cracks during seismic analysis.

16.3 Drainage System (drain effectiveness)

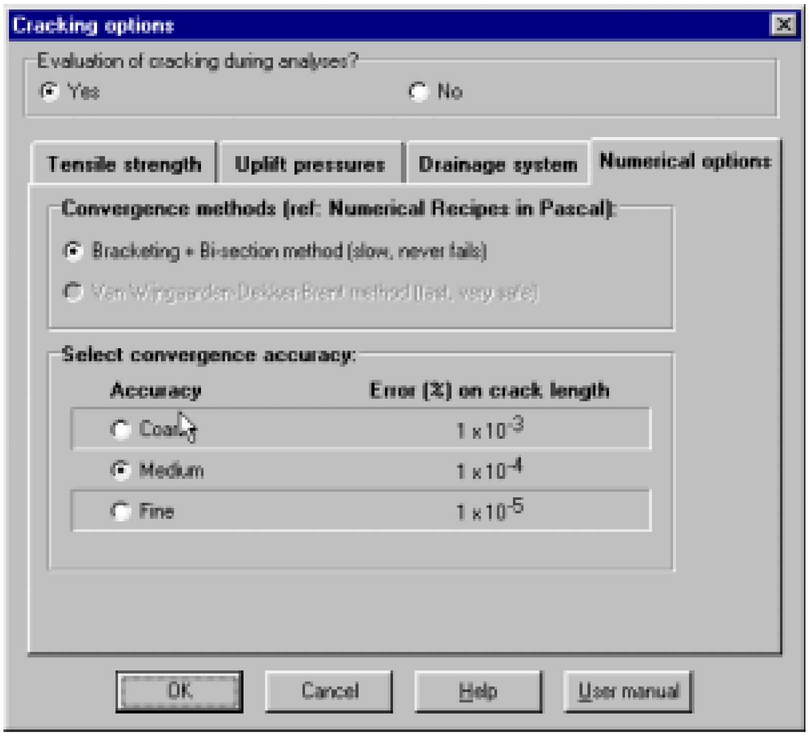


Upon cracking when drainage is considered, four options are offered to the user:

1. No drain effectiveness under any cracking condition.
2. No drain effectiveness when the crack reaches the drain line;
3. Full drain effectiveness, but with full uplift pressures applied between the reservoir and the drain line;
4. Full drain effectiveness with a linear decrement in uplift pressure starting from full reservoir pressure at the reservoir level to the drainage pressure at the drain line.

See options (1, 2, 3 & 4) in the dialog window for graphical presentation of those options.

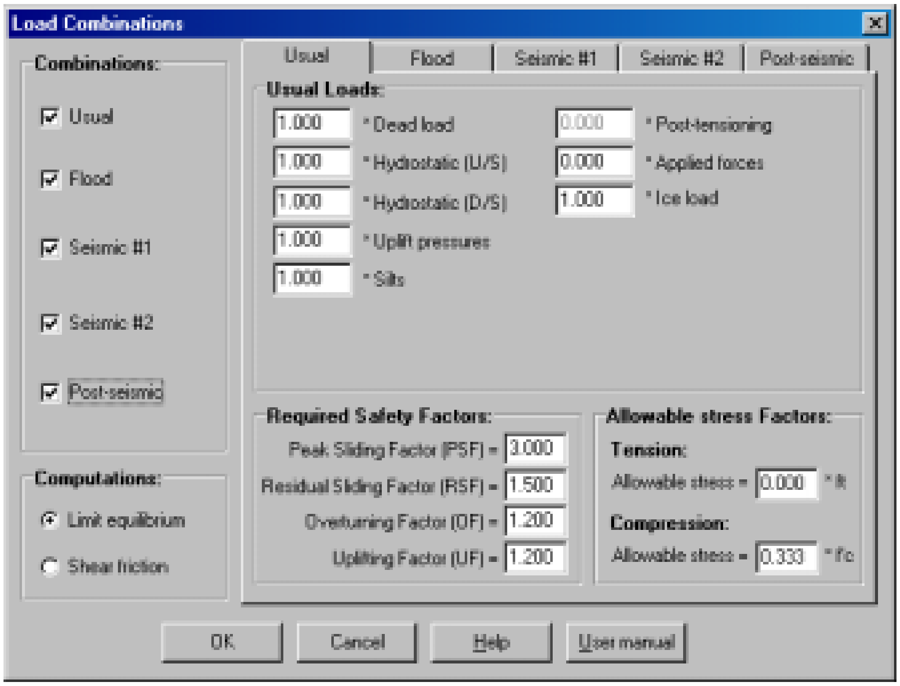
16.4 Convergence Parameter for Crack Length Computations



The crack length computations are based on the bisection method. The user may select from 3 level of accuracy based on the crack length error (%).

17 LOAD COMBINATIONS

17.1 Load Combinations and Load Conditions



There are five load combinations that could be activated by checking the appropriate item on the left of the window. For each load combination, user defined multiplication factors could be specified for each basic load conditions. This option is very useful to increase an applied load to reach a safety factor equal to 1, determining the ultimate strength of the dam.

17.2 Required Safety Factors

For each load combination, the required safety factors to ensure an adequate safety margin for structural stability are specified. These values are not used in the computational algorithm of the program. They are reported in the output results to facilitate the interpretation of the computed safety factors in comparison with the corresponding allowable values.

17.3 Allowable Stress Factors

For each load combination allowable stresses could be defined by applying multiplication factors to the tensile and compressive strengths. Various factors have been specified in dam safety guidelines to ensure an adequate safety margin to maintain structural integrity. These values are not used in the computational algorithm of the program. Allowable concrete stresses are reported in the output results to facilitate the interpretation of the computed stresses in comparison with the corresponding allowable values.

18 PROBABILISTIC SAFETY ANALYSIS (MONTE-CARLO SIMULATIONS)

18.1 Glossary

A glossary, adapted from ICOLD (1999), is included to define the main terms that are relevant to probabilistic and risk based safety analysis.

Annual Exceedance Frequency	Frequency at which an event of specified magnitude will be equalled or exceeded in any year.
Conditional Probability	The probability of an outcome, given the occurrence of some events. For example given that a flood has reached the crest of an embankment dam, the probability of the dam failing is a conditional probability.
Consequences	In relation to risk analysis, the outcome or results of a risk being realised. Impacts in the downstream as well as in the upstream areas of the dam resulting from failure of the dam or its appurtenances.
Deterministic	Leading to reasonably clear-cut solutions on the basis of prescriptive rules. Deterministic contrasts with probabilistic.
Factor of safety	In structural and other engineering systems, the ratio of system resistance to the peak design loads.
F-N curves	Curves that relate F, the frequency per year of causing N or more fatalities, to N. Such curves may be used to express societal risk criteria and to describe the safety levels of particular facilities.
Fragility curve	A function that defines the probability of failure as a function of an applied load level.
Frequency	A measure of likelihood expressed as the number of occurrences of an event in a given time or in a given number of trials.
Hazard	Threat; condition which may result from an external cause (eg. earthquake or flood), with the potential for creating adverse consequences. A source of potential harm or a situation with a potential cause loss.
Joint probability	The probability that two or more variables will assume certain values simultaneously or within particular intervals.
Likelihood	Used as a qualitative description of probability and frequency.
Monte Carlo procedure	A procedure that seeks to simulate stochastic processes by random selection of values in proportion to known probability density functions.
Probabilistic	Relating to a view that says that all that is known of natural phenomena is the probabilistic statement of what has occurred. Any procedure based on the application of the laws of probability.
Probability	A "probability" is a measure of the degree of confidence in

	a prediction, as dictated by the information, concerning the nature of an uncertain quantity or occurrence of an uncertain future event. It is an estimate of the likely magnitude of the uncertain quantity or likelihood of the occurrence of an uncertain future event.
Probability distribution function (PDF)	A function describing the relative likelihood that a random variable will assume a particular value in contrast to taking on other values.
Random variable	A quantity, the magnitude of which is not exactly fixed, but rather the quantity may assume any of a number of values and it is not known what value will be taken.
Reliability	Likelihood of successful performance of a given project element. It may be measured on an annualised basis or for some specified time period of interest. Mathematically, Reliability = 1 – Probability of failure.
Risk	Measure of the probability and severity of an adverse effect to life health, property, or the environment. Risk is estimated by the mathematical expectation of the consequences of an adverse event occurring (i.e. the product of the probability of occurrence and the consequence) or alternatively, by the triplet of scenario, probability of occurrence, and the consequence.
Scenario	A unique combination of states, such as initiating event, concurrent wind state, prior storage state, gate operating state, failure mode, downstream and tributary concurrent flows.
Sensitivity analysis	An analysis to determine the rate at which an output parameter varies, given unit change in one or more input parameters. Sensitivity can be visualised as the slope of the output parameter graph or surface at the relevant input parameter value or values.
Uncertainty	Refers to situations where the likelihood of potential outcomes cannot be described by objectively known probability density functions. More loosely used to include any variance in outcomes.

18.2 Basic Principle of a dam safety evaluation

• Definitions (Safe Dam, Risk) : Canadian Dam Safety Guidelines (CDA 1999) define:

Safe Dam as a "Dam which does not impose an unacceptable risk to people or property, and which meets safety criteria that are acceptable to the government, the engineering profession and the public",

Risk as "Measure of the probability and severity of an adverse effect to health, property, or the environment." Risk is estimated by the mathematical expectation of the consequences of an adverse event occurring (i.e., the product of the probability of occurrence and the consequences).

• Dam Safety Evaluation Procedure

1. Anticipate all failure modes (scenarios) possible.
2. Evaluate by appropriate methods (physical models, mathematical models) the probability of occurrence of these failure modes.
3. Examine the consequences of a failure; that is to quantify the expected damage for each failure mode that could induce a failure of the dam.
4. Evaluate the risk imposed by the failure of the dam. Risk is defined as the product of the failure probability and the damage consequences.

   Risk (consequence / time) = probability (event / time) x impact (consequence / event)

   Example (gravity dam 52m high):
   For a 10,000-years flood the u/s water level reaches 55m;
   Probability that the water level reaches 55m /10,000 years. (p_1=0.0001);
   Probability that the dam will fail when the water level is 55m (p_2);
   Probability of dam failure / 10,000 years (p (failure) = p_1 x p_2 : vulnerability);
   Consequences (endangered lives, economical ($)) when failure occurs.

5. Determine if the risk is unacceptable: The safety evaluation is thus linked with the notion of unacceptable (acceptable) risk that is not clearly defined and may vary as a function of sociological, economical, environmental, and technological considerations.

CADAM probabilistic analysis computes the probability of failure of a gravity dam (p2 in the above example) considering uncertainties in loading and strength parameters define in terms of suitable probability density functions (PDF).

It is then possible to perform a risk based safety assessment of the dam.

• Deterministic vs. Probabilistic Analyses

In dam safety guidelines, it is customary to define safety factors in terms of *allowable* stresses (forces). The calculations are performed using a deterministic model of the dam assuming specific numerical values for the loads and the strength parameters. For example, the sliding safety factor is defined as the ratio of the force resultant from the available resisting shear strength to the applied driving shear force along the lift joints. The factor of safety is thus a measure of reserve strength. It corresponds to the number by which the strength properties could be reduced before the occurrence of failure for a fixed loading condition.

The required values for a safety factor is defined to ensure a satisfactory dam performance considering uncertainties in three basic aspects: (1) the applied loads, (2) the strength parameters, and (3) the limits and assumptions inherent to the structural analysis method selected (the gravity method for CADAM see section 2.3).

A *probabilistic* analysis considers explicitly the uncertainties in the loading and strength parameters that are considered as random variables. The uncertainties in input parameters are then transformed in probability of failure of a dam. A probabilistic analysis requires more information than a deterministic analysis. For example, probability density functions (PDF) (normal, log-normal) are to be selected for the friction coefficient and cohesion; the mean values, and the standard deviation must then be specified.

18.3 Overview of CADAM Probabilistic Analysis Module

An overview of CADAM probabilistic analysis module is given in Figure 14.

• Objectives: The objectives of CADAM probabilistic analysis module is to compute the probability of failure of a dam-foundation-reservoir system as a function of the uncertainties (PDF) in loading and strength parameters that are considered random variables.

• Computational procedure – Monte Carlo Simulation: Due to concrete cracking, and related modifications in uplift pressures, the stress and stability analysis of a dam is in general a non-linear process. Monte Carlo simulation is used as the computational procedure to perform the probabilistic "non-linear" analysis in CADAM. Monte Carlo simulation technique "involve sampling at random to simulate artificially a large number of experiments and to observe the results" (Melchers 1999):

(1) a large number (up to 250,000) of loading and strength parameters are "sampled" at random within bounds of specified PDF to perform a large number of possible scenarios;

(2) stress and stability analyses are performed;

(3) Statistics are performed on the results (ex. sliding safety factors, SSF) to determined the probability of failure, pf:

$$p_f = \frac{n_f}{N} = \frac{n(SSF < 1)}{N}$$

N = total number of simulations
n_f = number of failures

The output results can also be analysed statistically to define the mean (μ), variance (σ^2), cumulative distribution function (CDF).

PROBABILISTIC SAFETY ANALYSIS

INITIAL DETERMINISTIC MODEL 1

- Define an initial CADAM 2000 dam-fondation-reservoir system model using the general input parameters;
- Be sure to define the load condition to be considered as random variables;
- Be sure to define the strength parameters to be considered as ramdom variables ;
- Activate the proper load combinations (usual, flood, earthquakes ...);
- Apply the appropriate multiplication factor such that load conditions considered as random variables are included in the load combination selected.

NOTE: It is important to define an initial model that is consistent with the parameters that will be used as random variables later on while using the probabilistic analysis option.

↓

PROBABILISTIC ANALYSIS 2

Activate probabilistic analysis option

↓

SELECTION OF RANDOM VARIABLES AND PROBABILITY DENSITY FUNCTIONS (PDF) 3

- Strength random variables:
  - Tensile strength;
  - Peak cohesion;
  - Residual cohesion;
  - Peak friction coefficient;
  - Residual friction coefficient.
- Load random variables:
  - Normal upstream reservoir elevation;
  - Flood upstream reservoir increase;
  - Silt elevation;
  - Silt volumetric weight;
  - Drain efficiency;
  - Floating debris;
  - Ice load;
  - Last applied force;
  - Horizontal peak ground acceleration.
- PDF: Uniform, Normal , Lognormal & User defined. (mean, Std deviation, cut-off values)

↓

SELECTION OF INPUT CONTROL PARAMETERS 4

- Load combination;
- Number of simulations (up to 250,000);

↓

SELECTION OF OUTPUT CONTROL PARAMETERS 5

- Identification of lift joint for output;
- Selection of output performance indicators;
- Sliding safety factors, crack length;
- Cumulative Distribution Function (CDF) - selction of number of division for numerical calculation;
- Probability of failure;
- Output files (data and PDF/CDF curves).

↓

COMPUTATIONAL PROCEDURES 6

(Monte-Carlo simulations)

1. Initial conditions (cracking, uplift pressures)-deterministic analysis from the selected load combination (genreral input parameter);
2. Generation of selected random variables;
3. Stress and stability analyses (output parameters);
4. Statistical analysis of output parameters (min, max, mean, std dev, PDF, CDF).

↓

INTERPRETATION OF RESULTS 7

(Check for convergence - Ex: increase no. of simulations)

Figure 14 Probabilistic Safety Analysis Procedure in CADAM

• Scope and Use: CADAM probabilistic analysis module can be useful:

1. For educational purpose to develop a basic understanding of the concepts and procedure required to perform a risk analysis.

2. To actually perform probabilistic (risk) analysis for a particular dam. It is then possible to construct fragility curve, F-N curves, compute reliability indices (as a function of $(1 - p_f)$).

3. To perform R&D in risk based dam safety assessment (ex. calibration of nominal strength (resistance R) reduction factor, ϕ, and load (L) factor,γ to develop limit state based safety evaluation format; $\phi R \geq \gamma L$).

4. To study different safety approaches. ex: strength requirements to ensure uniform risk during the service life of a dam.

18.4 Probability Distribution Function (PDF)

Random variables: A quantity, the magnitude of which is not exactly fixed, but rather the quantity may assume any of a number of values and it is not known what value will be taken. To perform a probabilistic analysis in CADAM some load conditions and/or strength parameters must be specified as random variables.

• Independent / dependent random variables: In CADAM the selected strength and loads parameters that are treated as random variables must be independent. The dependent variables are considered as follow:

Upstream reservoirs (normal and flood) will affect the following modeling parameters upon overtopping:

- Crest vertical water pressure: The pressure distribution will follow the defined pressures in the reservoir dialog box.
- Normal downstream reservoir elevation:
  1. If the initial upstream reservoir elevation is set below the crest elevation, then the downstream elevation will be increased by the overtopping occurring during the probabilistic analysis
  2. If the initial upstream reservoir is set over the crest elevation, then the downstream reservoir will be increased proportionally to the ratio between the initial height of the downstream reservoir and the initial height of the upstream reservoir overtopping.
- Floating debris and Ice load: An important overtopping might flush floating debris or ice cover. Please refer to reservoir dialog to setup these parameters.

The horizontal peak ground acceleration will change the following parameters:

- *All dependent accelerations* (VPGA, HPSA, HSGA, VSGA and HSSA) will be scaled proportionally to the ratio between the generated horizontal peak ground acceleration and the initial horizontal peak ground acceleration.

18.4.1 Basic statistical properties of random variables:

Consider a set of n data points $x_1, x_2, \ldots, x_n$

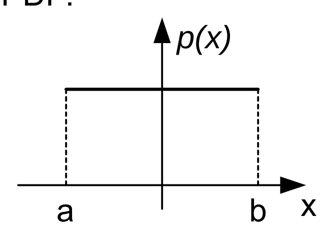
- *Mean:* $\mu = \sum_{i=1}^{n} \frac{x_i}{n}$
- *Median:* *the median (M) is the value of x such that it falls in the middle of the array of n values when they have been ordered from the least to the greatest numerical value.*
- *Variance:* $\sigma^2 = \sum_{i=1}^{n} \frac{(x_i - \mu)^2}{n}$
- *Standard deviation*: *σ is the positive square root of the variance.*
- *Skewness*: $\gamma = \frac{3(\mu - M)}{\sigma}$
- *p^{th} percentile* : *the p^{th} percentile of a set of n data points denoted by $P_{xx\%}$ is the value of x such that xx percent of the values are less than P and (100 – p) percent of the values are greater than P.*
- *Chebychef theorem*: *Given a set of n data points $x_1, x_2, \ldots x_n$ and a number k greater than or equal to 1, at least $(1 - 1/k^2)$ of the data points will lie within k standard deviations of their mean value.*

18.5 Probability Distribution Functions (PDF) available in CADAM

18.5.1 Uniform Distribution

The random variable X is defined on the interval a to b with the PDF:

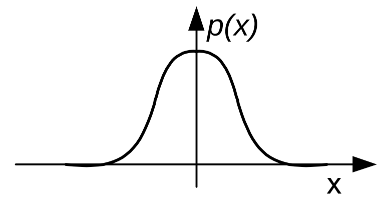
$$p(x) = \frac{1}{b-a} \qquad \textit{where} \quad a \le x \le b$$



18.5.2 Normal distribution

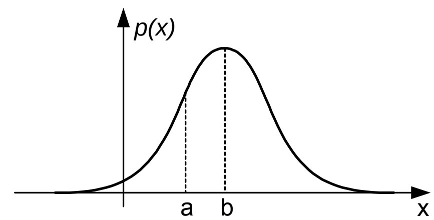
The random variable x is said to be normally distributed if its PDF is

$$p(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2} \qquad \begin{array}{c} -\infty \le x \le +\infty \\ -\infty \le \mu \le +\infty \\ \sigma > 0 \end{array}$$

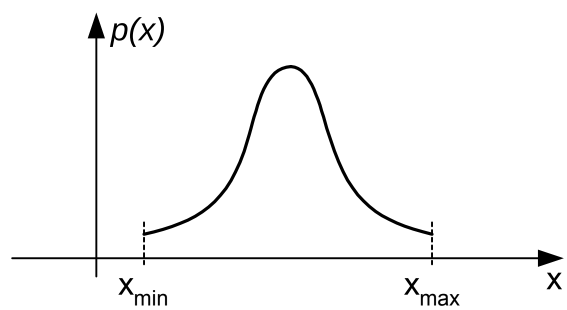


Computation of probability: The probability that a random variable will assume a value between a and b can be determined by computing the area under its PDF between a and b

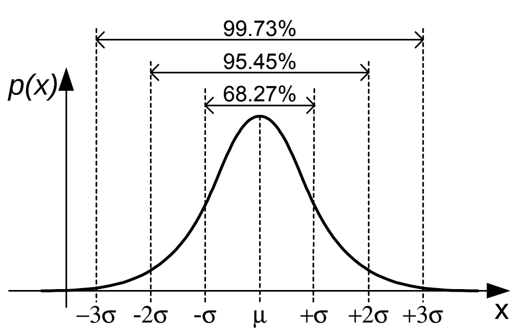
$$P\ (a \le x \le b) = \int_a^b p(x)\ dx$$

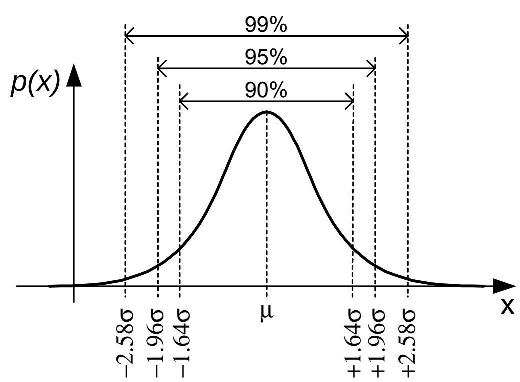


Cut-off values: In engineering problems, it is unlikely that a random variable can take any values up to minus or plus infinity. For example tensile strength cannot be infinite. To account for that, the user must specify cut-off values defining the lower bound (x_{min}) and upper bound (x_{max}) within which the numerical values of the random variable will be distributed.



Confidence interval: Consider the standard normal distribution of a random variable x with a unit standard deviation σ. For any normal distribution, 68.27% of the values of x lie within one standard deviation of the mean (μ), 95.45% of the values lie within two standard deviations of the mean, and 99.73 % of the values lie within three standard deviations of the mean.





Important note: In CADAM, it is recommended to keep cut-off values within five standard deviations of the mean to ensure computational accuracy. CADAM is using 1000 intervals to define PDF functions. Cut-off values that are far exceeding five standard deviations may generate computational difficulties. A data range within three standard deviations corresponds to a 99.73% confidence interval, while a data range within five standard deviations corresponds to a 99.99997% confidence interval.

18.5.3 Log-normal distribution

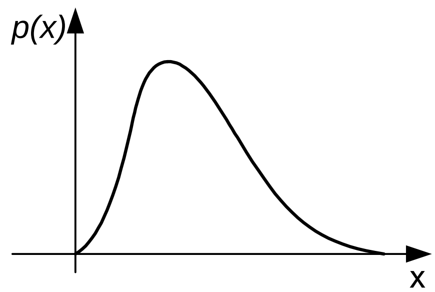
One advantage of the log-normal PDF over the normal PDF is that numerical values of data points following a log-normal distribution are always positive. The log-normal distribution corresponds to a transformation of variables. For example, one could replace water level by its logarithm and then apply the normal distribution to this data set to obtain the same results as if the log-normal PDF was applied directly to the water level (Lombardi 1988).

Consider the random variable x. Defining the random variable y by the transformation:

$$y = \ln x$$

the log-normal distribution of x is given by:

$$p(x) = \frac{1}{x\sigma_Y\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{\ln x - \mu_Y}{\sigma_Y}\right)^2} \qquad \mu > 0, \quad \sigma > 0$$

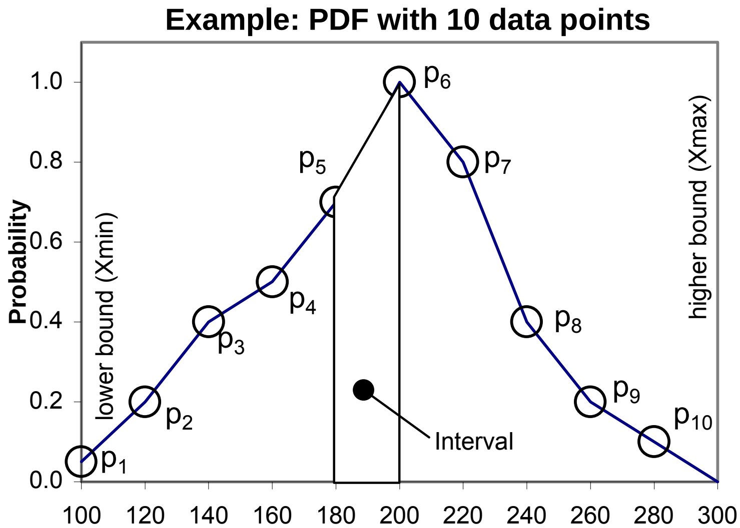


where μ_y and σ_y are the mean and standard deviation of Y, respectively. The following parameters of a log-normally distributed variable, X, can be define:

- Mean: $\mu_X = e^{(\mu_Y - \sigma_Y^2/2)}$
- Variance: $\sigma_X^2 = \mu_X^2 \left(e^{\sigma_Y^2} - 1\right)$
- Skewness: $\gamma_X = 3C_V + C_V^3$; $C_V = \sigma_X / \mu_X$ C_V is the coefficient of variation.

In structural engineering applications, the load and resistance parameters have often been considered to be log-normal random variables since they can not take negative values.

18.5.4 User defined PDF data points



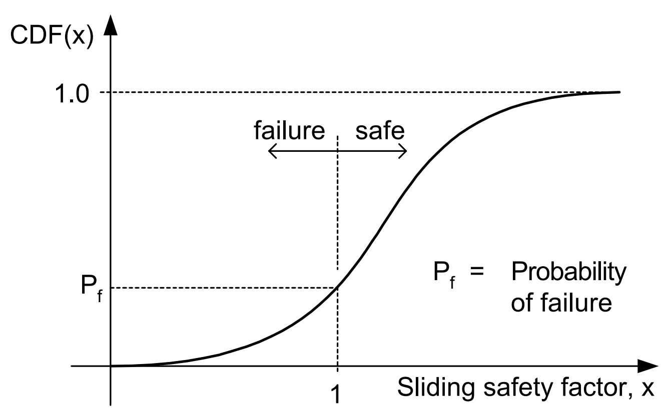
CADAM allows the user to provide his own PDF by importing data points from a text file (ASCII). The file format is simple: the first line is the number of data points (between 10 and 4000) while the rest of the file is composed of the data points, representing the ordinates of the PDF. A free format could be used for data points that must be separated by a space or a carriage return. Its is not imperative to normalize the function (probability values scaled between 0 and 1). The number of data points defines the number of intervals. The higher bound and the lower bound are defined in CADAM probabilistic analysis dialog window. The points are located at the beginning of each interval. The probability within one interval is interpolated between its reference point and the reference point of the next interval. The probability of the last interval is extrapolated towards zero. A minimum of 500 data points is recommended.

18.6 Cumulative Distribution Function (CDF)

Associated with each probability distribution function (PDF), *p(x)*, is *a Cumulative Distribution Function* (CDF), *P(x)*, which gives the probability that the random variable *x* will assume a value less than or equal to a stipulated value *X*.

$$P(x) = \text{Prob}(x \le X) = \sum_{-\infty}^{X} p(x) \qquad \text{where } \sum_{all\ x} p(x) = 1 \text{ must be satisfied.}$$

The next figure presents a CDF of a sliding safety factor. The probability of failure *(P_f)*, by sliding, is given for a safety factor equal to one (x = 1). The CDF graph may be displayed using the graphical result of CADAM.



18.7 Computational Procedures

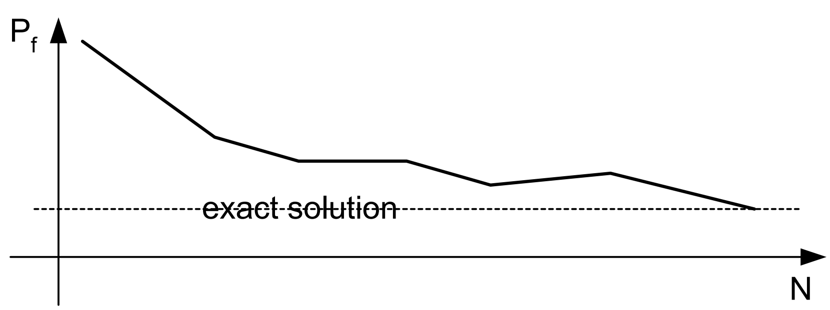
The computational procedure followed in Monte Carlo Simulation is summarized in box [6] in Figure 14.

18.7.1 Number of required simulations

Melchers (1999) presents different formulas to estimate the required number of simulations to ensure proper convergence to an accurate estimate of the probability of failure of the system analysed. The simplest formula is from Broding et al. (1964) that suggested:

$$N > \frac{-\ln(1-C)}{P_f}$$

Where N = number of simulations for a given confidence level C in the probability of failure P_f. For example, more than 3000 simulations are required for a 95% confidence level and $P_f=10^{-3}$. This total number of simulations should be adjusted as N times the number of independent random variables considered in the analysis. Melchers (1999) also mentions that other authors have indicated that N ≈ 10,000 to 20,000 to get 95% confidence limit depending on the complexity of the system analysed. We recommend 20,000 analysis per random variables.
To assess the convergence of Monte Carlo Simulations progressive estimate of P_f could be plotted as a function of N as the calculation proceeds.

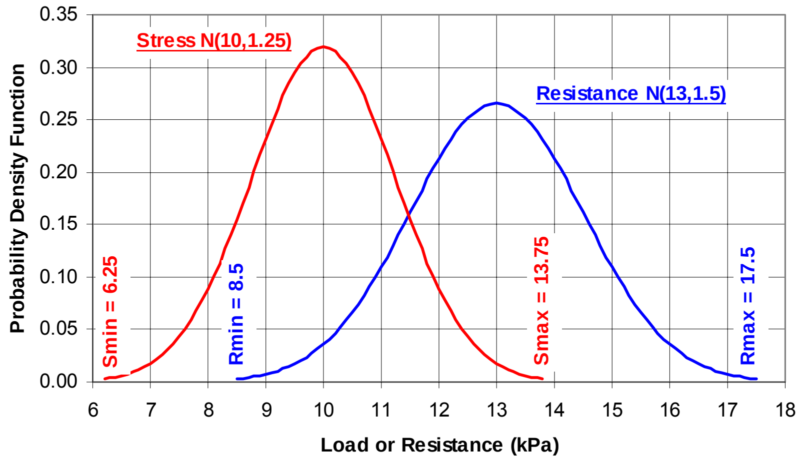


18.8 Practical Considerations

Random variables should not be allowed to take unrealistic values to obtain meaningful results from the probabilistic analysis. Appropriate cut-off values should be defined for that purpose. For example, while considering the reservoir level for a particular dam, it must always be remembered that to reach realistic water levels the whole reservoir must be properly contained with consideration of downstream water outflow. For example, secondary dikes at a lower elevation than the main concrete dam main may be overtopped and fail before the main concrete dam.

18.9 A Simple Example – Plain Concrete Bar in Tension

18.9.1 Normal distributions:



To illustrate the use of a probabilistic analysis in CADAM, we consider a simple bar in tension that has been analysed by Melchers (1999). This bar is modelled in CADAM to possess a unit cross-sectional area ($1m^2$). A user defined applied force induce a stress S that is normally (N) distributed with a mean of 10kPa and a standard deviation of 1.25kPa that is N (μ_S=10, σ_S=1.25). The resistance (R) of the bar is estimated to be N(μ_R=13, σ_R=1.5). The applied stress and the resistance are statistically independent random variables. The figure above shows the PDF curves of the stress and resistance. The CADAM file for this example is available in the demo directory as "bar1.dam".

Using a deterministic analysis the safety factor against a tensile failure is estimated to be SF = (mean Resistance) / (mean applied stress) = 13 / 10 = 1.3.

Using probabilistic analysis the failure event is defined as:

Failure = (Resistance < Stress)

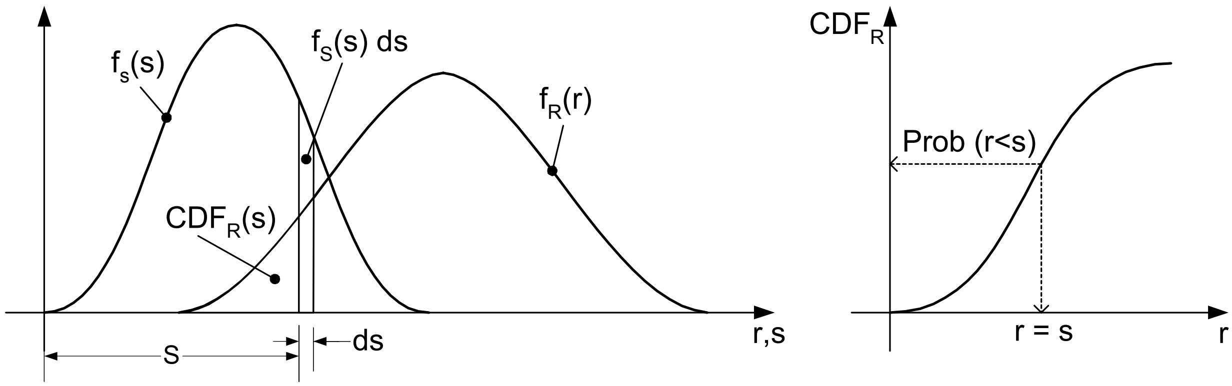
The probability of failure is then defined as:

$$P_f = \text{Prob}(R < S) = \iint\limits_{(r<s)} f_{rs}(r,s)\, dr\, ds$$

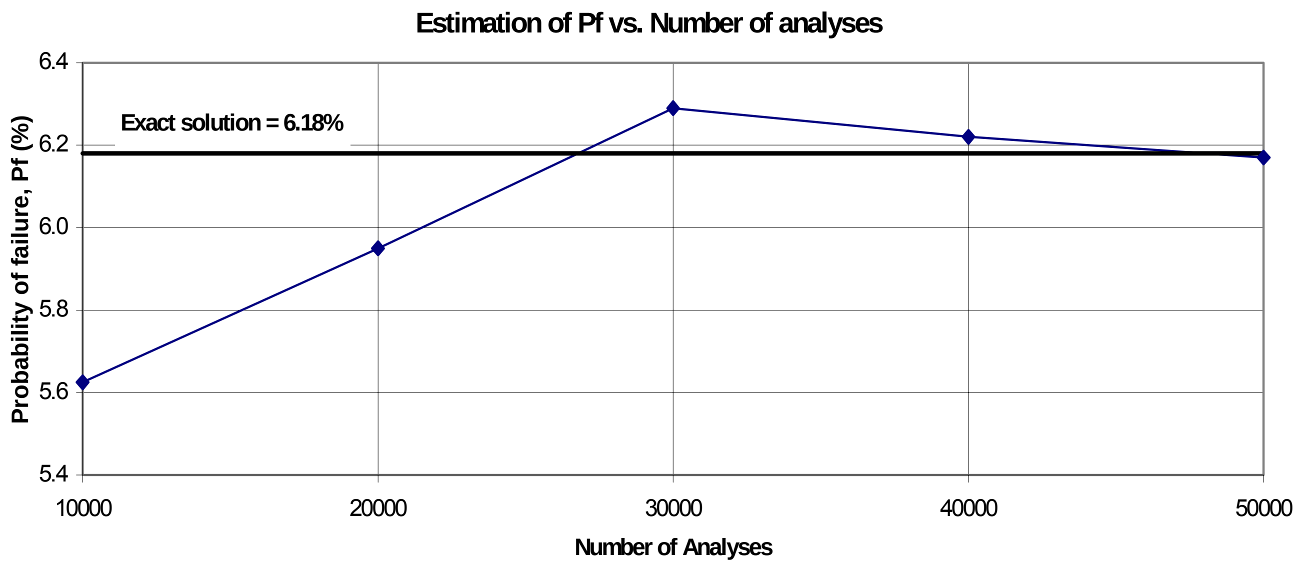
where $f_{rs}(r,s)$ denote the joint PDF of R and S. However since R and S are statistically independent:

$$P_f = \int_0^{\infty} CDF_R(s) \cdot f_s(s) \cdot ds$$

where $CDF_R(s)$ is the cumulative distribution function of R, and $f_S(s)$ is the PDF of S.



Since both *R* and *S* are normally distributed the exact result can be computed as $P_f = 0.0618$. The results obtained from CADAM2000 Monte-Carlo simulations are presented in the figure below as a function of the number of simulations. Cut-off values corresponding to three standard deviations from the mean have been used for both resistance and stress.

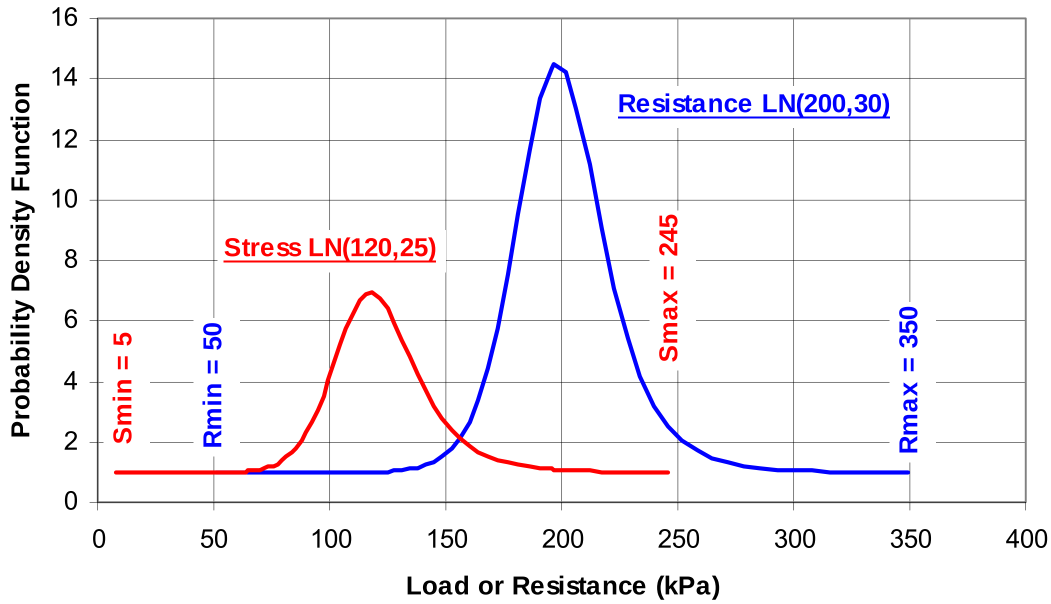


It is shown that to estimate P_f with a 95% confidence interval 20,000 simulations are required in this case. To get a 99% estimate 50,000 simulations are then required. Monte-Carlo simulations in CADAM use a random number generation technique that will always give a different computational result even if the analysis is repeated with the same number of simulations.

The effect of the selected cut-off values will affect the standard deviation of the generated values of the random variables. In fact, cut-off values get the generated values closer to the mean, therefore reducing the standard deviation specified by the user. The reduction factor is equivalent to the confidence interval for an infinite numbers of generated values. Moreover, cut-off values will affect the failure probability. CADAM will not accept cut-off values defining a range (from x_{min} to x_{max}) larger than 10 standard deviations.

18.9.2 Log-normal distributions:

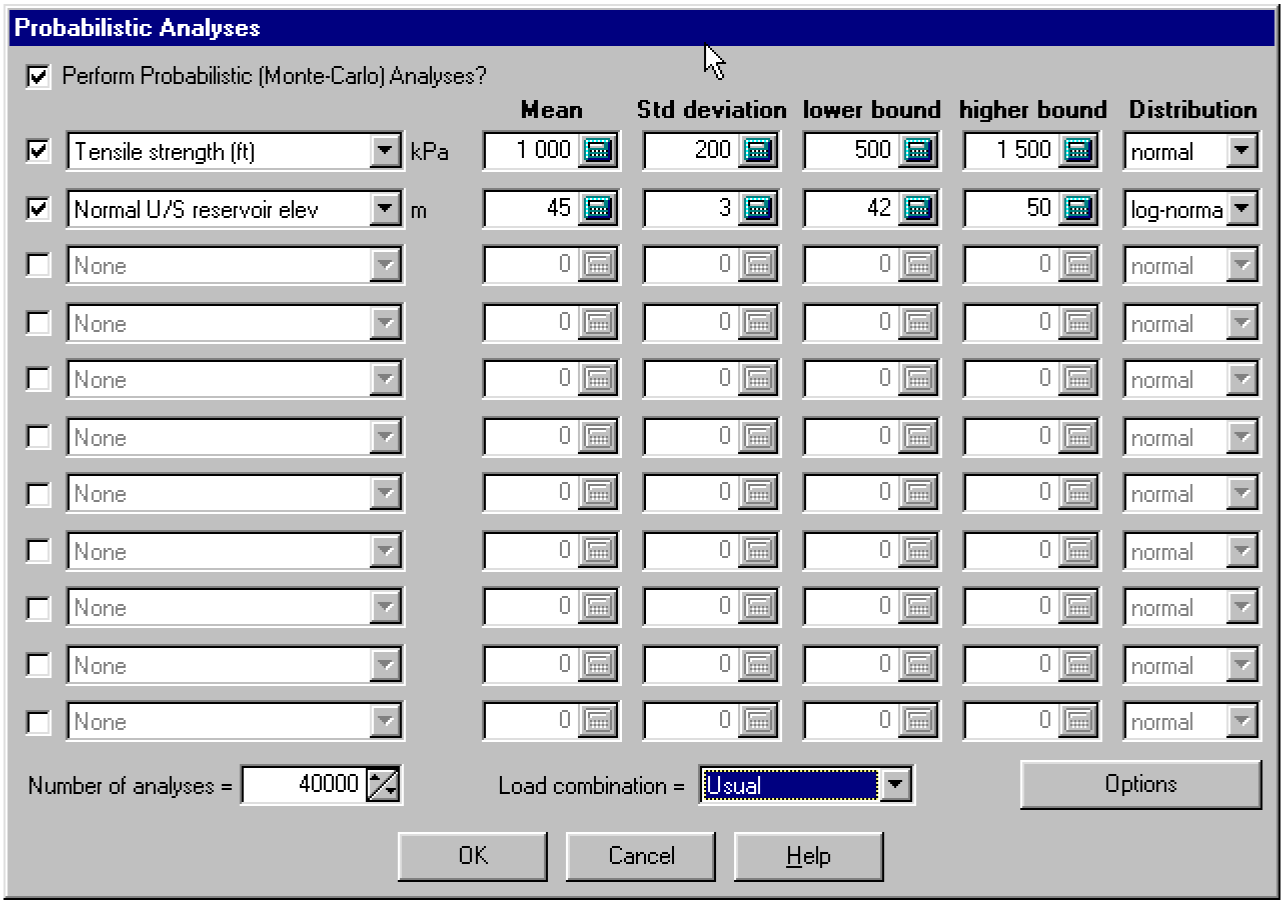
The above example of a bar in tension is repeated using log-normal distributions for R=LN(μ_R=200, σ_R=30) and S=LN(μ_S=120, σ_S=25).



The exact integration yields $P_f = 0.0203$.

CADAM Monte Carlo simulation gives $P_f = 0.0199$ for N = 40,000, while cut-off values were set for a total range of nearly ten standard deviations.

18.10 CADAM Input Parameters for a Probabilistic Analysis



This window allows the specification of input parameters for a probabilistic analysis. The first step is to select the random variables by checking the check boxes to enable the controls beside it. Then select the variable parameter from the scroll list. This list is composed of five strength parameters and nine loading parameters, which are:

<u>Strength Variable Parameters:</u>

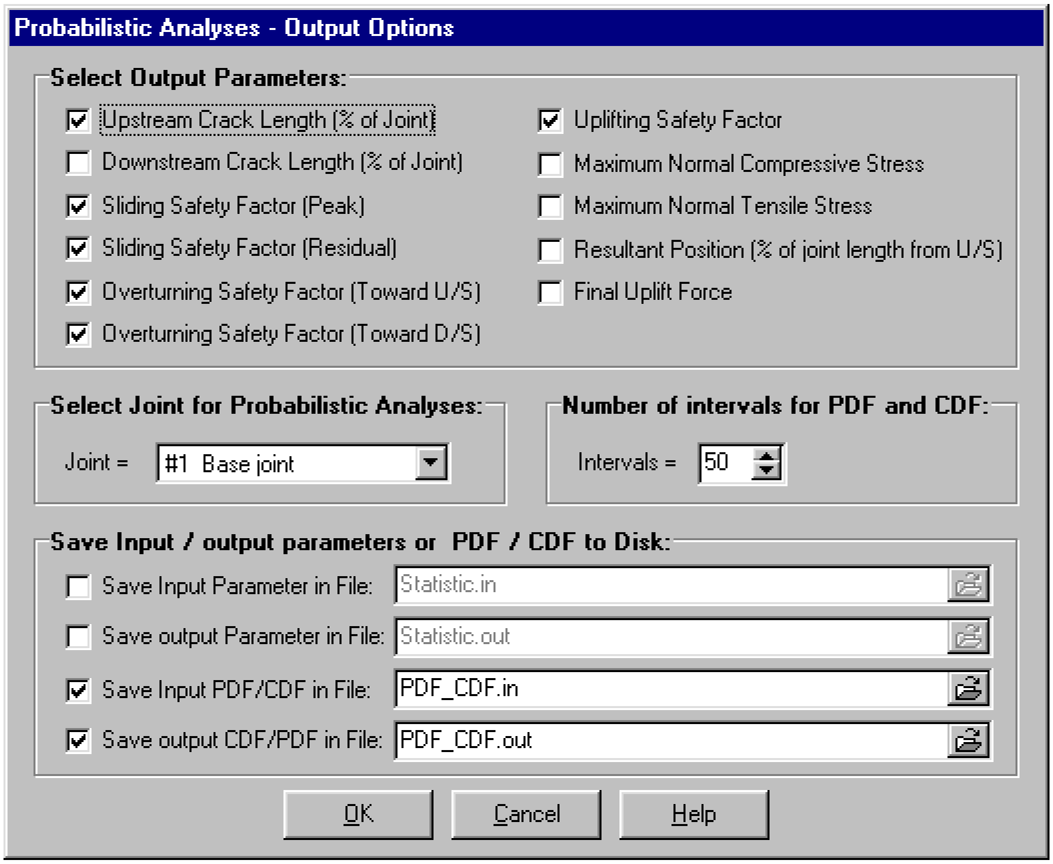
1. Tensile strength;
2. Peak cohesion;
3. Residual cohesion;
4. Peak friction coefficient;
5. Residual friction coefficient;

<u>Loading Variable Parameters:</u>

6. Normal upstream reservoir elevation;
7. Flood upstream reservoir increase;
8. Silt elevation;
9. Silt volumetric weight;
10. Drain efficiency;
11. Floating debris;
12. Ice load;
13. Last applied force;
14. Horizontal peak ground acceleration.

Monte-Carlo simulations require that random variable must be independent to each other. CADAM will thus consider that the cohesion (real or apparent) is independent of the tensile strength, which may not be the case. CADAM users have to be aware of the assumptions concerning random variables before proceeding with probabilistic analyses (see section 18.4 for dependent random variables in probabilistic analysis).

18.11 Output Parameters for Probabilistic Analyses



This windows is activated with the button "options" of the input parameters dialog box. The user has to select the output parameters that should be saved by simply checking the check box beside the parameter. Probabilistic analyses require significant memory. CADAM performs computational analyses for one lift joint.

The number of intervals for the PDF and CDF corresponds to the number of data points that defines the PDF and CDF of the input and output parameters.

Finally, CADAM allows to save each input and output parameters for every analysis in a file (ASCII), as well as their PDF and CDF.

19 INCREMENTAL LOAD ANALYSES

19.1 Overview

Objectives: In dam safety evaluation there is most often high uncertainties with the loading intensity associated with extreme events with very long return periods: (a) the reservoir elevation corresponding to the 10,000 yrs event or Probable Maximum Flood (PMF), and (b) the peak ground acceleration (PGA) (spectral ordinates) corresponding to the 10,000 yrs event or the Maximum Credible Earthquake.

It is essential to know the evolution of typical sliding safety factors (for peak and residual strengths) as well as performance indicators (ex. crack length) as a function of a progressive increase in the applied loading (i.e. reservoir elevation or PGA). It is then possible to evaluate for which loading intensity, safety factors will fall below allowable values such that proper action could be planned. The reservoir elevation or PGA (spectral ordinate) that will induce failure can also be readily evaluated (safety factors just below one). The concept of imminent failure flood is used in dam safety guidelines. A parallel could be established with earthquakes where the concept of imminent failure earthquake (ground motion) could be developed. There are also uncertainties for other loads such as ice forces acting under the usual load combination (ex. the magnitude of ice forces).

It is always possible to perform parametric analyses with CADAM by running a series of independent analyses while modifying the input parameters and then compiling the output results in graphical form. However, this procedure is rather cumbersome. To facilitate parametric analyses accounting for load uncertainties in the context of a series of deterministic analyses an INCREMENTAL LOAD ANALYSIS option has been implemented in CADAM. The *objective* is to automatically compute the evolution of safety factors and other performance indicators as a function of a user specified stepping increment applied to a single load condition (ex. either ice force, or reservoir elevation or PGA).

Procedure: The overall procedure while performing incremental load analysis is described in Figure 15. It must be emphasised that an initial dam model with the load condition to be incremented must be defined using the general input data modules before performing an incremental analysis.

Consistency in results: While performing an incremental load analysis, each load increment is applied with respect to the crack conditions that were prevailing while the model was initialised before the incremental load analysis. In most instances when the loading is increasing monotonically, the performance indicators will also tend to progress accordingly. However in some cases a different behaviour can be obtained:

- Example 1 : If floating debris are included while increasing the reservoir elevation, they could be flushed at a certain level thus decreasing the overturning moment and related crack length;

- Example 2: If the initialisation is performed with self-weight, it is possible that cracking will be initiated from the d/s face thus destroying the cohesive bond on a certain length along a joint, if the reservoir is subsequently increased CADAM will not activate cohesion on the part of the ligament that was damage while initialising the model.

<u>Practical considerations:</u> While increasing the reservoir level for a particular dam, it must always be remembered that to reach realistic water levels the whole reservoir must be properly contained with consideration of downstream water outflow. For example, secondary dikes at a lower elevation than the main concrete dam main may be overtopped and fail before the main concrete dam.

<u>INCREMENTAL LOAD ANALYSIS</u>

INITIAL DETERMINISTIC MODEL 1

- Define an initial CADAM dam-fondation-reservoir system model using the general input parameters
- Be sure to define the load condition to be incremented in the initial model
- Activate proper load combinations (usual, flood, earthquakes ...)
- Apply the appropriate multiplication factor such that the load condition is included in the load combination selected

NOTE: It is important to define an initial model that is consistent with the parameters that will be varied later on while using the incremental load analysis option.

↓

INCREMENTAL LOAD ANALYSIS 2
Activate incremental load analysis options

↓

SELECTION OF INPUT CONTROL PARAMETERS 3

- Load combination
- Load condition (Reservoirs (usual, flood), ice, applied forces, PGAH (pseudo-static, pseudo-dynamic))
- Lift joint

↓

COMPUTATIONAL PROCEDURE 4
CADAM (Initialisation)
Initialisation-initial conditions (cracking and related uplift pressure) computed from the specified load combination

↓

CADAM (incremental analyses) 5
Perform stress and stability analyses for each load increment

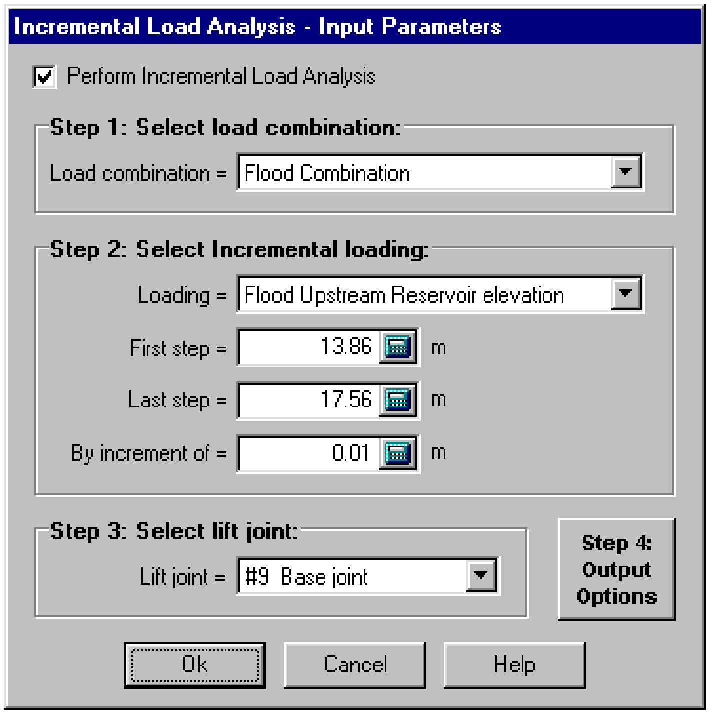
↓

SELECTION OF OUTPUT PARAMETERS 6

- Sliding safety factors (peak, residual)
- Other performance indicators (crack length ...)
- Graphical display
- Printed report, export to EXCEL or Clipboard

Figure 15 Incremental load analysis procedure.

19.2 CADAM input parameters for incremental load analysis



This window allows the specification of incremental load analysis parameters. The procedure consists of selecting a load combination, then a loading condition to be incremented for this combination, and finally a lift joint to be considered for the computation.

Seven types of load conditions could be incremented:

1. Normal upstream reservoir elevation
2. Flood upstream reservoir elevation
3. Horizontal peak ground acceleration
4. Ice load
5. Last applied force
6. Post-tensioning
7. Drain effectiveness

The type of load that could be incremented depends on the load combination and also on its previous inclusion in the model. For example, if the user wants to select the last applied force as the loading, at least a "force" load condition has to be included in the model.

Consistency is essential for incremental load analysis. For example, if the flood upstream reservoir elevation is selected as the incremental load and the first step (first elevation) is set below the normal upstream reservoir elevation, then there is an invalid assumption. In this case, CADAM will issue a warning to the user. The last applied force load condition is based on the last force defined in the force list. The direction of the incremented force will be applied in the same direction of the last force resultant.

19.2.1 Dependent variables

Increasing an "independent" load condition might involve changing certain dependent variables that are a function of the independent load. The rising of the upstream reservoir (operating or flood) above the crest will affect the downstream reservoir elevation as well as the vertical water pressure on the crest surface.

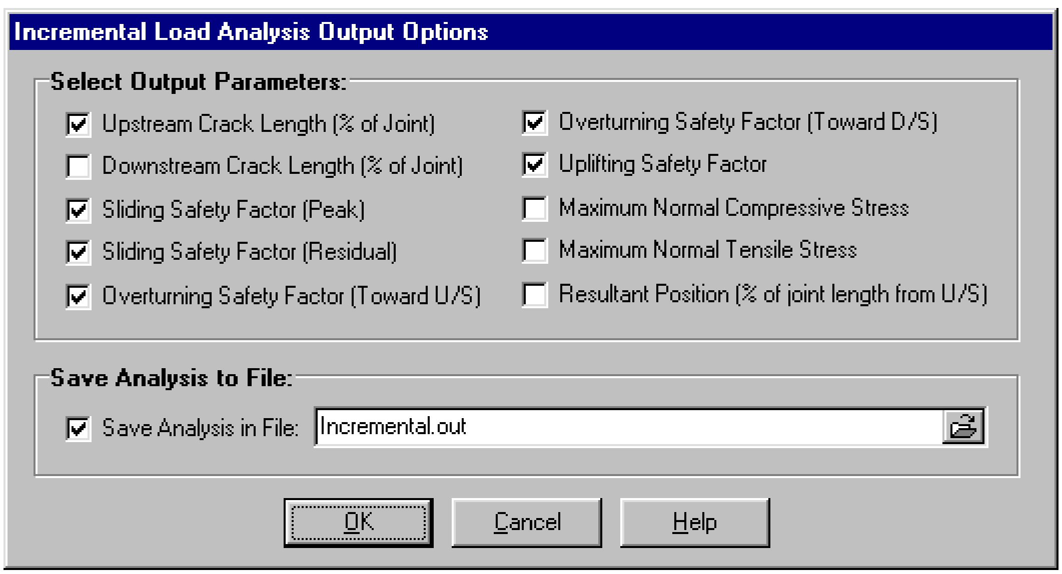
Dependent variables are related to the following independent load conditions:

1. <u>Upstream reservoir elevation</u> (operating & flood) will change:
   - *Crest overtopping vertical pressure*: The vertical load on the crest will be computed according to the pressure distribution defined by the user in the reservoir definition (see section 10.5).

- *Downstream reservoir elevation*: The elevation of the downstream reservoir will follow these rules:
    1. If the initial upstream reservoir elevation is set below the crest elevation, then the downstream elevation will be increased by the overtopping depth occurring during the incremental analysis.
    2. If the initial upstream reservoir is set above the crest elevation, then the downstream reservoir will be increase proportionally to the ratio between the initial height of the downstream reservoir and the initial height of the overtopping of the upstream reservoir.
- Uplift pressure: The uplift pressure distribution will be computed according to the incremented reservoir heights (upstream and downstream reservoirs).

2. Horizontal peak ground acceleration will change:
    - *All accelerations* (VPGA, HPSA, HSGA, VSGA and HSSA): that will be scaled proportionally to the ratio between the incremented independent horizontal peak ground acceleration and the initial horizontal peak ground acceleration specified in the initial CADAM model.

19.3 CADAM output parameters for incremental load analysis



This window is activated by the "Step 4: Output Options" button located in the previous window (Incremental Load Analysis - Input Parameters). This window allows the definition of the output parameters for an incremental load analysis. Crack lengths, safety factors, maximum normal stresses and the resultant position may be saved for every steps of the incremental analysis for plotting in CADAM or simply to be stored in a file.

PART III – STRESS AND STABILITY ANALYSES

20 STRESS AND STABILITY ANALYSES

Structural analyses of dam-foundation reservoir systems are generally performed:

- To interpret field data, explain the observed behaviour and investigate deterioration and damage mechanisms.
- To predict the structural stability and identify possible failure mechanisms under usual, unusual (ex. flood), and extreme (ex. seismic) loading scenarios.
- To assist in the development of remedial work, corrective measures, and most efficient rehabilitation methods of existing facilities.

Figure 16 emphasises that in a safety evaluation, the engineer must always relate the physical reality of the actual dam-foundation-reservoir system (Figure 18a) to the assumptions made in developing structural models to study the potential failure mechanisms (Figure 17), and to uncertainties related to those models as well as the required input parameters. Computer programs such as CADAM allows to perform parametric analyses to develop confidence intervals in which appropriate decisions could be taken regarding the safety of a particular dam and the need for remedial actions to increase safety, if necessary. The routine application of dam safety guidelines (ex. suggested material strength parameters) without questioning and taking actions (ex: visit to the site) to confirm the validity of the specified loading conditions, material parameters, and methods of analysis is dangerous.

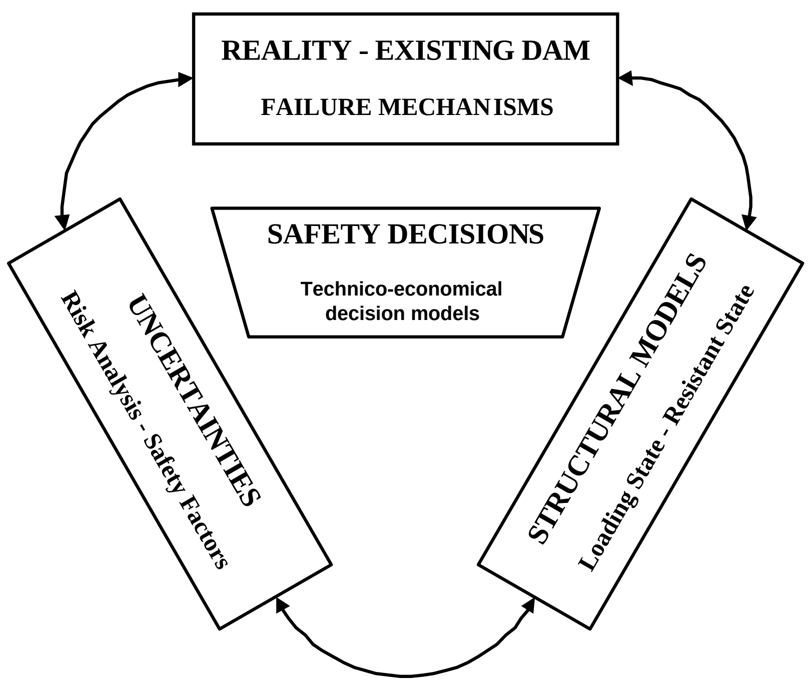


Figure 16 Structural safety evaluation of existing dams.

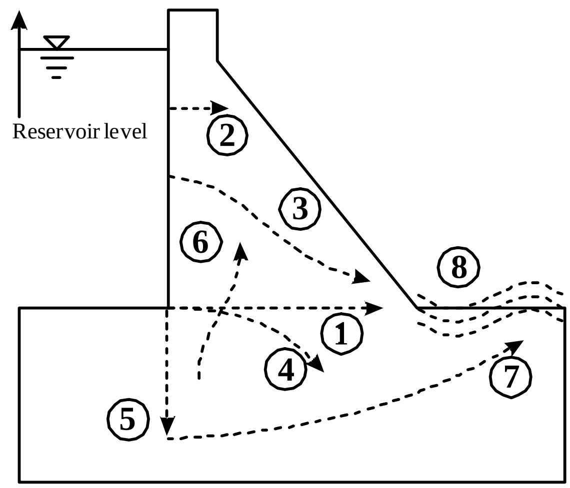


Figure 17 Failure mechanisms of gravity dams (1,2 horizontal cracks, 3,4 curvilinear cracks, 5 vertical foundation crack, 6 extension of existing foundation discontinuity in dam body, 7 sliding in foundation, 8 buckling failure of thin bedded strata).

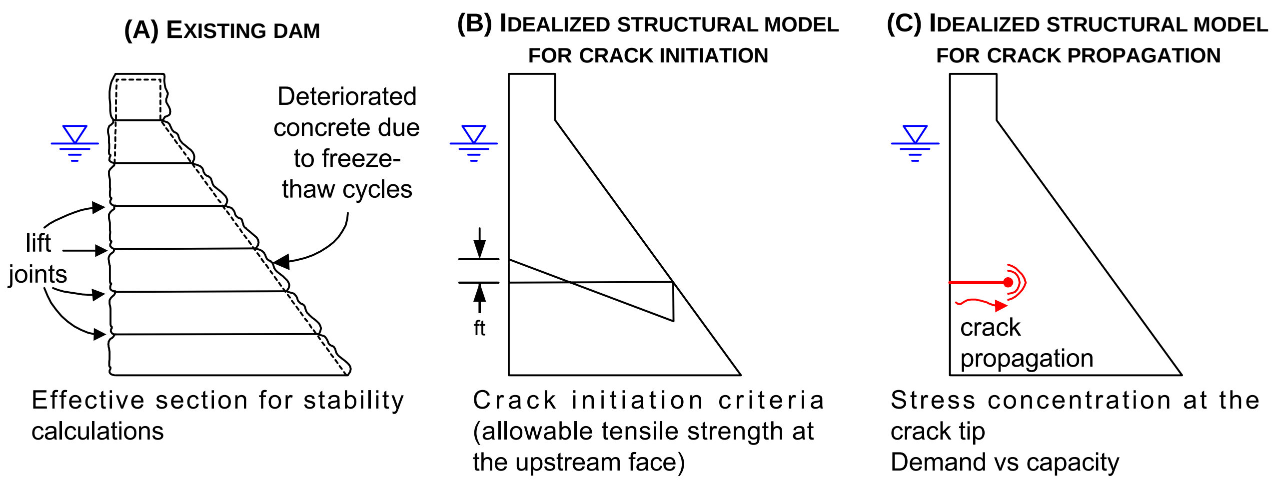


Figure 18 Existing dam vs. idealized structural models

20.1 Performing the Structural Analysis

To begin the structural analysis, it is required to select the Start Analysis Option. The first step performed by CADAM is to process the geometry data to compute joint lengths and tributary areas (volumes). Then all the loads acting on the structure are computed. For each load combination, the normal force resultant, the net driving shear (tangential) force resultant, and the overturning moments are computed about the centre line of the uncracked joint ligament. Using these forces resultants:

(a) The stress analysis is first performed to compute the potential crack length and compressive stresses along each joint;

(b) The sliding stability is performed along each joint considering the specified shear strength joint properties;

(c) The overturning stability is performed by computing the position of the resultant of all forces along each joint;

(d) Additional performance indicators such as the floating (uplifting) safety factor are computed.

This chapter presents a brief review of the key computational procedures used in CADAM. Appendix C, presenting flowcharts related to structural safety evaluation of concrete dams, should be consulted in complement to this chapter. References to detailed closed form formulas available from the dam engineering literature are also given.

A special attention has been given to the presentation of CADAM output results, such that intermediate calculations are displayed. The user should then be able to validate by hand calculations all computed results.

20.2 Stress Analysis and Crack Length Computations

As indicated in section 2.3 CADAM is based on the gravity method using beam theory to compute normal stresses to the crack plane (Figure 19a). Shear stresses are computed assuming a parabolic distribution for the uncracked section (USBR 1976). For a cracked section (Figure 19b), the shear stress distribution on the uncracked ligament is affected by the stress concentration near the crack tip and will be modified to a more or less triangular shape (Lombardi 1988). Shear stresses for crack plane are not computed by CADAM. Sliding stability is performed using shear force resultant acting on the ligament. However, to validate the assumption of a horizontal crack plane, the magnitude and orientation of principal stresses should be studied on the ligament. For that purpose simplified calculations could be made based on an assumed shear stress distribution.

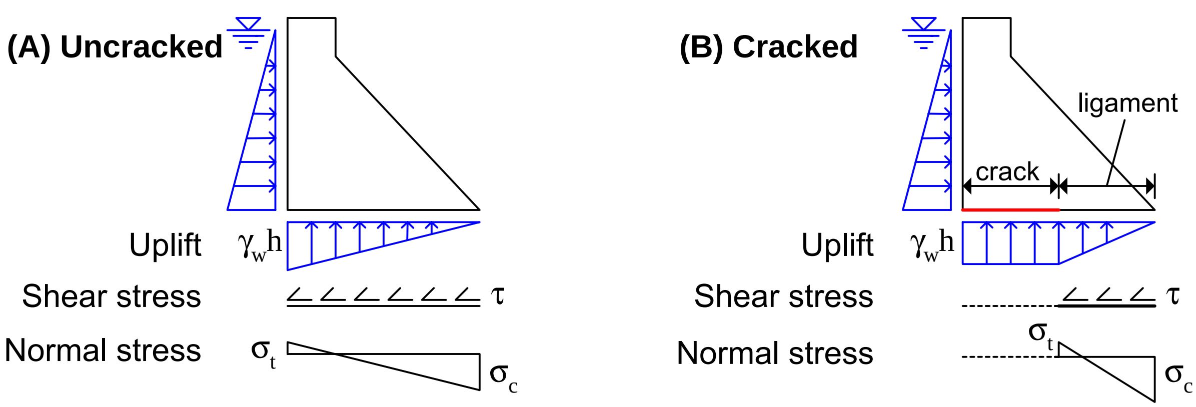


Figure 19 Effect of cracking on uplift pressures and stress distribution.

In several instances, as a crack propagates along a lift joint in contact with the reservoir, water under pressure penetrates in the crack and produce "uplift" pressures. Figure 19b shows an example of the build-up of full uplift pressure in a crack. It is obvious that the crack length computation is coupled with the uplift build-up in the crack.

Closed form formulas for crack length computations: Closed form formulas have been developed to compute crack length for simple undrained cases considering a no-tension material for a horizontal crack plane (Corns et al. 1988a, USBR 1987, FERC 1991) and even for some more complicated cases considering drainage, and tensile strength within the assumption of beam theory (ANCOLD 1991, Lo et al. 1990 with linear distribution of normal stresses). However, to consider a range of complex cases such as inclined joints with various drainage conditions, it is more efficient to compute the crack length from an iterative procedure (USBR 1987).

Iterative Procedure for Crack Length Calculation: CADAM uses the iterative procedure summarised in Figure 20 to compute the crack length. Once the crack initiation criterion indicates the formation of a crack, the iterative calculation begins. The crack length is increased incrementally and the uplift pressures are updated according to the selected drainage options until the crack propagation criterion indicates crack arrest. As indicated in section 10.1 two different crack criteria (initiation and propagation) are supported by CADAM.

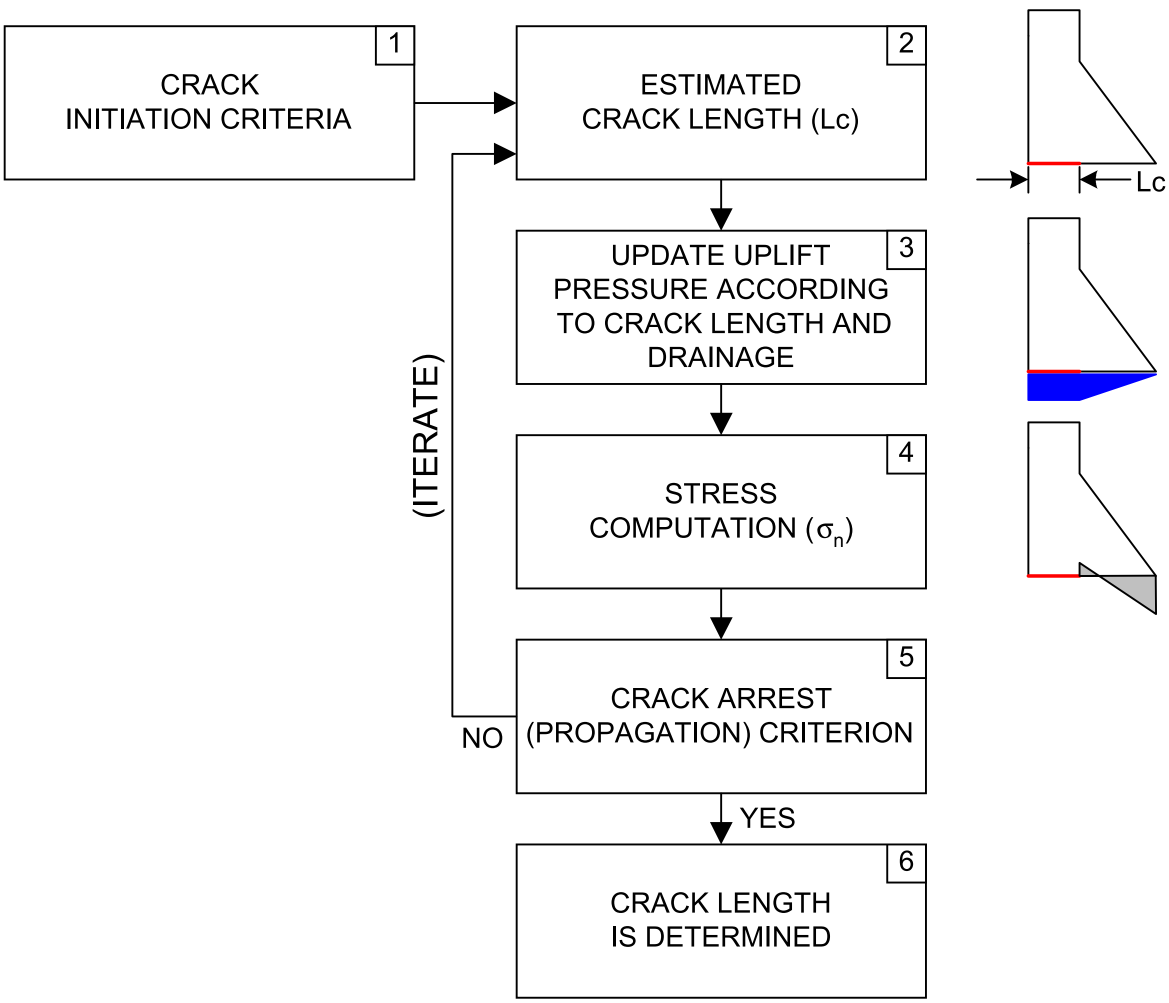


Figure 20 **Iterative procedure for crack length computations.**

The uplift pressures could be considered as external forces and the stress at the crack tip, σ_n, is computed while including uplift pressures in the force resultant (USACE 1995, USBR 1987 (crack propagation iterative procedure)). This calculation produces a linear normal stress distribution even in the case where a nonlinear uplift pressure distribution is present along the base due to drainage.

$$\sigma_n = \frac{\Sigma V}{A} \pm \frac{\Sigma M\, c}{I}$$

ΣV = Sum of all vertical load **including** uplift pressures
A = Area of uncracked ligament
ΣM = Moment about the center of gravity of the uncracked ligament of all loads **including** uplift pressures
I = Moment of inertia of the uncracked ligament
c = distance from center gravity of the uncracked ligament to the location where the stresses are computed

Alternatively, the stress at the crack tip is computed from total stresses without uplift pressure. The uplift pressure is then subtracted from total stress to obtain total effective, σ_n, to be used in the crack initiation criterion (USBR 1987) or in the crack initiation and propagation (FERC 1991)

$$\sigma_n = \frac{\Sigma \overline{V}}{A} \pm \frac{\Sigma \overline{M}\, c}{I} + u$$

$\Sigma \overline{V}$ = Sum of all vertical load **excluding** uplift pressures
A = Area of uncracked ligament
$\Sigma \overline{M}$ = Moment about the center of gravity of the uncracked ligament of all loads **excluding** uplift pressures
I = Moment of inertia of the uncracked ligament
c = distance from center gravity of the uncracked ligament to the location where the stresses are computed
u = uplift pressure at the location considered

Zienckiewicz (1958, 1963) studied the effect of pore pressures on stress distribution in porous elastic solid such as concrete dams considering the need to satisfy both (a) the stress condition for equilibrium, and (b) strain compatibility, in an elementary volume. It was indicated that a nonlinear pore pressure distribution would in itself generate internal stresses within the porous elastic body considered with a marked tendency for the effective stresses to be linear.

<u>Crack initiation (propagation) from u/s and d/s faces</u>

While performing static or seismic stress analysis, cracks could be initiated and propagated either from the u/s or the d/s face.

Consideration of Inclined Joints

Figure 21 shows the uplift pressure distribution along a cracked inclined joint. In this case the uplift pressure is applied in the normal direction to the cracked plane to perform the stress and stability analyses using geometric properties (area, inertia) computed in the local coordinate system along the inclined joint.

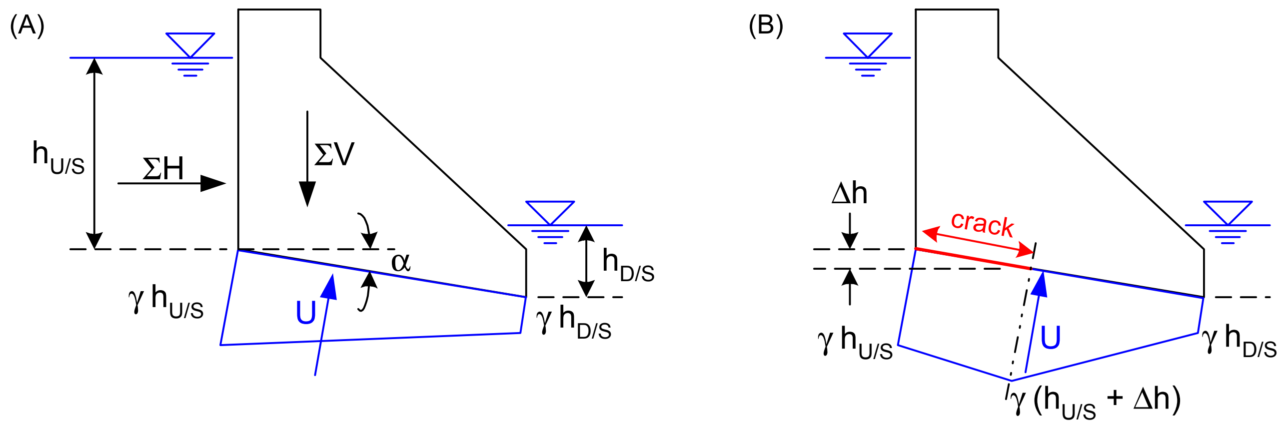


Figure 21 Dam with sloped joint (a): uncracked; (b) cracked.

20.3 Sliding Stability Analysis

Basic formula for horizontal sliding plane (static loads)

The basic shear-friction sliding safety factor (SSF) formula along a horizontal plane is given as:

$$SSF = \frac{(\sum \overline{V} + U)\tan\phi + c\,A_C}{\sum H}$$

$\sum \overline{V}$ = Sum of vertical forces excluding uplift pressure
U = Uplift pressure force resultant
ϕ = friction angle (peak value or residual value)
c = cohesion (apparent or real, for apparent cohesion a minimal value of compressive stress, σ_n, to determine the compressed area upon which cohesion could be mobilised could be specified - see section 7.1)
A_C = Area in compression
$\sum H$ = Sum of horizontal forces

Basic formula for horizontal sliding plane (seismic loads, vertical u/s face)

In seismic analysis, the sliding safety factor (SSF) is computed from:

$$SSF = \frac{(\sum \overline{V} + U + Q_V)\tan\phi + c\,A_C}{\sum H + \sum H_d + Q_h}$$

$\sum \overline{V}$ = Sum of vertical static forces excluding uplift pressure
Q_V = Vertical concrete inertia forces
U = Uplift pressure force resultant
$\sum H_d$ = Sum of horizontal concrete inertia forces
Q_h = Horizontal hydrodynamic forces
ϕ = Friction angle (peak value or residual value)
c = cohesion (apparent or real)
A_C = Area in compression
$\sum H$ = Sum of horizontal static forces

CADAM performs sliding safety factor calculations considering both the peak shear strength and the residual shear strength of the joints (CDA 1999).

<u>Effect of Post-tension Forces (ex. static load, horizontal sliding plane)</u>

Post-tensioned anchors are often used to increase the normal compressive stresses along lift joints to control tensile cracking and increase the sliding resistance of the joints (section 11).

Post-tension forces as <u>active</u> load: In most instances post-tension forces have been considered as active loads; that is the horizontal component of the post-tension force, P_{dh}, being placed in the denominator of the sliding safety factor formula. In this case P_{dh} is algebraically added to the other horizontal forces acting externally on the structure (ex. hydrostatic thrust):

$$SSF = \frac{\left(\sum \overline{V} + U + P_V\right)\tan\phi + c\ A_C}{\sum H + P_{dh}}$$

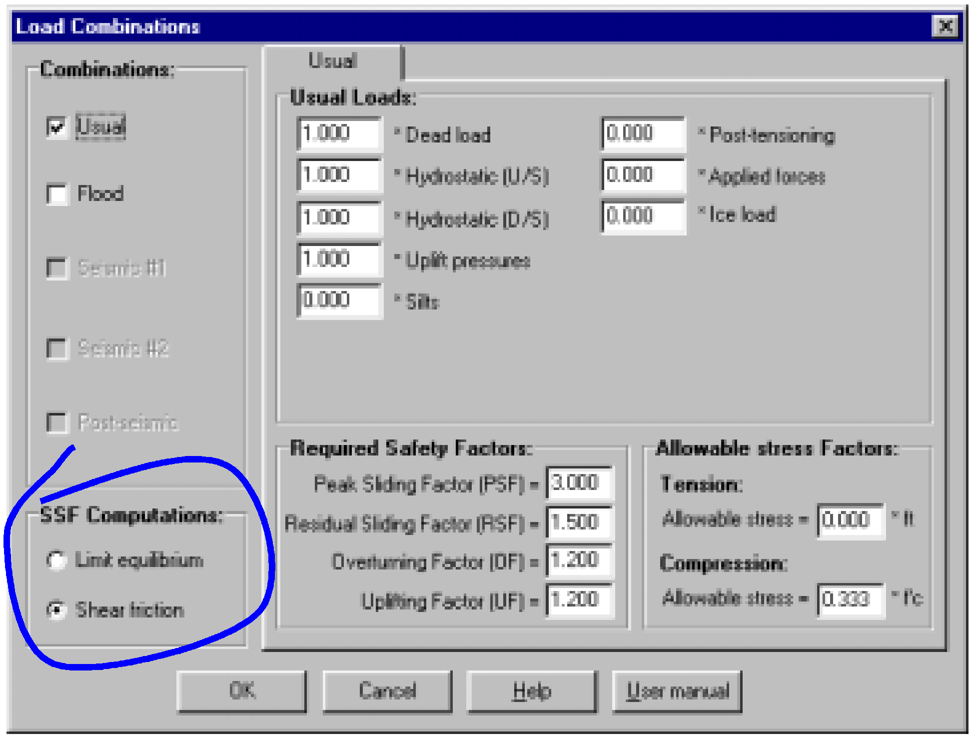
$\sum \overline{V}$ = Sum of vertical forces excluding uplift pressure
U = Uplift pressure resultant
ϕ = Friction angle (peak value or residual value)
c = Cohesion (apparent or real)
A_c = Area in compression
$\sum H$ = Sum of horizontal forces
P_v = Vertical component of anchor force (P_c, P_{dV} section 11)
P_{dh} = Horizontal component of horizontal force

Post-tension forces as <u>passive</u> loads: In this case, P_{dh} is placed in the numerator of the shear-friction sliding safety factor formula. In this approach P_{dh} is added directly to the sliding resistance provided by the vertical force component of the anchor. This approach is more conservative that the consideration of P_{dh} as an active force (see Corns et al. 1988b (p.593) for a more comprehensive discussion).

$$SSF = \frac{\left(\sum \overline{V} + U + P_V\right)\tan\phi + c\ A_C + P_{dh}}{\sum H}$$

Inclined Joints (ex. static loads)

The sliding safety factors for inclined joints could be computed either from the limit equilibrium method or the shear-friction method (see Corns et al. 1988 pp. 481-483 for more details) by activating the proper option in CADAM (see figure below).



Inclined Joints (ex. static loads) Sliding Safety Factors computed from the shear friction method:

In the shear friction method, the sliding safety factor is computed as the ratio of the maximum horizontal driving force that can be resisted (sliding resistance), R, and the summation of horizontal driving forces, ΣH.

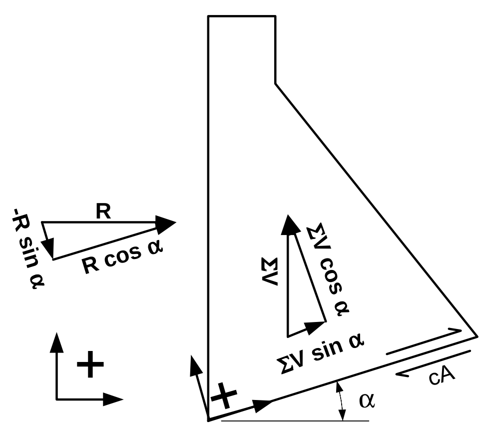
$$SSF = \frac{R}{\Sigma H}$$

ΣV include vertical uplift pressure. Taking the sum of tangential forces to the inclined plane equal to zero:

$$R\cos\alpha + \Sigma V\sin\alpha + (\Sigma V\cos\alpha - R\sin\alpha)\tan\phi - cA = 0$$

and solving for R:

$$R = -\Sigma V\tan(\phi+\alpha) + \frac{cA}{\cos\alpha(1-\tan\phi\tan\alpha)}$$



Inclined Joints (ex. static loads) Sliding Safety Factors computed from the limit equilibrium method:

When the lift joint considered is inclined, force resultants have to be computed in the normal and tangential directions to the joint to evaluate the sliding safety factor:

$$SSF = \frac{\left|\left(\sum \overline{V}\cos(\alpha) - \sum H\sin(\alpha) + U\right)\right|\tan\phi + c\,A_C}{\left|\sum H\cos(\alpha) + \sum V\sin(\alpha)\right|}$$

$\left(\sum \overline{V}\cos(\alpha) - \sum H\sin(\alpha)\right)$ = Sum of normal forces to the sliding plane

$\left(\sum \overline{V}\sin(\alpha) + \sum H\cos(\alpha)\right)$ = Sum of tangential forces to the sliding plane

U = Uplift force resultant normal to the inclined joint;

α = Angle with respect to the horizontal of the sliding plane.

Passive Wedge Resistance

CADAM allows the consideration of the passive resistance of a rock wedge located at the toe of the dam while computing the sliding safety factor (Corns et al. 1988, Underwood 1976 (Figure 22)). When a passive rock wedge resistance is considered, the SSF should be computed using the shear friction method.

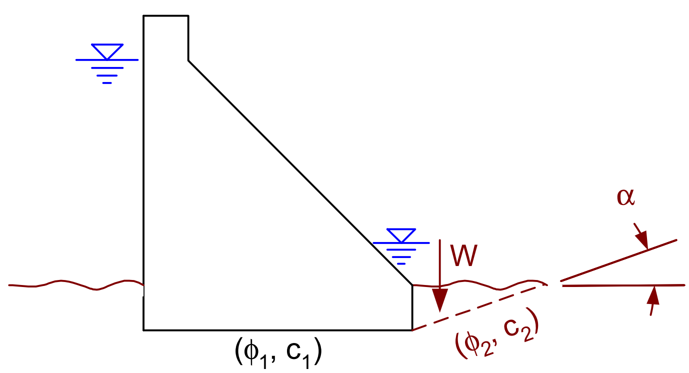


Figure 22 Passive wedge resistance.

$$SSF = \frac{\left(\sum \overline{V} + U\right)\tan\phi_1 + c_1\,A_{C1} + \left[\dfrac{c_2\,A_2}{\cos\alpha\,(1-\tan\phi_2\,\tan\alpha)} + W\tan(\alpha+\phi_2)\right]}{\sum H}$$

W = Saturated weight of the rock wedge;

A_2 = Area along the rock wedge failure plane.

Underwood (1976) pointed out that the peak strengths from the passive wedge and the weak joint may not be additive since the deformation rates are often unequal. Note that for illustrative purposes, the SSF equation is computed here for a horizontal joint.

20.4 Overturning Stability Analysis

Crack length and compressive stresses: The overturning stability could be verified by limiting the crack length such that the allowable compressive stress is not exceeded.

Location of force resultant

The location of the force resultant along the joint is the other performance indicator that is used to assess the overturning stability of the section above the crack plane considered. The location of the resultant with respect to the upstream end of the joint is computed from:

$$L_{FR} = \frac{\sum M_{U/S}}{\sum V}$$

$\Sigma M_{U/S}$ =Summation of moments about the upstream end of the joint,
ΣV = Summation of vertical forces including uplift pressures.

In the CADAM output, L_{FR} is expressed in a percentage of the total length of the joint from the upstream end. When the force resultant is located within the middle third of the section analysed, there is no tensile stresses. For well-proportioned gravity dams the overturning is unlikely. A sliding failure mechanism at the downstream toe will rather have a tendency to occur after a significant uplifting of the upstream heel.

Overturning safety factor: As an additional indicator of overturning stability, the overturning safety factor (OSF) is computed as:

$$OSF = \frac{\sum M_S}{\sum M_O}$$

ΣM_S = Sum of stabilising moment about the downstream or the upstream end of the joint considered,
ΣM_O = Sum of destabilising (overturning) moments.

20.5 Uplifting (Floating) Stability Analysis

In the case of significant immersion, the dam must resist to the vertical thrust coming from the water pressure that tend to uplift it. The safety factor against this "floating" failure mechanism is computed as:

$$USF = \frac{\sum \overline{V}}{U}$$

$\sum \overline{V}$ = Sum of vertical loads excluding uplift pressures (but including the weight of water above the submerged components),
U = Uplift forces due to uplift pressures.

20.6 Safety Evaluation for Static Loads

Load Conditions, Combinations and Safety Evaluation Format

By proper definition of basic loading condition parameters and multiplication factors to form load combinations, a variety of loading scenarios could be defined to assess the safety of the dam-foundation-reservoir system:

Silt pressure: For static load conditions, the horizontal static thrust of the submerged silt deposited along the u/s face of the dam is computed from Figure 23:

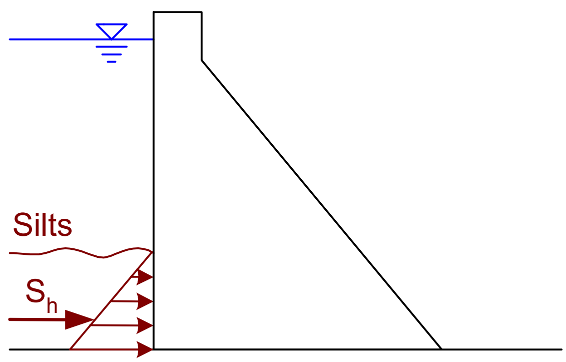


Figure 23 Triangular silt pressure distribution

$$Sh = \tfrac{1}{2} K \gamma'_S h_{silt}^2$$

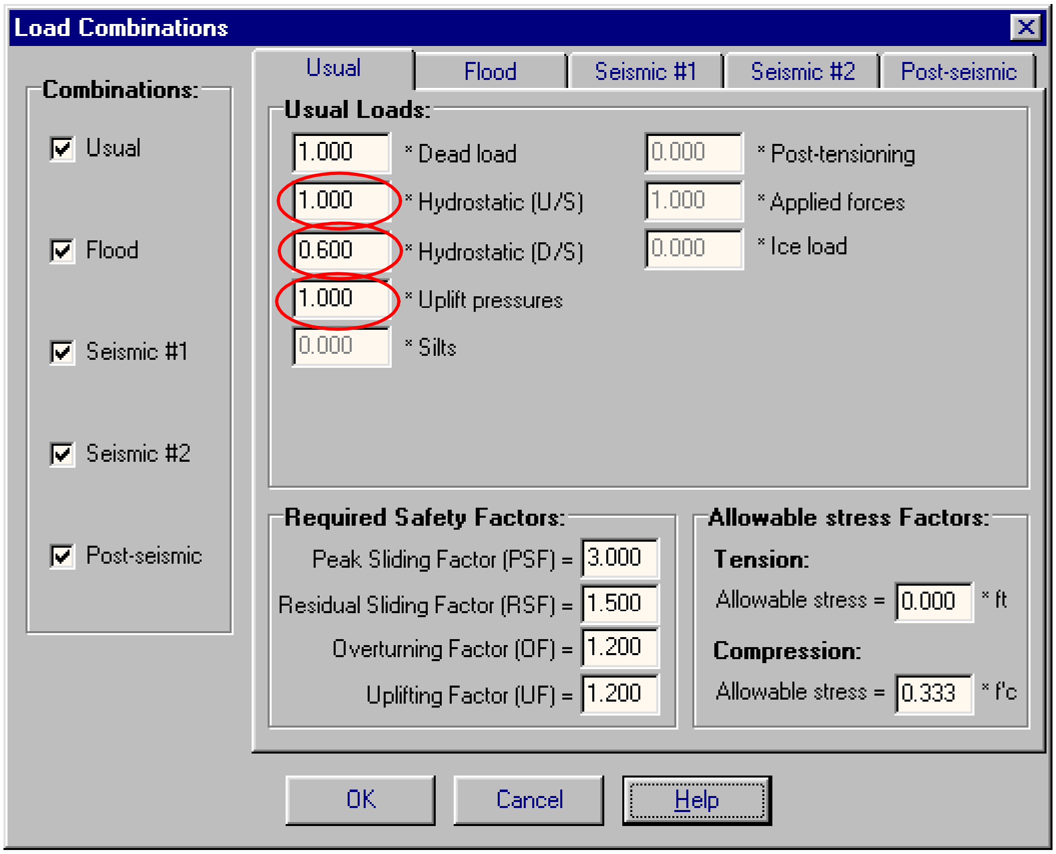
K = Earth pressure coefficient	Fluid	$K = 1.0$
	At rest	$K = 1 - \sin(\phi)$
	Active	$K = (1 - \sin(\phi))/(1 + \sin(\phi))$
	Passive	$K = (1 + \sin(\phi))/(1 - \sin(\phi))$

γ'_s = submerged unit weight of silt ($\gamma'_s = \gamma_{saturated\ silt} - \gamma_{water}$)
h_{silt} = depth of silt
ϕ = internal friction angle

Along a sloped face, a vertical silt force component is also computed from the submerged weight of the silt acting above the inclined surface. Since the reservoir hydrostatic pressure is applied down to the base of the dam, it is appropriate to consider only the added pressure due to silt by using its submerged unit weight.

Tailwater condition: USACE (1995) mentions that the effective tailwater depth used to calculate pressures and forces acting on the d/s face of an overflow section may be reduced to 60% of the full water depth due to fluctuations in the stilling basin (hydraulic jump). However, the full tailwater depth is to be used to calculate the uplift pressure at the toe of the dam regardless of the overflow conditions. Further discussion of water pressure acting on overflow sections have been presented by Brand (1999) and Léger et al. (2000).

To model an effective tailwater depth of 60% of the full depth CADAM Load Combinations window allow to specify different multiplication factors hydrostatic (u/s), hydrostatic (d/s) and uplift pressures as follows



In this case the tailwater uplift pressure is computed using the full tailwater depth while the 0.6 factor applies to the tailwater hydrostatic pressures (and water weight on the d/s face).

<u>Increasing applied load to induce failure:</u> Different strategies have been adopted to study the safety margin of concrete dams as a function of the uncertainties in the applied loading and material strength parameters (see Appendix C for a detailed flowchart). In some cases, the applied loads are increased to induce failure (ex. u/s, d/s water levels are increased, ice loads, water density etc). The safety margin is then assessed by comparing the magnitude of the load inducing failure with that of the applied load for the combination under study. CADAM can be used effectively to perform this type of study using a series of analyses while increasing the applied loads either through the basic loading input parameters or by applying appropriate load condition multiplication factors while forming the load combinations or by activating the incremental load analysis option.

<u>Reducing material strength to induce failure:</u> In a different approach, the specified strength of material are reduced while inputting basic data (friction coefficient (tan ϕ), cohesion, tensile strength, etc…). Series of analyses are then performed until a safety factor of 1 is reached for

particular failure mechanisms. Comparing the material strength inducing failure to the expected material strength could then assess the safety margin.

Limit analysis (ANCOLD 1991): The Australian National Committee on Large Dams (1991) presented a dam safety evaluation format based on a limit state approach. Various magnification and reduction factors are applied to basic load conditions and material strength parameters to reflect related uncertainties. By adjusting the input material parameters, and applying the specified load multiplication factors, CADAM could be used to perform limit analysis of gravity dams as described by ANCOLD (1991).

20.7 Safety Evaluation for Seismic Loads

Concrete Inertia Forces in Pseudo-Static Analysis: The horizontal and vertical concrete inertia forces are computed as the product of the concrete mass by the applied base accelerations in the horizontal and vertical directions, respectively (peak ground acceleration or sustained acceleration).

Hydrodynamic Pressures This section presents a brief summary of the formulation implemented in CADAM to model hydrodynamic pressures for seismic analysis using the pseudo-static method (see section 13).

Westergaard Added Masses – Vertical u/s face

For an assumed rigid gravity dam with vertical u/s face, the added horizontal hydrodynamic force Hd(y) increases following a parabolic distribution according to the following equation:

$$H_d(y) = \tfrac{2}{3}\, K_\theta\, C_e\, (acc)\sqrt{h}\,\left(y^{1.5}\right)$$

- $H_d(y)$= Additional total hydrodynamic horizontal force acting above the depth y for a unit width of the dam;
- K_θ = Correction factor for the sloping dam faces with angle θ from the vertical. To compute the horizontal force $K_{\theta H} = \cos^2\theta$ can be used as a first approximation, while the vertical force can be estimated from $K_{\theta V} = \sin\theta\cos\theta$; Alternatively, USBR (1987) present a detailed formulation for $K_{\theta H}$ (see also Figure 24 adapted from Corns et al. 1988);
- C_e = Factor depending principally on depth of water and the earthquake vibration period characterising the frequency content of the applied ground motion;
- acc = Horizontal seismic acceleration coefficient applied at the base of the dam expressed in term of peak ground acceleration or spectral acceleration (fraction of g);
- h = Total depth of the reservoir;
- y = Distance below reservoir surface.

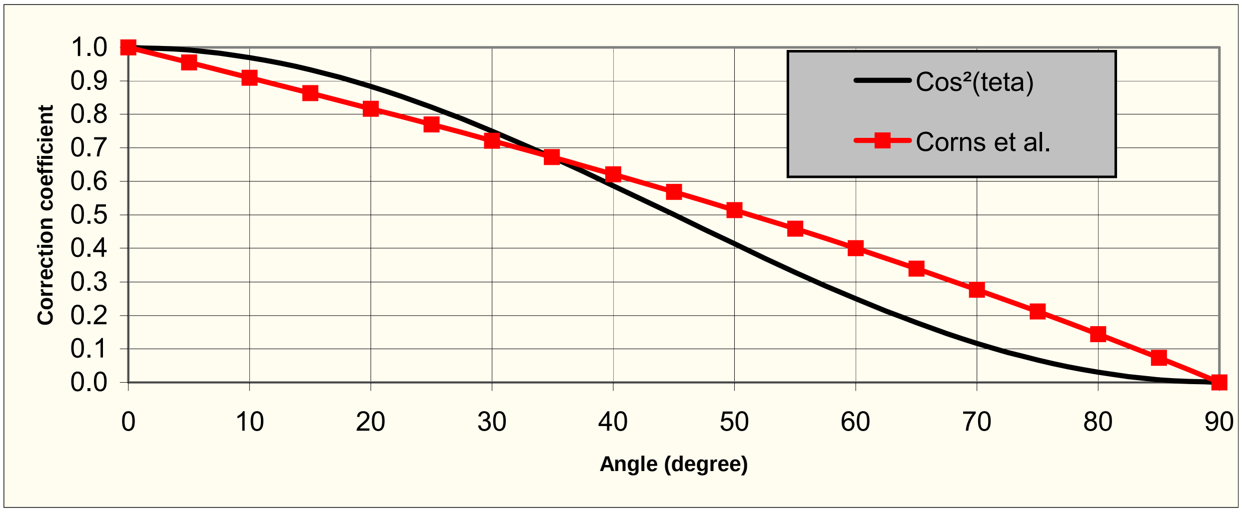


Figure 24 Correction factor (K_θ) adapted from Corn et al. (1988)

USBR (1987) considers the following for inclined faces (Figure 25):

"For dams with a combination vertical and sloping face, the procedure to be used is governed by the relation of the height of the vertical portion to the total height of the dam as follows:

- *If the height of the vertical portion of the upstream face of the dam is equal or greater than one-half of the total height of the dam, analyse as if a vertical throughout.*
- *If the height of the vertical portion of the upstream face of the dam is less than one-half of the total height of the dam, use the pressures on the sloping line connecting to the point of intersection of the upstream face of the dam and reservoir surface with the point of intersection of the upstream face of the dam and the foundation."*

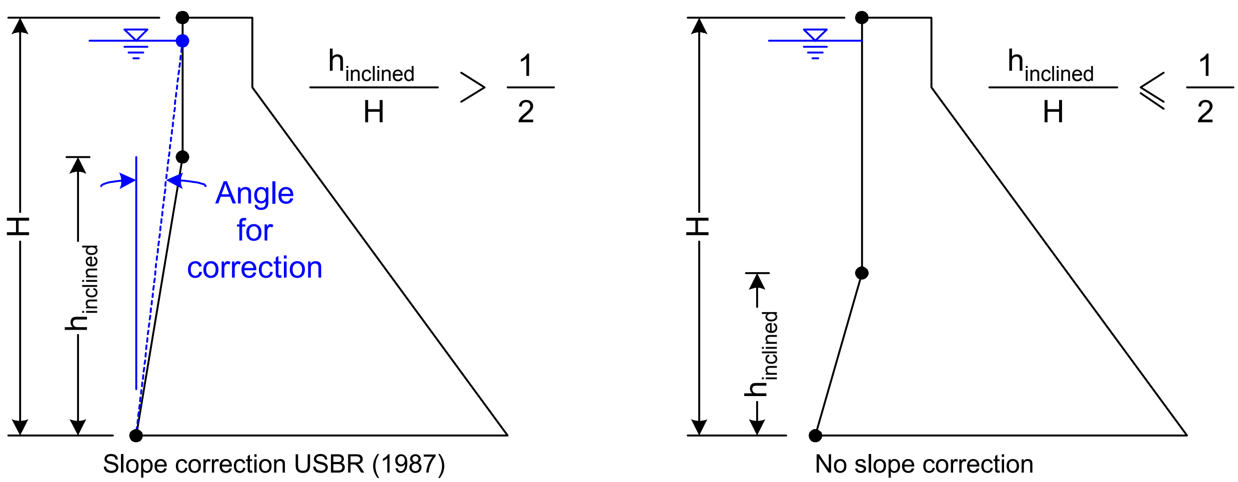


Figure 25 USBR (1987) slope correction for an inclined upstream face

CADAM applies USBR (1987) slope correction method to upstream reservoirs as well as downstream reservoirs in the calculation of added hydrodynamic forces.

The Westergaard approximation for the C_e coefficient is:

Metric: $$C_e = \left(\frac{0.543}{0.583}\right)\left(\frac{7}{8}\right)\left(9.81\frac{kN}{m^3}\right)C_c = 7.99C_c \quad \text{where}: \; C_c = \frac{1}{\sqrt{1-7.75\left(\frac{h}{1000t_e}\right)^2}} \quad \text{(kN·sec·m)}$$

Imperial: $$C_e = \left(\frac{0.543}{0.583}\right)\left(\frac{7}{8}\right)\left(0.0624\frac{kip}{ft^3}\right)C_c = 0.051C_c \quad \text{where}: \; C_c = \frac{1}{\sqrt{1-0.72\left(\frac{h}{1000t_e}\right)^2}} \quad \text{(kip·sec·ft)}$$

t_e = Period to characterise the seismic acceleration imposed to the dam (sec);
h = Total depth of the reservoir.

In the previous equations, the coefficient C_c is a correction factor to account for water compressibility.

Figure 26 shows the influence of the reservoir bottom elevation on the static and dynamic pressure distributions.

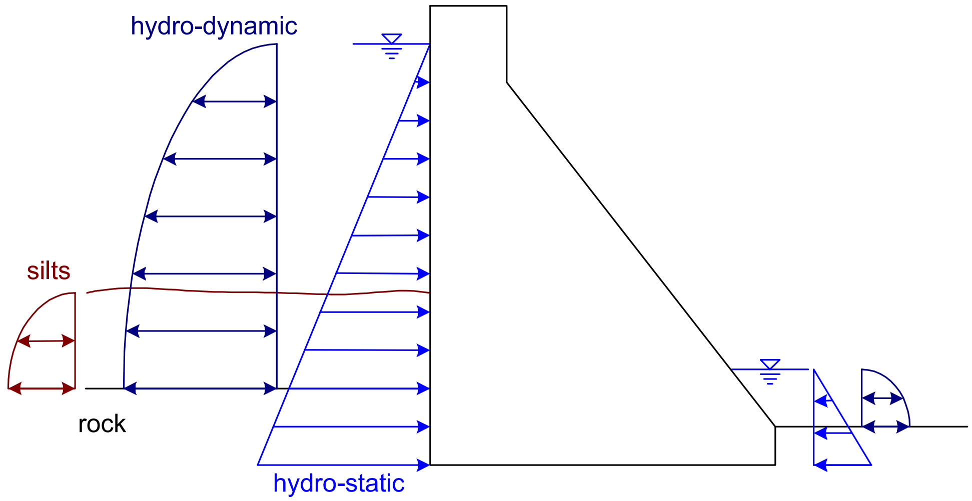


Figure 26 Influence of reservoir bottom elevation on dynamic and static pressure distributions

The point of application of the hydrodynamic force is at 0.4 y above the base of the parabola considered. For verification purposes CADAM outputs the total added hydrodynamic forces acting at the u/s (d/s) face of the dam.

Generalised Westergaard Formulation – sloped u/s face

The basic Westergaard added mass formulation for a vertical u/s face assumes earthquake acceleration normal to the dam face. However, several concrete dams are built while varying the normal orientation to the u/s face. Examples are gravity dams with sloped u/s faces or arch dams with doubly curved u/s face. The Westergaard added mass formulation has been extended to compute hydrodynamic forces of concrete dams for which the orientation of the u/s face relative to the ground motions varies from point to point (Clough 1985). The pressure, P_{ni}, acting at any point "i" on the u/s face is expressed as (Figure 27):

$$P_{ni} = \tfrac{7}{8}\,\rho_w\, H \sqrt{1-\frac{y_i}{H_i}}\;\ddot{r}_{ni} = \hat{P}_{ni}\,\ddot{r}_{ni}$$

H_i = Water depth at the vertical section containing point "i";
H = Total depth of reservoir;
y_i = Height of the point "i" in this section;
r_{ni} = Normal acceleration component at point "i".

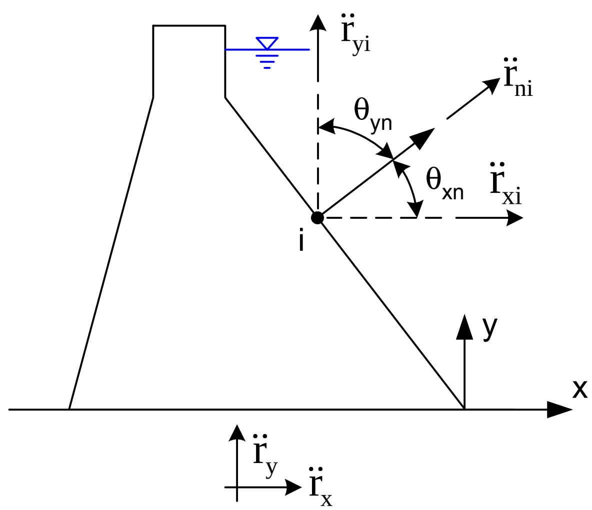


Figure 27 Generalised Westergaard formulation

In a compact notation $\hat{P}_{ni}$ represents the pressure per unit normal acceleration. In 2D the normal acceleration to the u/s face is derived from the direction cosines between the Cartesian coordinates and the normal (Figure 27).

$$\ddot{r}_{ni} = \begin{bmatrix}\cos\theta_{xn} & \cos\theta_{yn}\end{bmatrix} \begin{bmatrix}\ddot{r}_{xi} \\ \ddot{r}_{yi}\end{bmatrix}$$

Or

$$\ddot{r}_{ni} = [L_{ni}]\;[\ddot{r}_i]$$

The normal pressure function, P_{ni}, is converted to a corresponding normal force function, F_{ni}, by multiplying by the surface area, Ai, tributary to point "i"

$$F_{ni} = P_{ni}\ A_i = \hat{P}_{ni}\ \ddot{r}_{ni}\ A_i = \hat{P}_{ni}\ [L_{ni}][\ddot{r}_i]A_i$$

Finally, the normal force F_{ni} is resolved into Cartesian coordinates to compute the horizontal and vertical force resultant acting on the u/s face.

$$F_{xi} = F_{ni}\ \cos\theta_{xn}$$
$$F_{yi} = F_{ni}\ \cos\theta_{yn} = F_{ni}\ \sin\theta_{xn}$$

There is no rational basis for assuming that Westergaard parabolic pressure distribution for rigid dam with a vertical u/s face will apply to dams with u/s face of arbitrary geometry. However, the above formulation has been found to be fairly accurate when there are no significant lateral variations of hydrodynamic pressures across the u/s face.

Westergaard formulation d/s face

When a tailwater depth is specified, horizontal hydrodynamic pressure acting on the d/s face is computed from the Westergaard formulation with a correction for the slope of the d/s face.

Dynamic Silt pressures

Different approaches based on soil dynamics could be used to evaluate the hydrodynamic thrust developed by the silt. As a first approximation CADAM uses a two layer fluid model along the u/s face. It is thus assumed that there is liquefaction of the silt during the earthquake. The silt is considered as a liquid with a density larger that water. The Westergaard formulation is then used to compute the added mass (FERC 1991). The use of Westergaard solution for the silt is an approximation to more rigorous solutions considering the two layer fluid model, as those presented by Chen and Hung (1993).

In that context, the active earth pressure for the static thrust component is questionable. If the assumption of a two layer fluid model is retained, it would be appropriate to use K =1 (silt=fluid) for the static condition. The oscillatory motion of the u/s face is thus assumed to "liquefy" the silt layer in contact with the dam.

As for the reservoirs, the dynamic silt pressure is influenced by an inclination of the upstream face of the dam. CADAM applies the same rules for slope correction to dynamic silt pressure distribution as for reservoirs.

Vertical Acceleration of Reservoir Bottom and Hydrostatic Pressure

In addition to the vertical motion of the u/s face of the dam, some analysts consider the effect of the vertical acceleration of the reservoir bottom on the applied hydrostatic pressures (Figure 28). According to d'Alembert principle, an upward vertical acceleration of the rock is going to produce an increase in the effective volumetric weight of water ($\gamma_e = \rho_w (g + acc_V)$) for an incompressible reservoir, where ρ_w is the volumetric mass of water and g is the acceleration of gravity. The increase in the volumetric weight of water produces an increase in the initially applied hydrostatic pressures on the submerged parts of the dam. In reverse, rock acceleration directed downward produces a reduction in the effective volumetric weight of water ($\gamma_e = \rho_w (g - acc_V)$) and related initial hydrostatic pressures. These considerations are independent of the Westergaard hydrodynamic pressure computations.

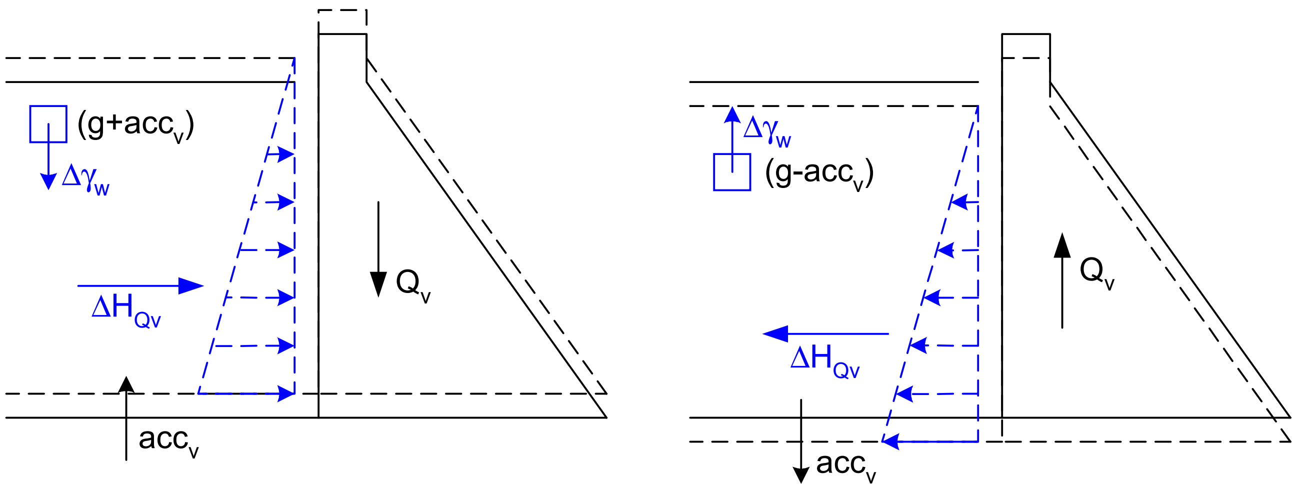
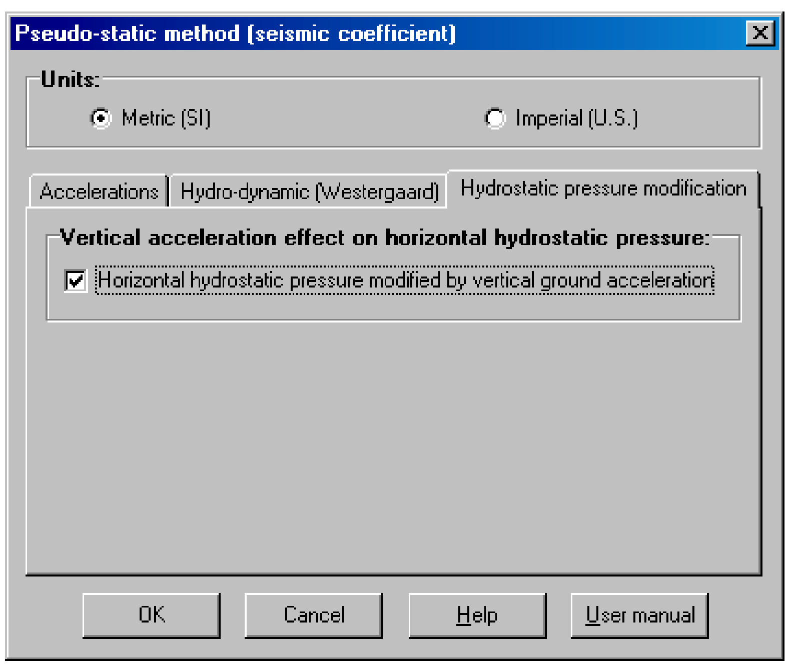


Figure 28 **Vertical acceleration of reservoir bottom and hydrostatic pressures.**

CADAM includes the effect of the vertical rigid body acceleration of the reservoir bottom on the initial hydrostatic pressures. The user can unable this option in the pseudo-static and pseudo-dynamic dialog boxes as shown in the next figure:



Uplift Pressures in Cracks During Earthquakes

Due to the lack of historical and experimental evidences, there is still a poor knowledge on the transient evolution of uplift pressures in cracks due to the cyclic movements of the crack surfaces during earthquakes.

- **ICOLD** (1986) mentions: "The assumption that pore pressure equal to the reservoir head is instantly attained in cracks is probably adequate and safe".
- **USACE** (1995) and **FERC** (1991) assume that uplift pressures are unchanged by earthquake load (i.e at the pre-earthquake intensity during the earthquake).
- **USBR** (1987) mentions: "When a crack develops during an earthquake event, uplift pressure within the crack is assumed to be zero".
- **CDSA** (1997) mentions: "In areas of low seismicity, the uplift pressure prior to the seismic event is normally assumed to be maintained during the earthquake even if cracking occurs. In areas of high seismicity, the assumption is frequently made that the uplift pressure on the crack surface is zero during the earthquake when the seismic force are tending to open the crack".

CADAM provides three options to consider the transient evolution of uplift pressures in cracks (Figure 29) during earthquakes (see section Uplift Pressures in Cracks): (a) no uplift pressures in the opened crack, (b) uplift pressures remain unchanged, (c) full uplift pressures applied to the crack section irrespective of the presence of drains.

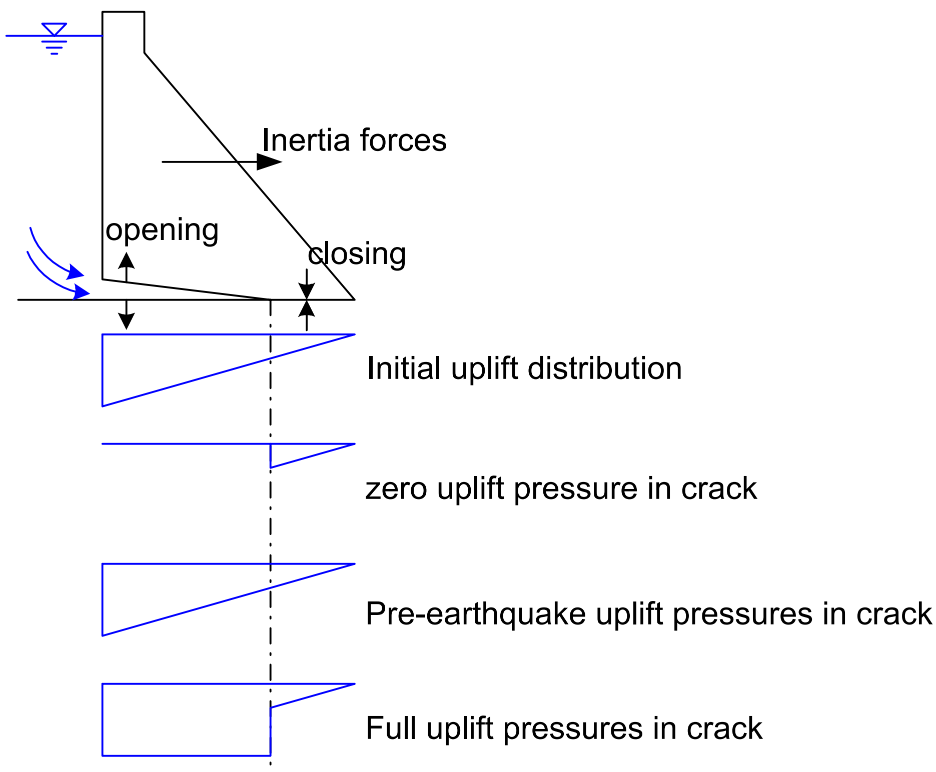


Figure 29 Transient evolutions of uplift pressures in seismically induced crack.

Pseudo-Dynamic Analysis

In pseudo-dynamic analyses, the hydrodynamic pressures acting on the u/s face are computed from an analytical formulation taking into account water compressibility as derived by Chopra and Fenves (Chopra 1988, Fenves and Chopra 1987, 1986, 1985a,b, 1984). Any slope of the u/s face is neglected in these calculations. However, the weight of water above the inclined portion is modified according to the imposed vertical accelerations at the base of the dam. The added hydrodynamic pressures acting on the d/s face are computed only in the horizontal direction using the Westergaard formulation for a sloping face.

In the vertical direction, the dam is assumed rigid. The concrete inertia forces are computed as the product of the vertical base acceleration and the concrete mass. The incidence of the vertical acceleration of the reservoir bottom on the initial hydrostatic pressure could be included using a similar approach to that used in the pseudo-static method.

Crack length computation

In a pseudo-dynamic analysis, the moment and axial force acting on the lift joint considered are computed from the selected modal combination rule. The resulting moment and axial force are then used to compute the related stresses and crack length. This approach is generally conservative. In linear (uncracked) analysis, it is more appropriate to compute stresses separately for the first mode and the higher modes and then apply the modal combination rule to stresses. However, this approach, adopted in linear analysis, is not suitable to estimate crack length in a consistent manner with pseudo-static calculations, especially if uplift pressures are to be varied within the seismic crack (ex. No uplift pressure in an opened crack).

Moreover, it is assumed that the period of vibration of the dam is unaffected by cracking which is obviously an approximation that might be overcome only if transient nonlinear dynamic analysis are considered.

Seismic cracking from u/s and d/s faces

CADAM allows cracking to initiate either from the u/s face or the d/s face depending upon the orientation of the base acceleration and related inertia forces. Separate analyses could be performed successively with the base acceleration pointing u/s and d/s to estimate the cumulative damage reducing the cohesion that could be mobilised along the joint considered.

20.8 Safety Evaluation for Post-Seismic Conditions

Effect of Seismically Induced Cracks on Sliding Safety

The cohesion (real or apparent) is considered null along the seismically induced crack length to compute the sliding safety factors in post-seismic condition.

Uplift Pressure in Seismically Induced Cracks for Post-Seismic Analysis

- CDSA (1997) mentions: "disruption of the dam and/or the foundation condition due to an earthquake should be recognised in assessing the internal water pressure and uplift assumptions for the post-earthquake case".
- According to CDSA (1997) a conservative assumption for post-seismic uplift pressures would be to use the full reservoir pressure in earthquake-induced cracks in the post-seismic safety assessment. However, as an alternative, the post-seismic load case could be defined from the calculation of the crack mouth opening width, crack length and drainage conditions to delineate uplift pressures.
- According to FERC (1991), the uplift pressures to be used for the post-seismic condition are the same that were acting prior to the earthquake. That is the pre-earthquake uplift pressure intensity is used immediately after the earthquake.

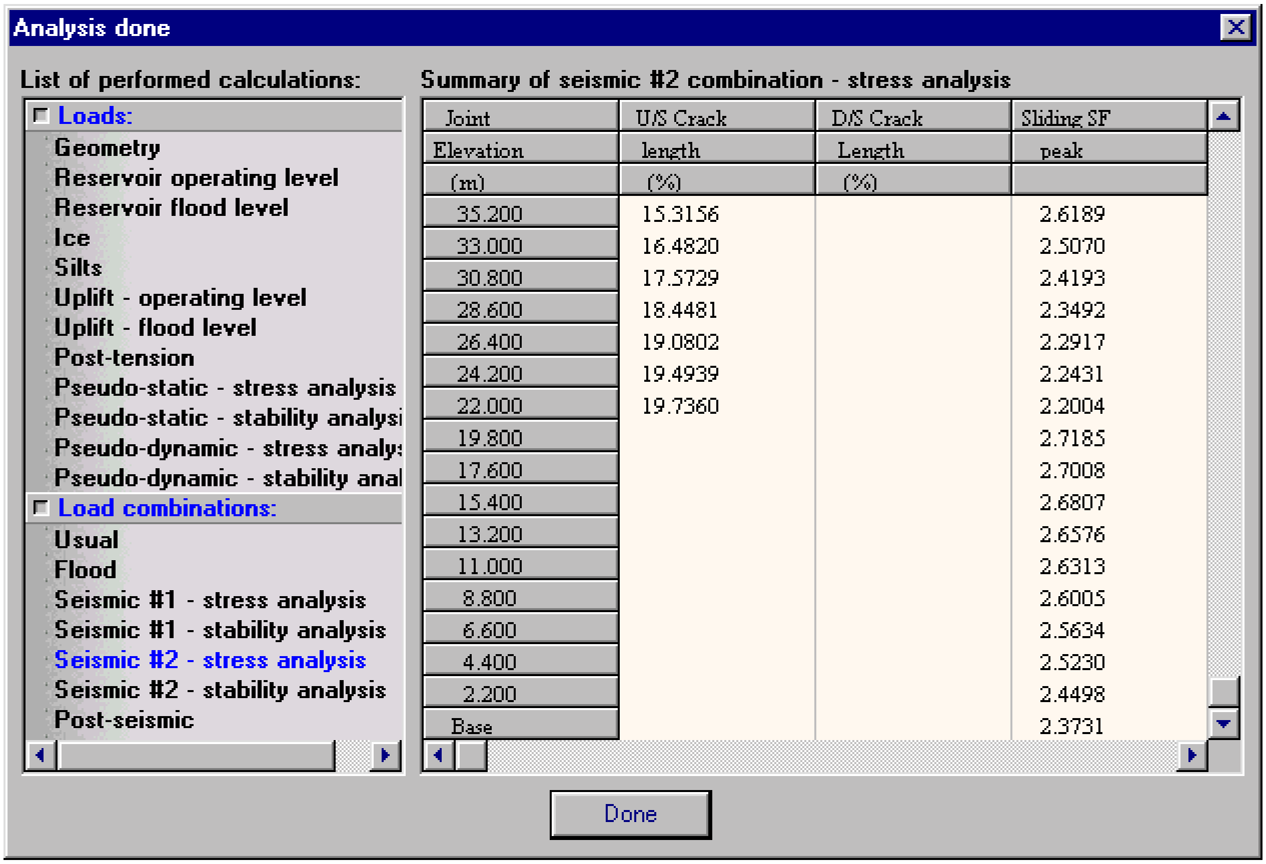
Crack Length Computation in Post-Seismic Analysis

If the full reservoir pressure is assumed to be developed in seismically induced crack, a new calculation of the crack length (stress analysis) must be performed to obtain a solution that is in equilibrium. In that case the seismically induced crack may propagate more, or may close along the joint.

PART – IV PROGRAM OUTPUT

21 OUTPUT RESULTS

21.1 Interactive Display of Tabular Data



Joint Elevation (m)	U/S Crack length (%)	D/S Crack Length (%)	Sliding SF peak
35.200	15.3156		2.6189
33.000	16.4820		2.5070
30.800	17.5729		2.4193
28.600	18.4481		2.3492
26.400	19.0802		2.2917
24.200	19.4939		2.2431
22.000	19.7360		2.2004
19.800			2.7185
17.600			2.7008
15.400			2.6807
13.200			2.6576
11.000			2.6313
8.800			2.6005
6.600			2.5634
4.400			2.5230
2.200			2.4498
Base			2.3731

Figure 30 Interactive display of analysis data

The above window (Figure 30) is activated each time a new analysis is performed. This window allows the user to get a fast overview of the analysis results. Select from the list of the performed calculations and CADAM will fill the worksheet with the corresponding selection.

21.2 Interactive Stress Plots Along Joints

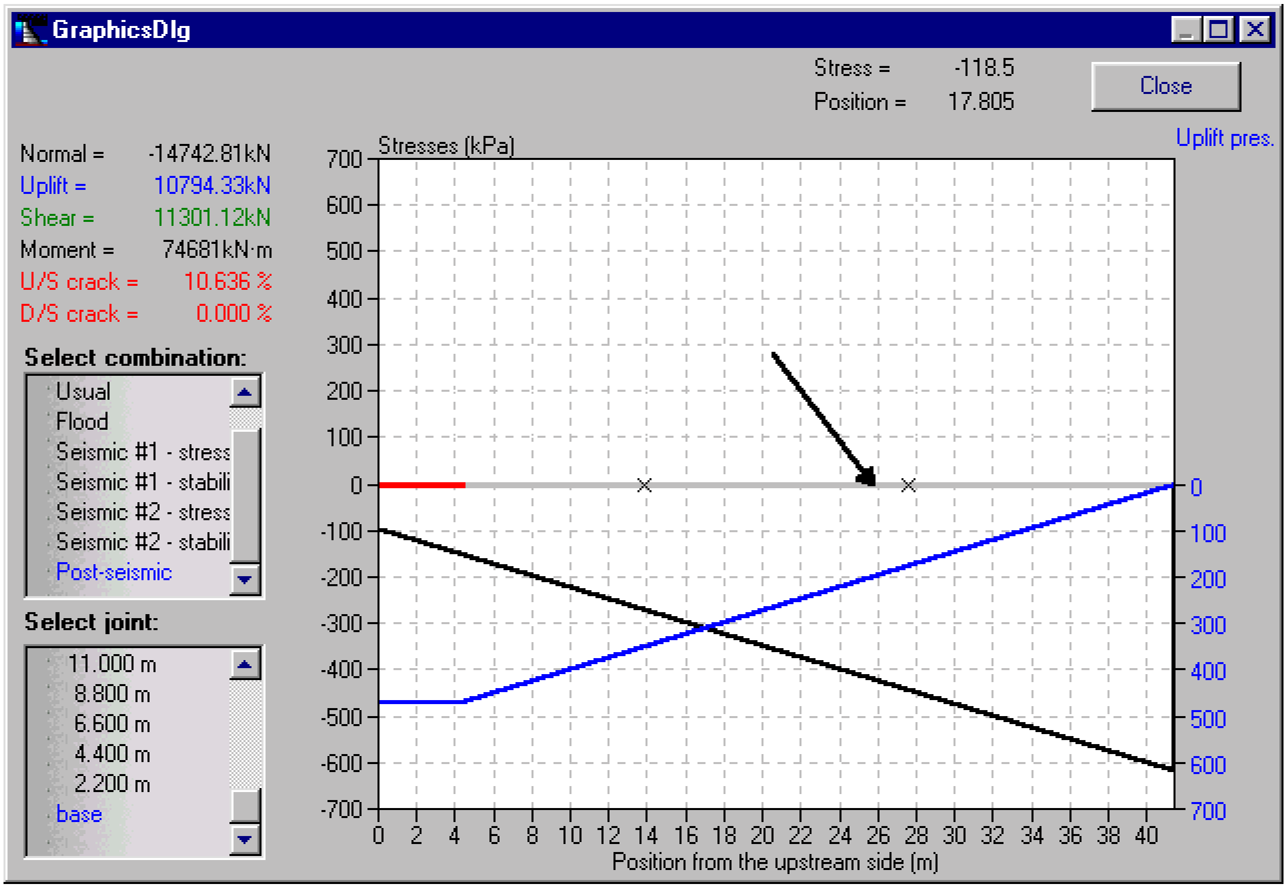


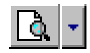
Figure 31 Stress plot along joint

The above window (Figure 31) is used to plot stresses (normal stress, shear stress, uplift pressures), resultant position and crack lengths (U/S and D/S). In presence of cracking, shear stress distribution is not plotted. This window is activated by the button  located on the shortcut bar or by the *graphical views* option located in the *results* menu. There are two required selections to activate the plot. One selection is the load combination and the other is the joint elevation. The user select from the lists on the left side of the window simply by clicking on the appropriate values.

21.3 Internal Reports

CADAM may generate 4 different reports:

1. Input parameters;
2. Loads;
3. Analysis results;
4. Stability drawings

To activate a report, click on the arrow of the scroll down button  to display the reports list and then select the desired one. The report list is also available from the *reports* option located in the *results* menu. Figure 32 shows an example of one of the CADAM reports. These reports can be printed and can be saved in two distinct formats:

1. Quick report file format (only available within CADAM);
2. Text file format (only text).

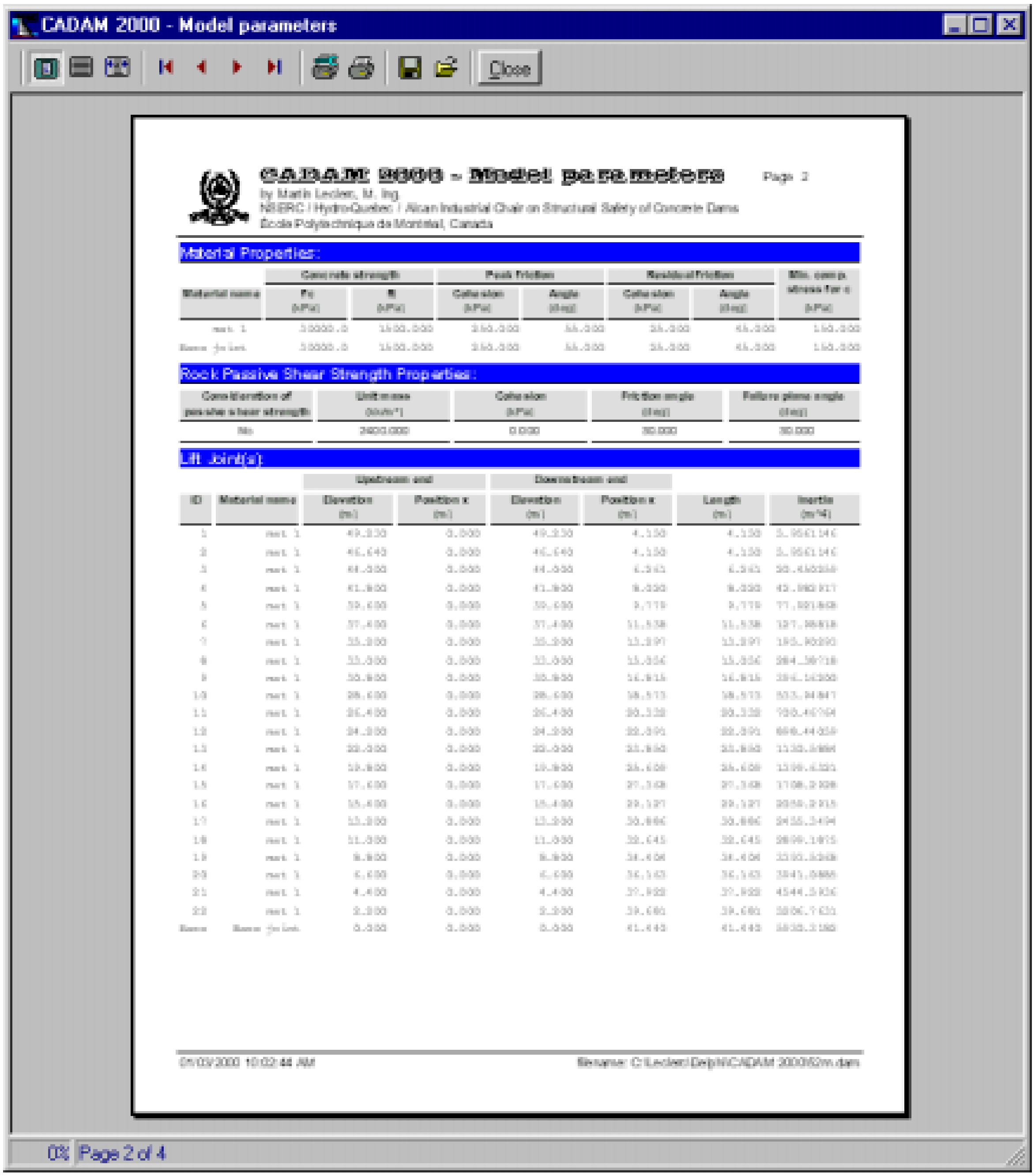


Figure 32 Example of a CADAM report

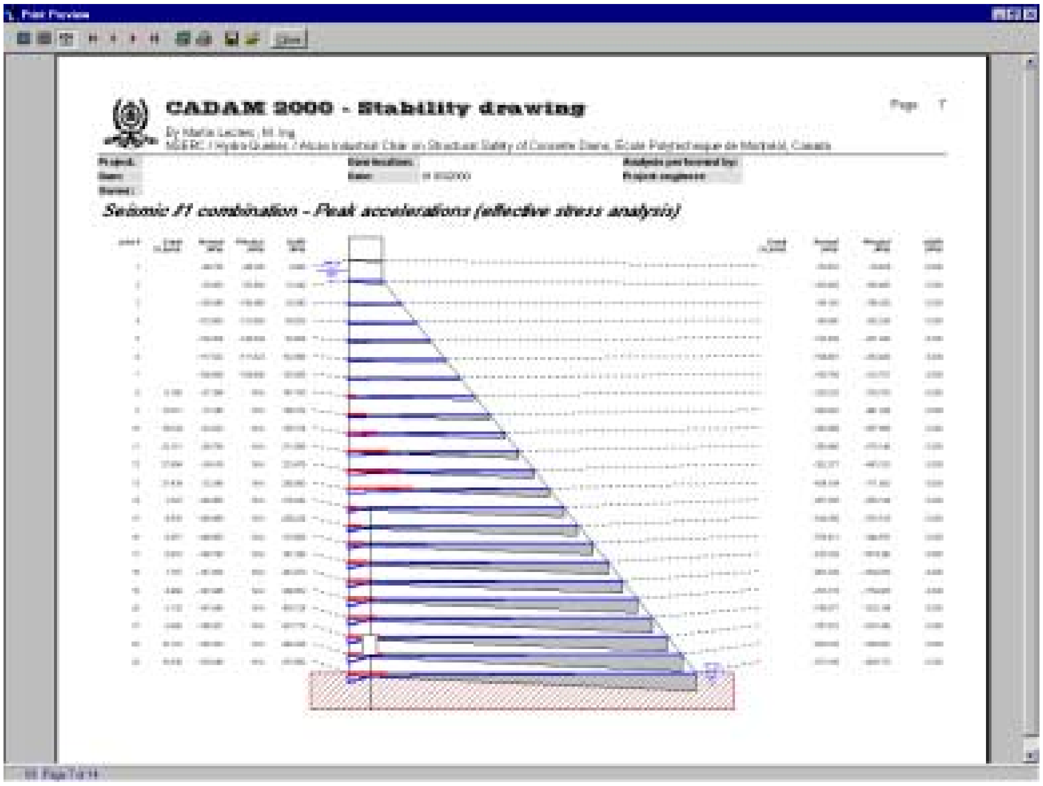


Figure 33 Example of a CADAM stability drawing report (stresses)

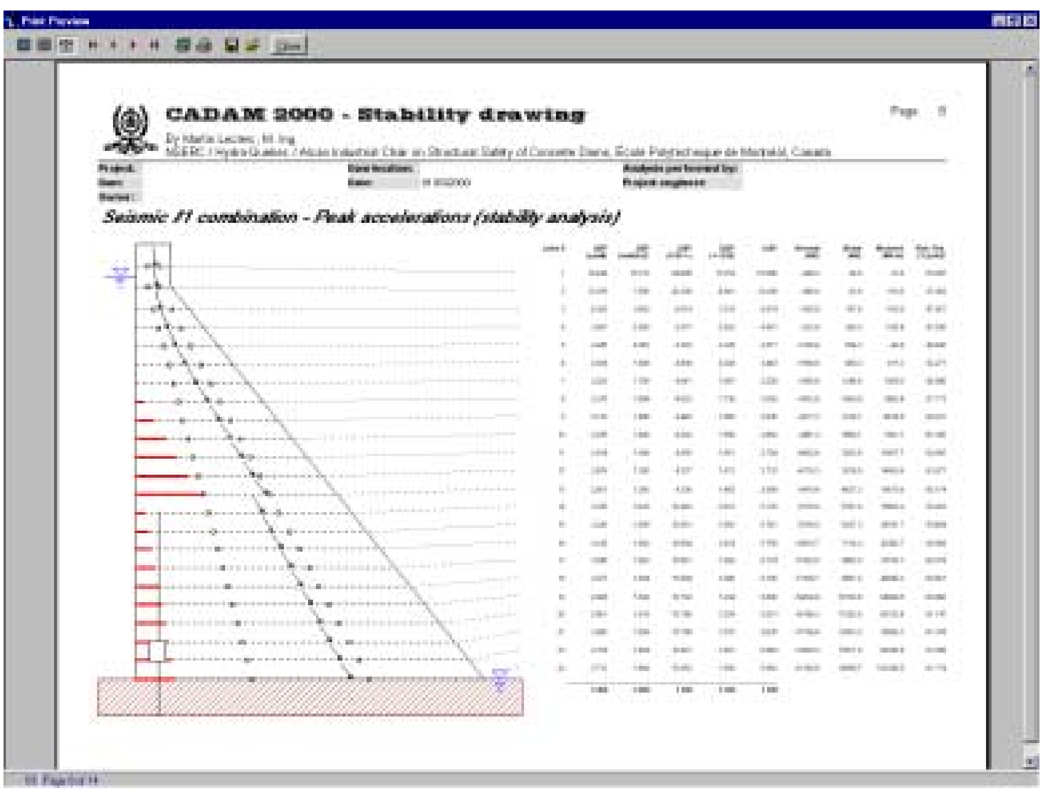
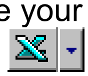


Figure 34 Example of a CADAM stability drawing report (safety factors)

21.4 Export Files to Microsoft Excel

CADAM is able to use Microsoft Excel (Version 5 and later) to generate three types of report:

1. Input parameters;
2. Loads;
3. Analysis results.

Microsoft Excel must be installed on your system; otherwise this option (MS Excel reports) will fail and may freeze your system. To activate a Microsoft Excel report, click on the arrow of the scroll down button  to display the report list and then select the desired one. The report list is also available from the *MS Excel* option located in the *results* menu. Figure 35 presents an example of Microsoft Excel input parameters report generated from CADAM.

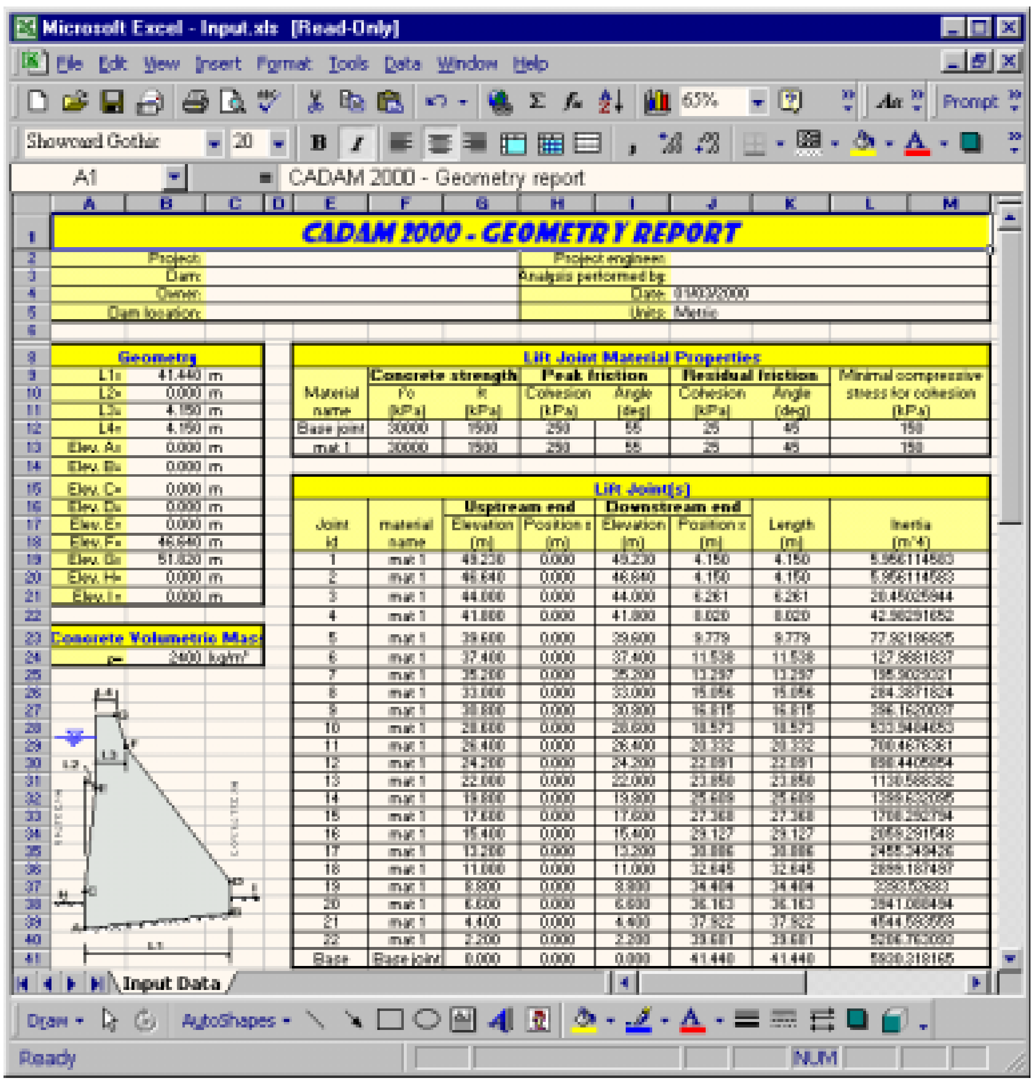


Figure 35 Example of a Microsoft Excel report generated from CADAM

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APPENDIX A – VALIDATION OF CADAM

Pseudo-dynamic seismic evaluation of Pine Flat Dam

The following presentation of Pine Flat Dam seismic evaluation is taken from Chopra (1988). The pseudo-dynamic method presented in Chopra (1988) is compared to CADAM computational accuracy. Pine Flat Dam geometry is shown in Figure 1 as well as the model used in CADAM (Figure 2).

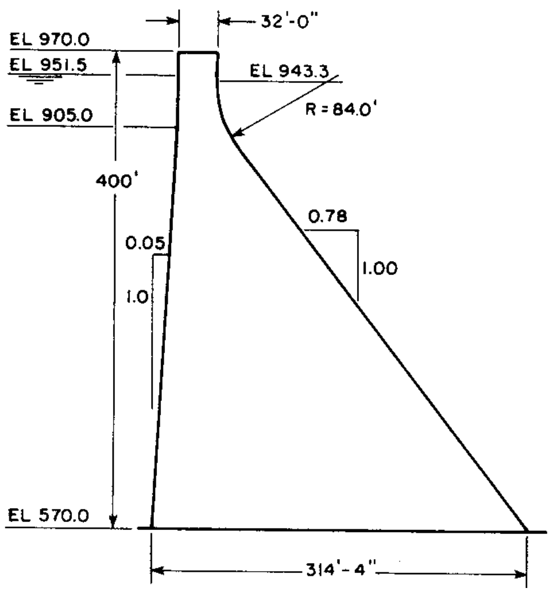


Figure 1 Pine Flat Dam Cross-Section

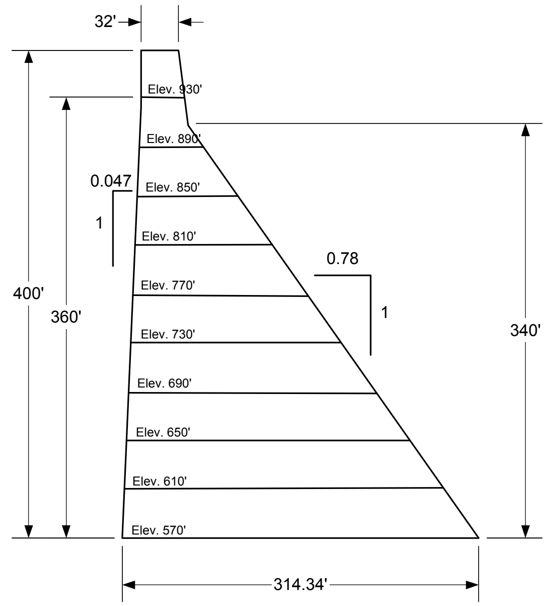


Figure 2 Cross-section for CADAM

Dam properties:	Reservoir properties	Foundation properties:
E_s = 3 250 000 psi	ρ_w = 62.4 lb/ft³	E_f = 3 250 000 psi
ρ_c = 155 lb/ft³	α = 0.5	η_f = 0.10
ξ_1 = 0.05		

To characterise the downstream curve near the crest, CADAM model is slightly adjusted from the original cross section in order to approach the dam weight as well as the generalised mass computed by Chopra (1988). This adjustment results in a reduced amount of mass (-0.8%) near the crest, and an increase of mass (+0.3%) near the base as compared to the simplified dam model used by Chopra (1988).

Four cases are used to illustrate the interaction of the reservoir and the foundation on the dynamic response of the dam:

1. Empty reservoir with rigid rock foundation;
2. Full reservoir with rigid rock foundation;
3. Empty reservoir with flexible rock foundation;
4. Full reservoir with flexible rock foundation.

For each case, comparisons between Chopra's and CADAM results are presented.

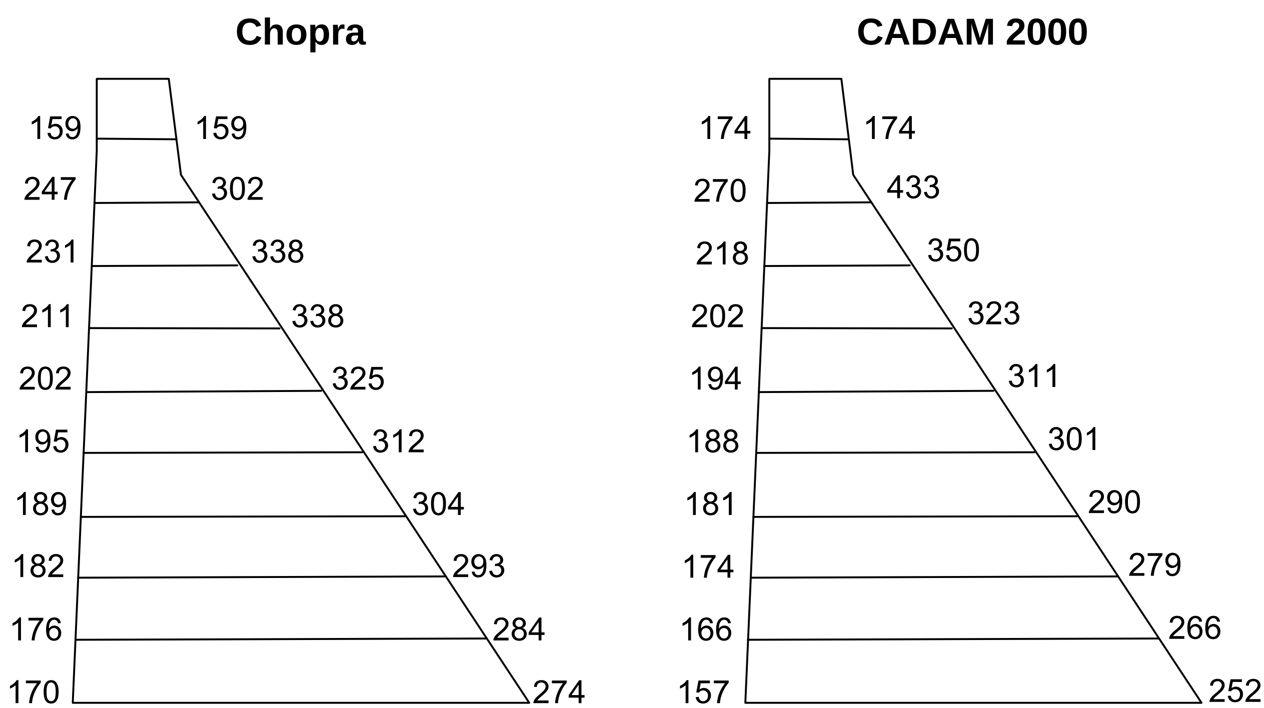
Case 1 – Empty reservoir and rigid foundation rock

Parameters from simplified procedure:

CADAM file name: Pine Flat (Pseudo-dynamic method - CASE 1).dam
Ground acceleration: 0.18g
Spectral acceleration: 0.429g

	Chopra	**CADAM**
R_r	1.0	1.0
R_f	1.0	1.0
ξ_r	0	0
ξ_f	0	0
$\tilde{T}_1$	0.311	0.311
$\tilde{\xi}_1$	0.050	0.050

Maximal principal stresses:



Maximal principal stresses (in psi) - Initial static stresses are excluded.

Case 1 - Empty reservoir & Rigid foundation rock.

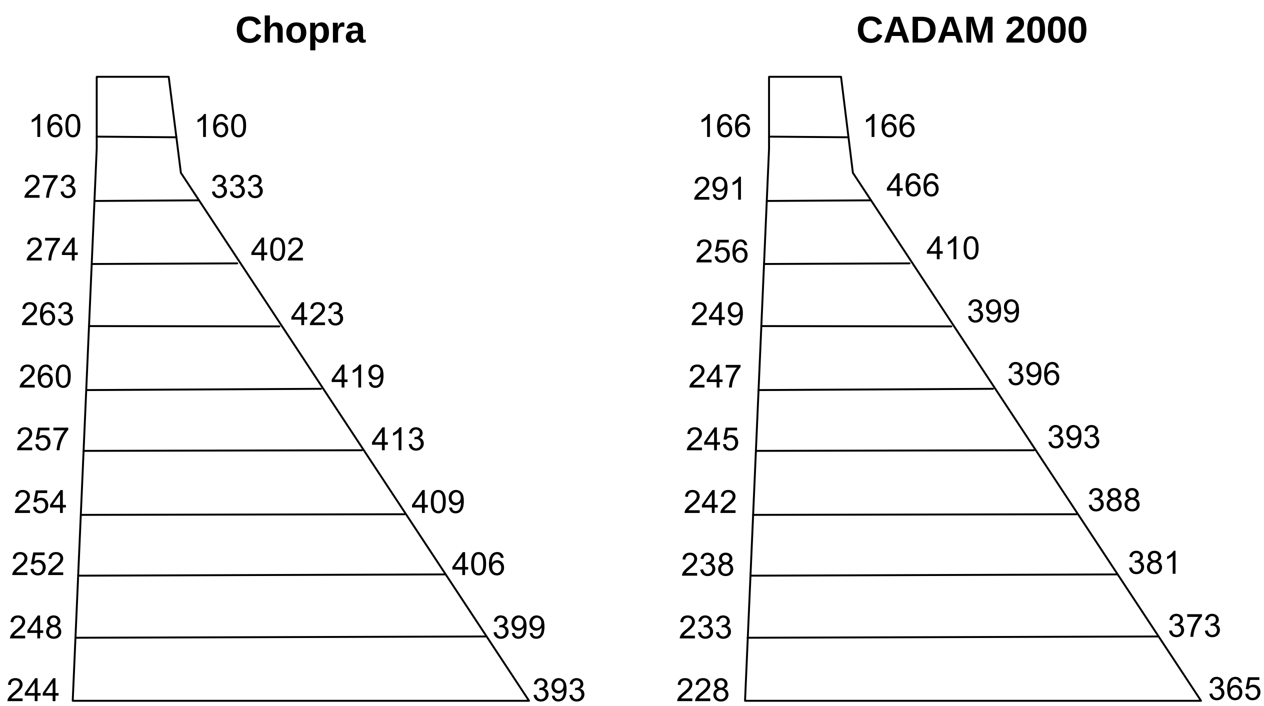
Case 2 – Full reservoir and rigid foundation rock

Parameters from simplified procedure:

CADAM file name: Pine Flat (Pseudo-dynamic method - CASE 2).dam
Ground acceleration: 0.18g
Spectral acceleration: 0.312g

	Chopra	**CADAM**
R_r	1.213	1.231
R_f	1.0	1.0
ξ_r	0.030	0.034
ξ_f	0	0
$\tilde{T}_1$	0.377	0.383
$\tilde{\xi}_1$	0.071	0.074

Maximal principal stresses:



Maximal principal stresses (in psi) - Initial static stresses are excluded.

Case 2 - Full reservoir & Rigid foundation rock.

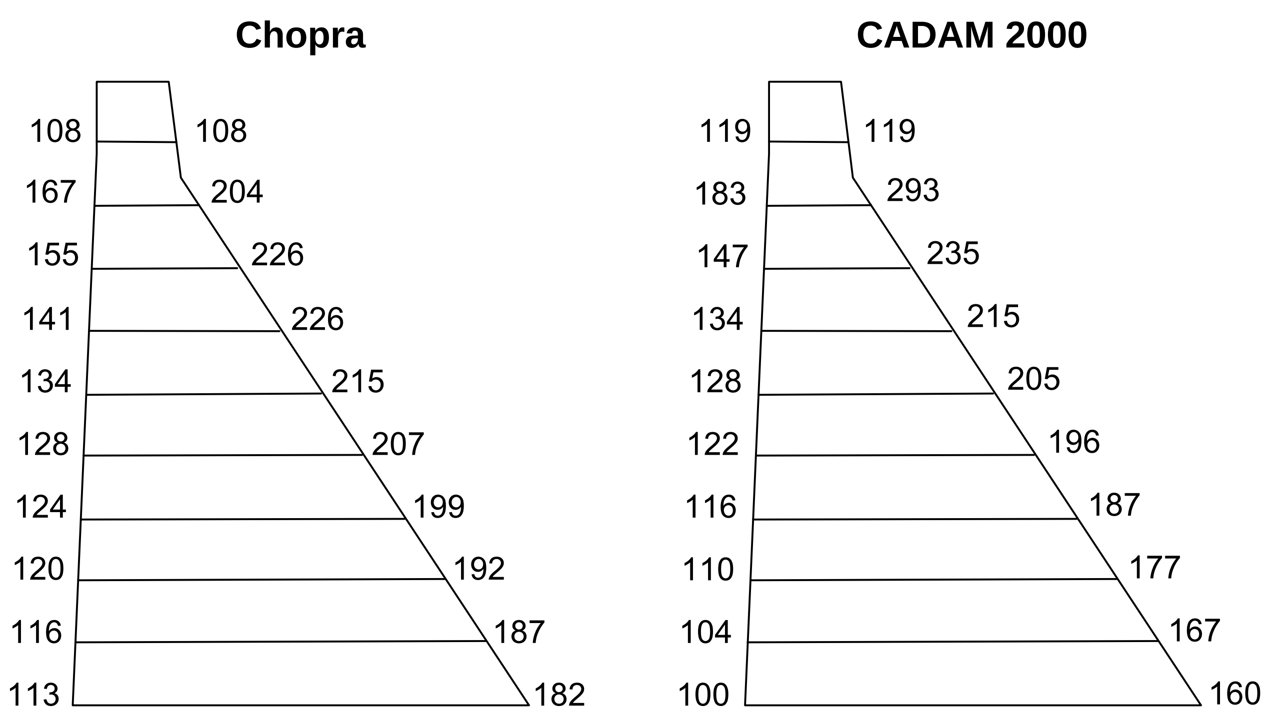
Case 3 – Empty reservoir and flexible foundation rock

<u>Parameters from simplified procedure:</u>

CADAM file name: Pine Flat (Pseudo-dynamic method - CASE 3).dam
Ground acceleration: 0.18g
Spectral acceleration: 0.281g

	Chopra	CADAM
R_r	1.0	1.0
R_f	1.187	1.187
ξ_r	0	0
ξ_f	0.068	0.068
$\tilde{T}_1$	0.369	0.369
$\tilde{\xi}_1$	0.098	0.098

<u>Maximal principal stresses:</u>



Maximal principal stresses (in psi) - Initial static stresses are excluded.

Case 3 - Empty reservoir & flexible foundation rock.

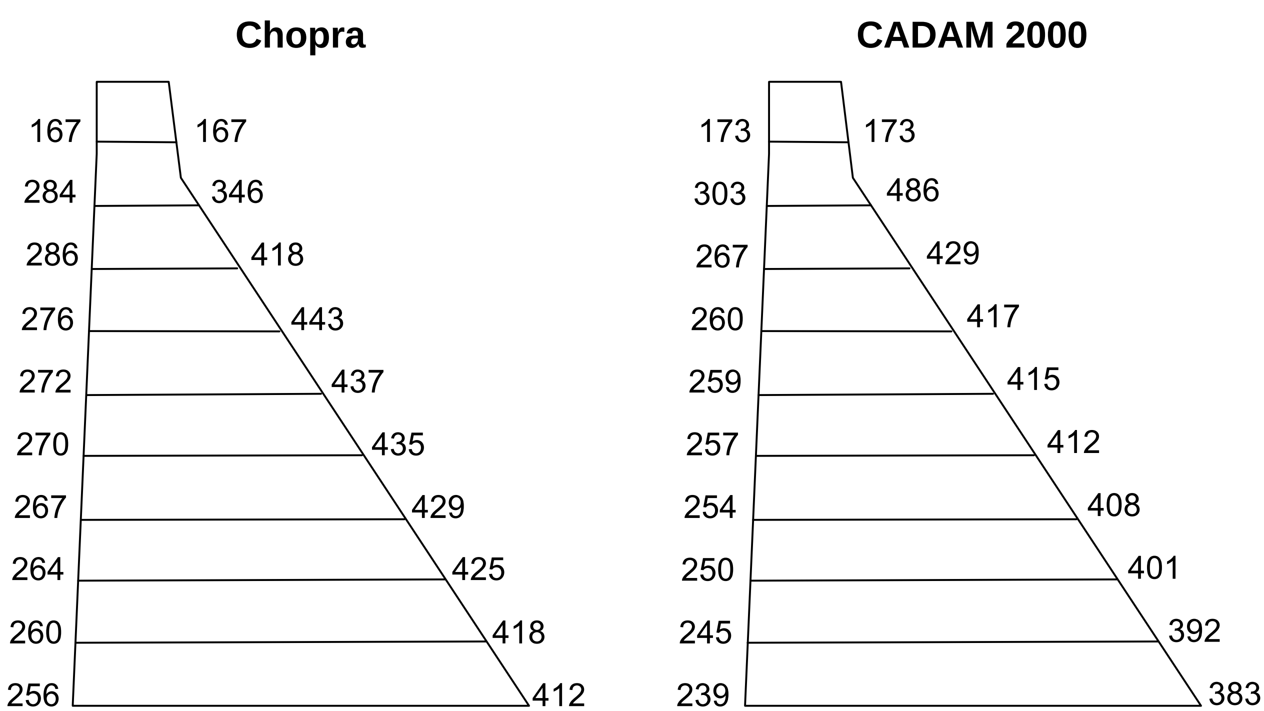
Case 4 – Full reservoir and flexible foundation rock

CADAM file name: Pine Flat (Pseudo-dynamic method - CASE 4).dam
Ground acceleration: 0.18g
Spectral acceleration: 0.327g

Parameters from simplified procedure:

	Chopra	**CADAM**
R_r	1.213	1.231
R_f	1.187	1.187
ξ_r	0.030	0.037
ξ_f	0.068	0.068
$\tilde{T}_1$	0.448	0.454
$\tilde{\xi}_1$	0.123	0.126

Maximal principal stresses:



Maximal principal stresses (in psi) - Initial static stresses are excluded.

Case 4 - Full reservoir & flexible foundation rock.

The differences between Chopra (1988) and CADAM computations might be explained by the following:

1. CADAM interpolates in and between all tables of Chopra's simplified procedure while it appears that Chopra (1988) uses the nearest value.

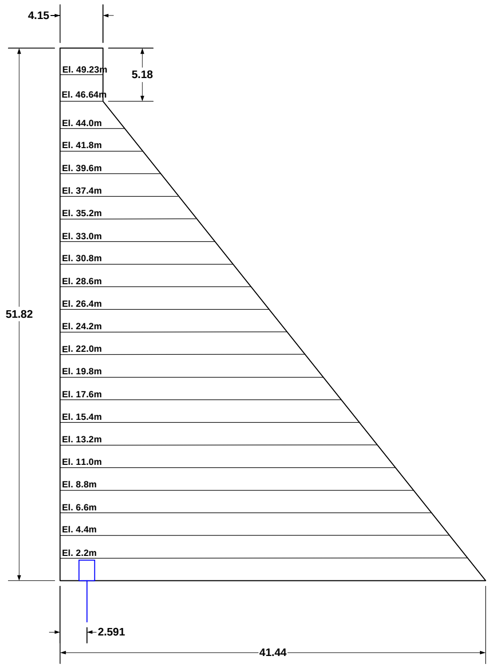
2. The downstream slope located at the joint elevation 890' is more inclined in CADAM model, resulting in a much higher principal stress at the downstream face. CADAM uses two straight-line segments to represent the downstream face of the dam, while Chopra (1988) uses three straight-line segments.

3. CADAM divides the cross-section in more layers than the joints spacing for a better computational accuracy;

4. The cross-section of Pine Flat Dam used in CADAM is thus slightly different from the real cross section as explained previously.

APPENDIX B – ADDITIONAL CADAM DEMO FILES

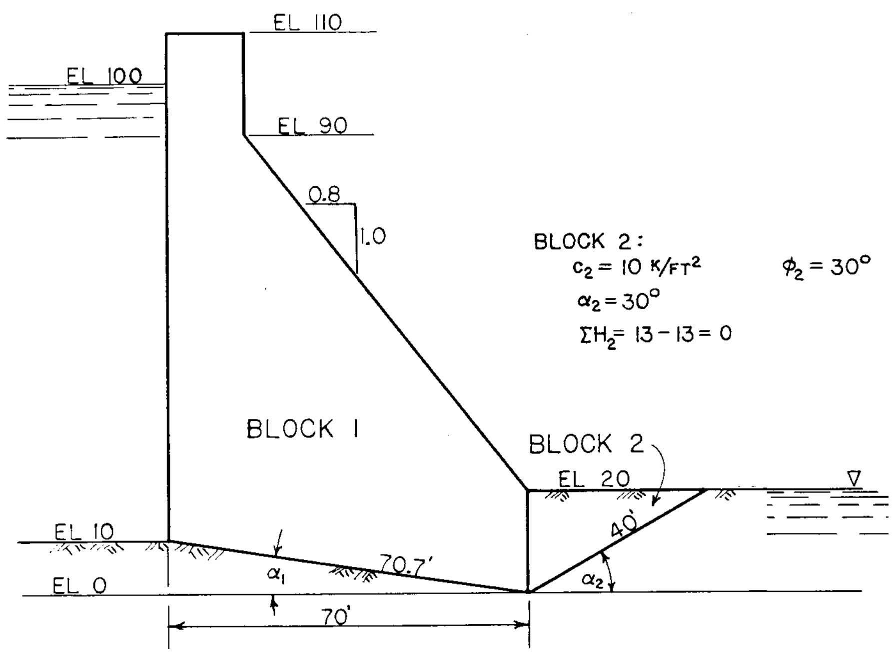
52m high dam model



CADAM file name: 52m.dam

110ft high dam with an inclined base (Shear friction method)

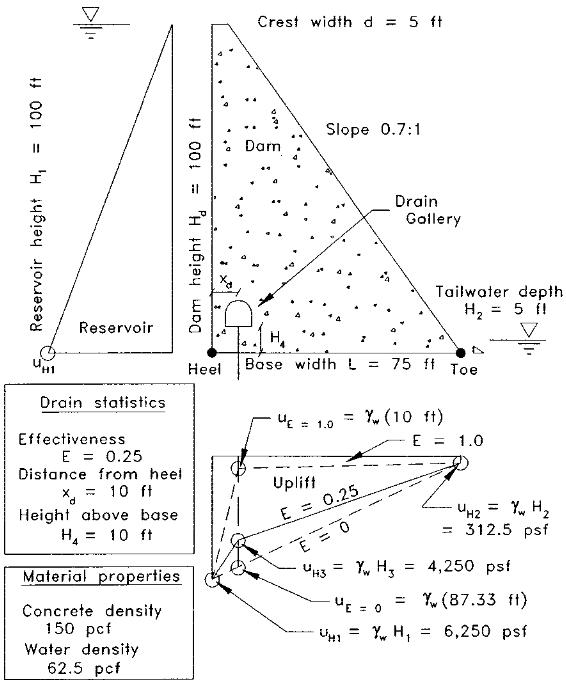
CADAM file name: Passive rock.dam



- SSF shear friction method = 4.2 (Corns et al. 1988, p. 484)
- CADAM SSF shear friction method = 4.1

Validation example (from USACE 2000, http://www.wes.army.mil/ITL/itlpubl.html)

Problem:



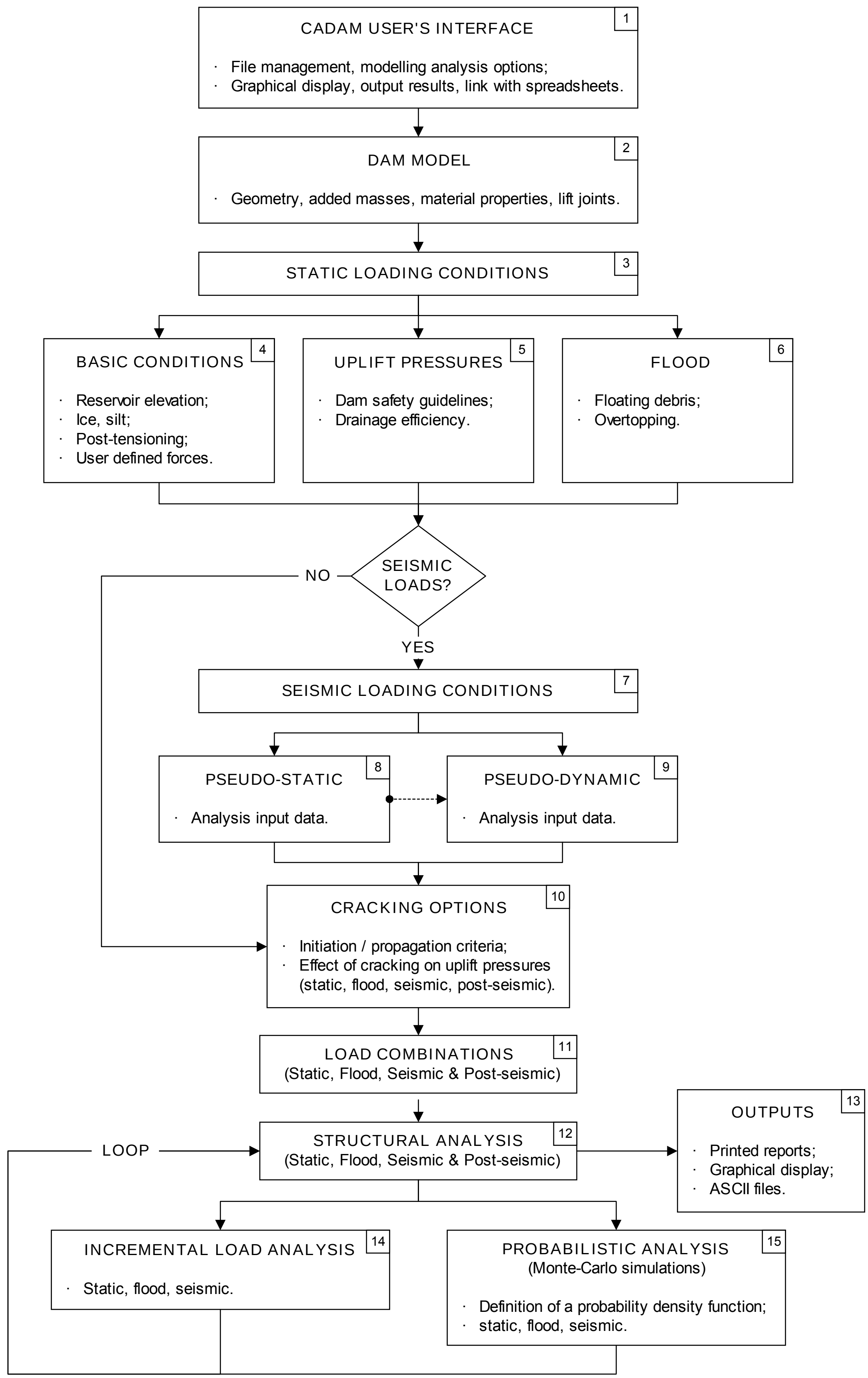
Unit weight of water:

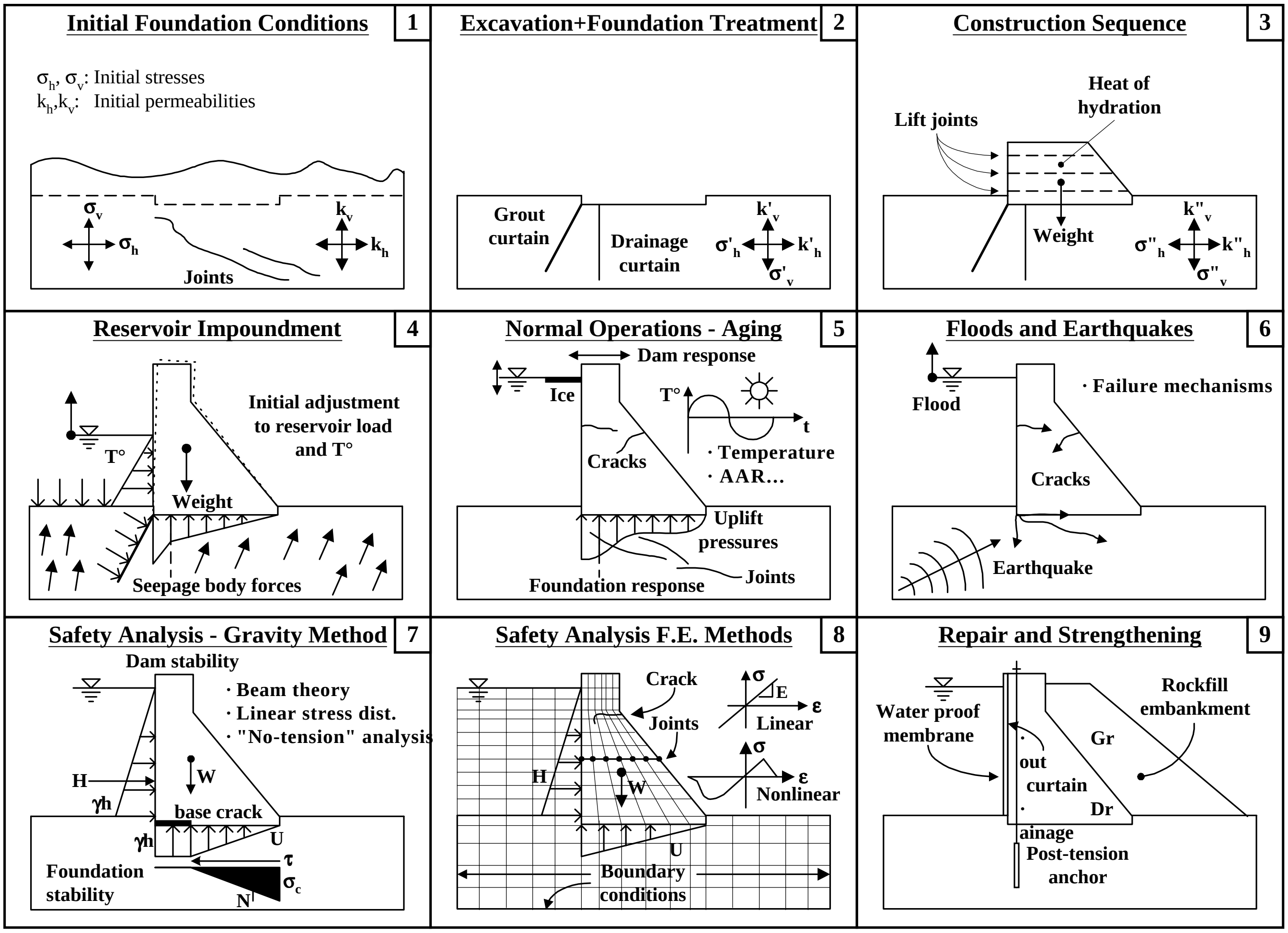
- USACE: 62.5 pcf
- USBR: 62.5 pcf
- FERC: 62.4 pcf

Results:

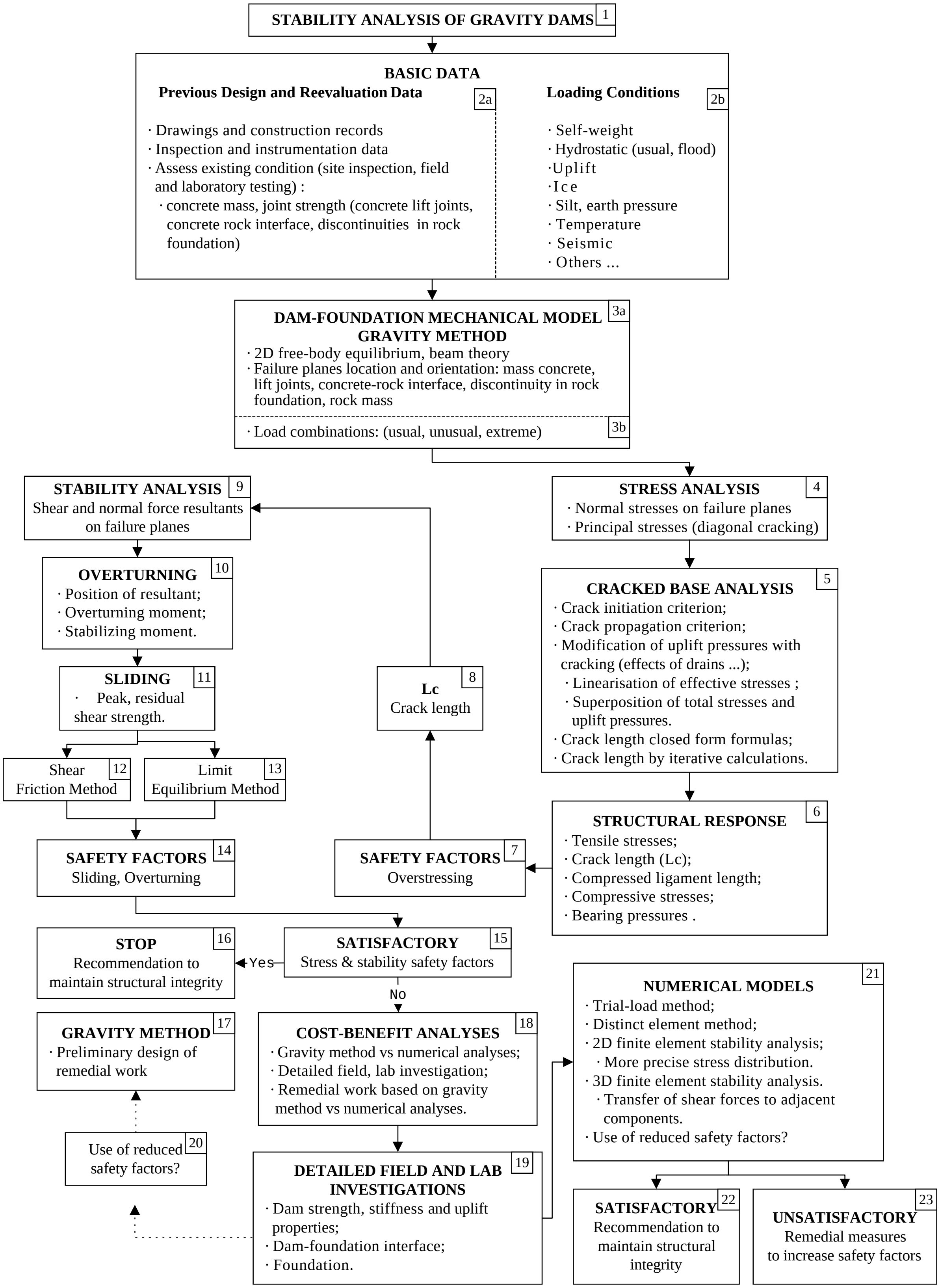
CADAM input file	Guideline used	CADAM computed crack length	Published USACE 2000 computed crack length
USACE 100ft.dam	USACE 1995	8.23 ft	8.23 ft
USBR 100ft.dam	USBR 1987	30.735 ft	30.735 ft
FERC 100ft.dam	FERC 1999	7.64 ft	7.64 ft

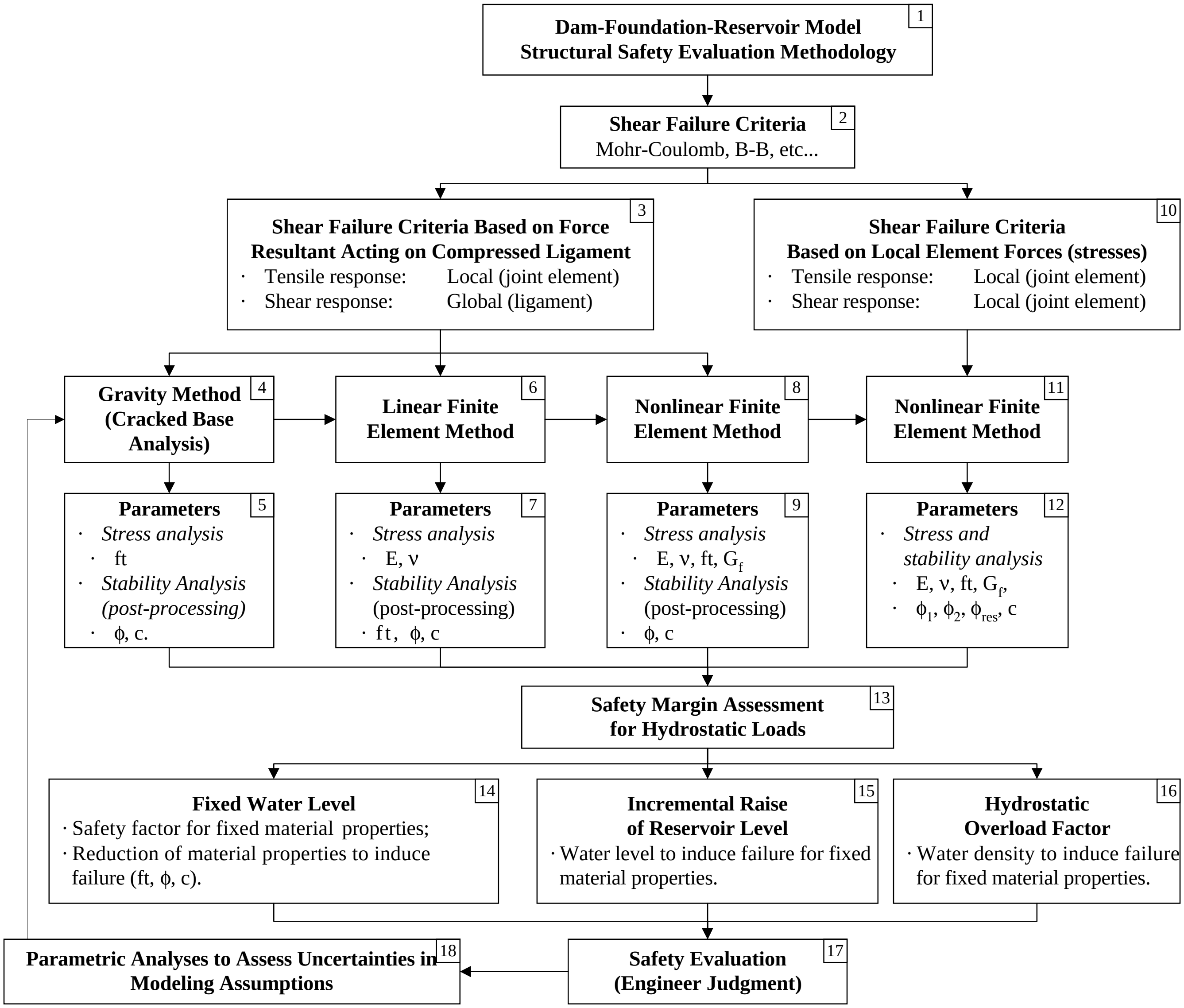
APPENDIX C - FLOWCHARTS RELATED TO STRUCTURAL SAFETY EVALUATION OF CONCRETE DAMS


CADAM USER'S INTERFACE
File management, modelling analysis options;
Graphical display, output results, link with spreadsheets.
1
DAM MODEL
Geometry, added masses, material properties, lift joints.
2
STATIC LOADING CONDITIONS
3
BASIC CONDITIONS
Reservoir elevation;
Ice, silt;
Post-tensioning;
User defined forces.
4
UPLIFT PRESSURES
Dam safety guidelines;
Drainage efficiency.
5
FLOOD
Floating debris;
Overtopping.
6
SEISMIC LOADS?
NO
YES
SEISMIC LOADING CONDITIONS
7
PSEUDO-STATIC
Analysis input data.
8
PSEUDO-DYNAMIC
Analysis input data.
9
CRACKING OPTIONS
Initiation / propagation criteria;
Effect of cracking on uplift pressures (static, flood, seismic, post-seismic).
10
LOAD COMBINATIONS
(Static, Flood, Seismic & Post-seismic)
11
LOOP
STRUCTURAL ANALYSIS
(Static, Flood, Seismic & Post-seismic)
12
OUTPUTS
Printed reports;
Graphical display;
ASCII files.
13
INCREMENTAL LOAD ANALYSIS
Static, flood, seismic.
14
PROBABILISTIC ANALYSIS
(Monte-Carlo simulations)
Definition of a probability density function;
static, flood, seismic.
15

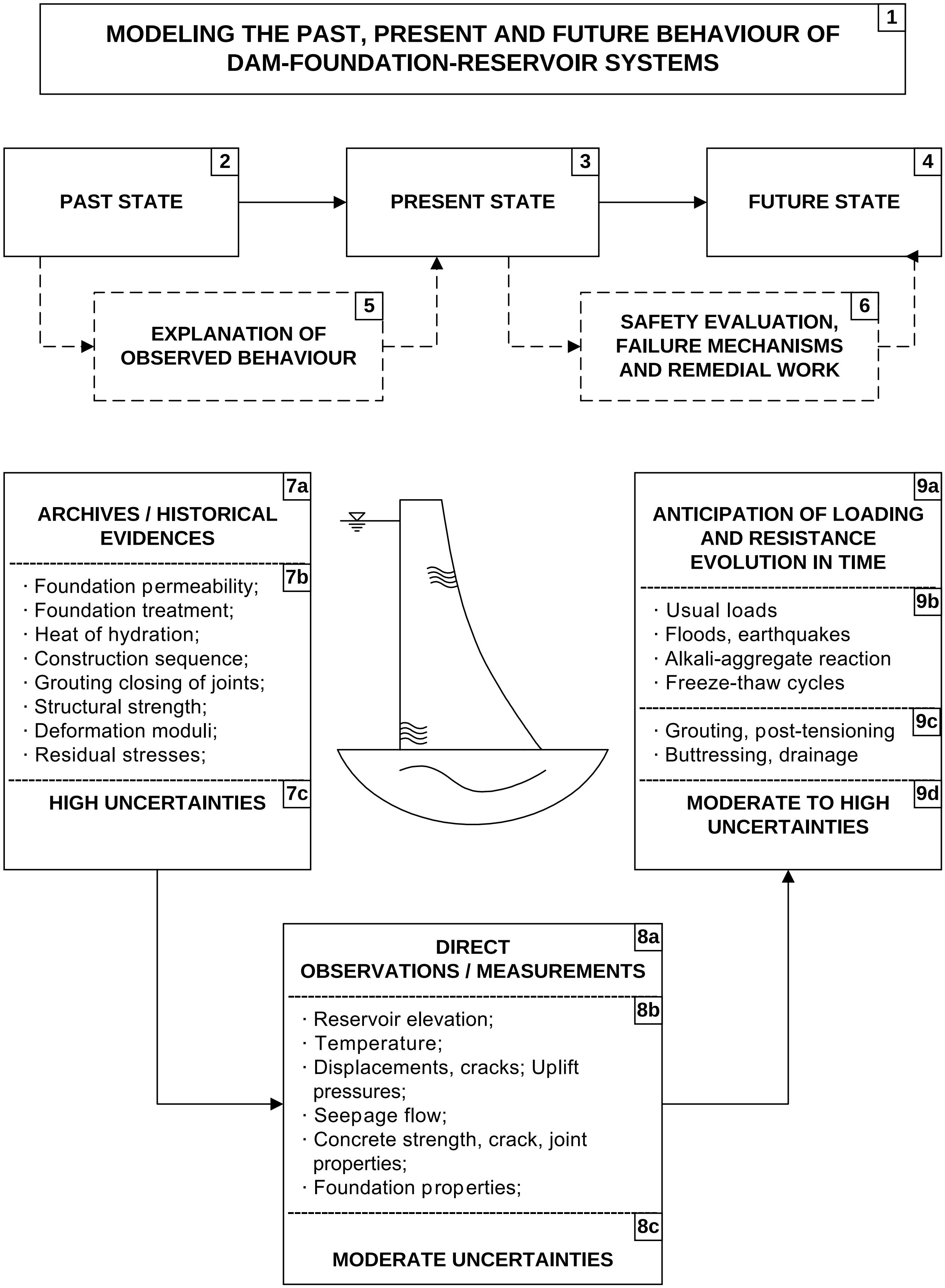


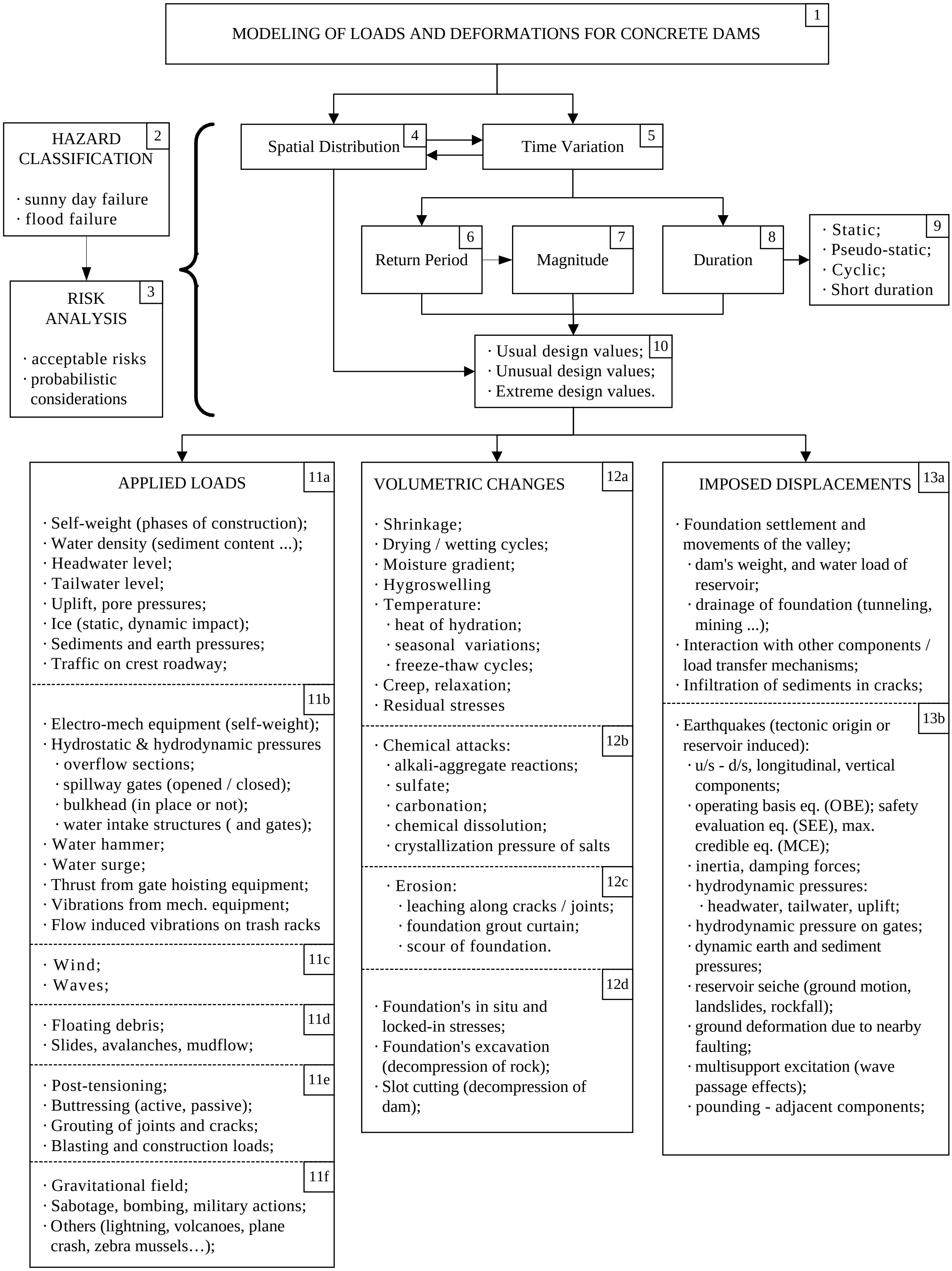
Initial Foundation Conditions
1
σh, σv: Initial stresses
kh,kv: Initial permeabilities
σv
σh
kv
kh
Joints
Excavation+Foundation Treatment
2
Grout curtain
Drainage curtain
k'v
σ'h
k'h
σ'v
Construction Sequence
3
Heat of hydration
Lift joints
Weight
k"v
σ"h
k"h
σ"v
Reservoir Impoundment
4
Initial adjustment to reservoir load and T°
T°
Weight
Seepage body forces
Normal Operations - Aging
5
Dam response
Ice
T°
t
Cracks
· Temperature
· AAR...
Uplift pressures
Joints
Foundation response
Floods and Earthquakes
6
Flood
· Failure mechanisms
Cracks
Earthquake
Safety Analysis - Gravity Method
7
Dam stability
· Beam theory
· Linear stress dist.
· "No-tension" analysis
H
γh
W
base crack
γh
U
τ
σc
N
Foundation stability
Safety Analysis F.E. Methods
8
Crack
Joints
σ
E
ε
Linear
σ
ε
Nonlinear
H
W
U
Boundary conditions
Repair and Strengthening
9
Water proof membrane
Rockfill embankment
Gr
out curtain
Dr
ainage
Post-tension anchor

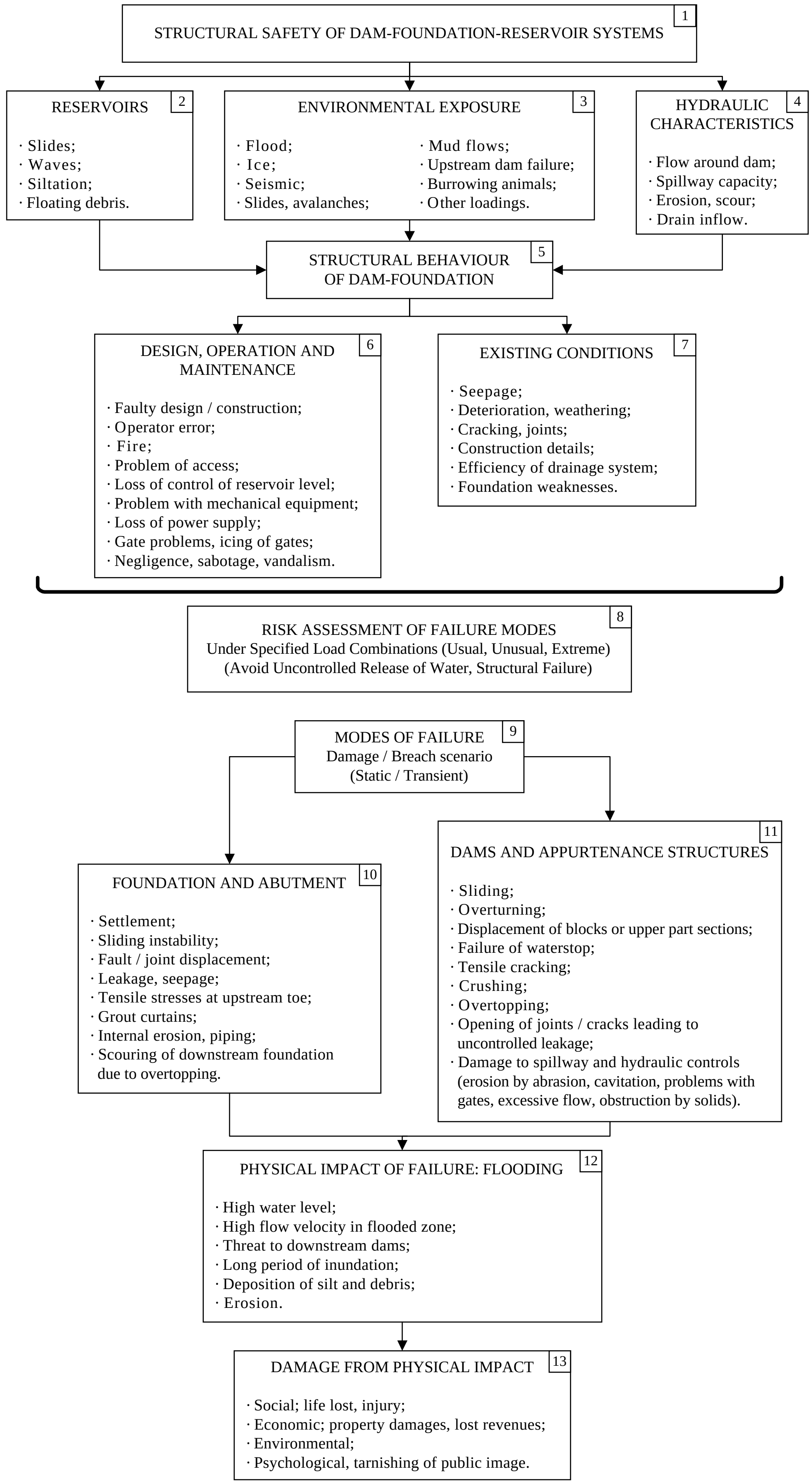

STABILITY ANALYSIS OF GRAVITY DAMS 1
BASIC DATA
Previous Design and Reevaluation Data 2a
· Drawings and construction records
· Inspection and instrumentation data
· Assess existing condition (site inspection, field and laboratory testing) :
· concrete mass, joint strength (concrete lift joints, concrete rock interface, discontinuities in rock foundation)
Loading Conditions 2b
· Self-weight
· Hydrostatic (usual, flood)
·Uplift
·Ice
· Silt, earth pressure
· Temperature
· Seismic
· Others ...
DAM-FOUNDATION MECHANICAL MODEL GRAVITY METHOD 3a
· 2D free-body equilibrium, beam theory
· Failure planes location and orientation: mass concrete, lift joints, concrete-rock interface, discontinuity in rock foundation, rock mass
· Load combinations: (usual, unusual, extreme) 3b
STABILITY ANALYSIS 9
Shear and normal force resultants on failure planes
STRESS ANALYSIS 4
· Normal stresses on failure planes
· Principal stresses (diagonal cracking)
OVERTURNING 10
· Position of resultant;
· Overturning moment;
· Stabilizing moment.
CRACKED BASE ANALYSIS 5
· Crack initiation criterion;
· Crack propagation criterion;
· Modification of uplift pressures with cracking (effects of drains ...);
· Linearisation of effective stresses ;
· Superposition of total stresses and uplift pressures.
· Crack length closed form formulas;
· Crack length by iterative calculations.
SLIDING 11
· Peak, residual shear strength.
Lc 8
Crack length
Shear Friction Method 12
Limit Equilibrium Method 13
STRUCTURAL RESPONSE 6
· Tensile stresses;
· Crack length (Lc);
· Compressed ligament length;
· Compressive stresses;
· Bearing pressures .
SAFETY FACTORS 14
Sliding, Overturning
SAFETY FACTORS 7
Overstressing
STOP 16
Recommendation to maintain structural integrity
Yes
SATISFACTORY 15
Stress & stability safety factors
No
NUMERICAL MODELS 21
· Trial-load method;
· Distinct element method;
· 2D finite element stability analysis;
· More precise stress distribution.
· 3D finite element stability analysis.
· Transfer of shear forces to adjacent components.
· Use of reduced safety factors?
GRAVITY METHOD 17
· Preliminary design of remedial work
COST-BENEFIT ANALYSES 18
· Gravity method vs numerical analyses;
· Detailed field, lab investigation;
· Remedial work based on gravity method vs numerical analyses.
Use of reduced safety factors? 20
DETAILED FIELD AND LAB INVESTIGATIONS 19
· Dam strength, stiffness and uplift properties;
· Dam-foundation interface;
· Foundation.
SATISFACTORY 22
Recommendation to maintain structural integrity
UNSATISFACTORY 23
Remedial measures to increase safety factors



1
Dam-Foundation-Reservoir Model
Structural Safety Evaluation Methodology
2
Shear Failure Criteria
Mohr-Coulomb, B-B, etc...
3
Shear Failure Criteria Based on Force Resultant Acting on Compressed Ligament
· Tensile response: Local (joint element)
· Shear response: Global (ligament)
10
Shear Failure Criteria Based on Local Element Forces (stresses)
· Tensile response: Local (joint element)
· Shear response: Local (joint element)
4
Gravity Method (Cracked Base Analysis)
6
Linear Finite Element Method
8
Nonlinear Finite Element Method
11
Nonlinear Finite Element Method
5
Parameters
· Stress analysis
· ft
· Stability Analysis (post-processing)
· φ, c.
7
Parameters
· Stress analysis
· E, ν
· Stability Analysis (post-processing)
· ft, φ, c
9
Parameters
· Stress analysis
· E, ν, ft, G_f
· Stability Analysis (post-processing)
· φ, c
12
Parameters
· Stress and stability analysis
· E, ν, ft, G_f,
· ϕ_1, ϕ_2, ϕ_{res}, c
13
Safety Margin Assessment for Hydrostatic Loads
14
Fixed Water Level
· Safety factor for fixed material properties;
· Reduction of material properties to induce failure (ft, φ, c).
15
Incremental Raise of Reservoir Level
· Water level to induce failure for fixed material properties.
16
Hydrostatic Overload Factor
· Water density to induce failure for fixed material properties.
18
Parametric Analyses to Assess Uncertainties in Modeling Assumptions
17
Safety Evaluation (Engineer Judgment)


1
MODELING THE PAST, PRESENT AND FUTURE BEHAVIOUR OF DAM-FOUNDATION-RESERVOIR SYSTEMS
2
PAST STATE
3
PRESENT STATE
4
FUTURE STATE
5
EXPLANATION OF OBSERVED BEHAVIOUR
6
SAFETY EVALUATION, FAILURE MECHANISMS AND REMEDIAL WORK
7a
ARCHIVES / HISTORICAL EVIDENCES
7b
· Foundation permeability;
· Foundation treatment;
· Heat of hydration;
· Construction sequence;
· Grouting closing of joints;
· Structural strength;
· Deformation moduli;
· Residual stresses;
7c
HIGH UNCERTAINTIES
9a
ANTICIPATION OF LOADING AND RESISTANCE EVOLUTION IN TIME
9b
· Usual loads
· Floods, earthquakes
· Alkali-aggregate reaction
· Freeze-thaw cycles
9c
· Grouting, post-tensioning
· Buttressing, drainage
9d
MODERATE TO HIGH UNCERTAINTIES
8a
DIRECT OBSERVATIONS / MEASUREMENTS
8b
· Reservoir elevation;
· Temperature;
· Displacements, cracks; Uplift pressures;
· Seepage flow;
· Concrete strength, crack, joint properties;
· Foundation properties;
8c
MODERATE UNCERTAINTIES


1
MODELING OF LOADS AND DEFORMATIONS FOR CONCRETE DAMS
2
HAZARD CLASSIFICATION
· sunny day failure
· flood failure
3
RISK ANALYSIS
· acceptable risks
· probabilistic considerations
4
Spatial Distribution
5
Time Variation
6
Return Period
7
Magnitude
8
Duration
9
· Static;
· Pseudo-static;
· Cyclic;
· Short duration
10
· Usual design values;
· Unusual design values;
· Extreme design values.
11a
APPLIED LOADS
· Self-weight (phases of construction);
· Water density (sediment content ...);
· Headwater level;
· Tailwater level;
· Uplift, pore pressures;
· Ice (static, dynamic impact);
· Sediments and earth pressures;
· Traffic on crest roadway;
11b
· Electro-mech equipment (self-weight);
· Hydrostatic & hydrodynamic pressures
· overflow sections;
· spillway gates (opened / closed);
· bulkhead (in place or not);
· water intake structures (and gates);
· Water hammer;
· Water surge;
· Thrust from gate hoisting equipment;
· Vibrations from mech. equipment;
· Flow induced vibrations on trash racks
11c
· Wind;
· Waves;
11d
· Floating debris;
· Slides, avalanches, mudflow;
11e
· Post-tensioning;
· Buttressing (active, passive);
· Grouting of joints and cracks;
· Blasting and construction loads;
11f
· Gravitational field;
· Sabotage, bombing, military actions;
· Others (lightning, volcanoes, plane crash, zebra mussels…);
12a
VOLUMETRIC CHANGES
· Shrinkage;
· Drying / wetting cycles;
· Moisture gradient;
· Hygroswelling
· Temperature:
· heat of hydration;
· seasonal variations;
· freeze-thaw cycles;
· Creep, relaxation;
· Residual stresses
12b
· Chemical attacks:
· alkali-aggregate reactions;
· sulfate;
· carbonation;
· chemical dissolution;
· crystallization pressure of salts
12c
· Erosion:
· leaching along cracks / joints;
· foundation grout curtain;
· scour of foundation.
12d
· Foundation's in situ and locked-in stresses;
· Foundation's excavation (decompression of rock);
· Slot cutting (decompression of dam);
13a
IMPOSED DISPLACEMENTS
· Foundation settlement and movements of the valley;
· dam's weight, and water load of reservoir;
· drainage of foundation (tunneling, mining ...);
· Interaction with other components / load transfer mechanisms;
· Infiltration of sediments in cracks;
13b
· Earthquakes (tectonic origin or reservoir induced):
· u/s - d/s, longitudinal, vertical components;
· operating basis eq. (OBE); safety evaluation eq. (SEE), max. credible eq. (MCE);
· inertia, damping forces;
· hydrodynamic pressures:
· headwater, tailwater, uplift;
· hydrodynamic pressure on gates;
· dynamic earth and sediment pressures;
· reservoir seiche (ground motion, landslides, rockfall);
· ground deformation due to nearby faulting;
· multisupport excitation (wave passage effects);
· pounding - adjacent components;


1
STRUCTURAL SAFETY OF DAM-FOUNDATION-RESERVOIR SYSTEMS
2
RESERVOIRS
· Slides;
· Waves;
· Siltation;
· Floating debris.
3
ENVIRONMENTAL EXPOSURE
· Flood;
· Ice;
· Seismic;
· Slides, avalanches;
· Mud flows;
· Upstream dam failure;
· Burrowing animals;
· Other loadings.
4
HYDRAULIC CHARACTERISTICS
· Flow around dam;
· Spillway capacity;
· Erosion, scour;
· Drain inflow.
5
STRUCTURAL BEHAVIOUR OF DAM-FOUNDATION
6
DESIGN, OPERATION AND MAINTENANCE
· Faulty design / construction;
· Operator error;
· Fire;
· Problem of access;
· Loss of control of reservoir level;
· Problem with mechanical equipment;
· Loss of power supply;
· Gate problems, icing of gates;
· Negligence, sabotage, vandalism.
7
EXISTING CONDITIONS
· Seepage;
· Deterioration, weathering;
· Cracking, joints;
· Construction details;
· Efficiency of drainage system;
· Foundation weaknesses.
8
RISK ASSESSMENT OF FAILURE MODES
Under Specified Load Combinations (Usual, Unusual, Extreme)
(Avoid Uncontrolled Release of Water, Structural Failure)
9
MODES OF FAILURE
Damage / Breach scenario
(Static / Transient)
10
FOUNDATION AND ABUTMENT
· Settlement;
· Sliding instability;
· Fault / joint displacement;
· Leakage, seepage;
· Tensile stresses at upstream toe;
· Grout curtains;
· Internal erosion, piping;
· Scouring of downstream foundation due to overtopping.
11
DAMS AND APPURTENANCE STRUCTURES
· Sliding;
· Overturning;
· Displacement of blocks or upper part sections;
· Failure of waterstop;
· Tensile cracking;
· Crushing;
· Overtopping;
· Opening of joints / cracks leading to uncontrolled leakage;
· Damage to spillway and hydraulic controls (erosion by abrasion, cavitation, problems with gates, excessive flow, obstruction by solids).
12
PHYSICAL IMPACT OF FAILURE: FLOODING
· High water level;
· High flow velocity in flooded zone;
· Threat to downstream dams;
· Long period of inundation;
· Deposition of silt and debris;
· Erosion.
13
DAMAGE FROM PHYSICAL IMPACT
· Social; life lost, injury;
· Economic; property damages, lost revenues;
· Environmental;
· Psychological, tarnishing of public image.

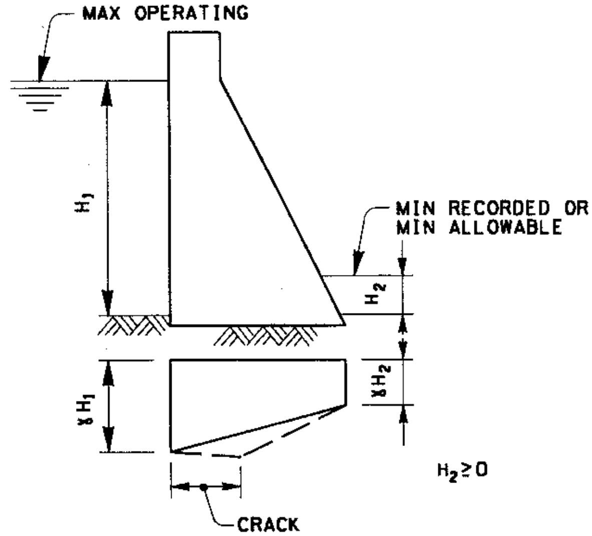
APPENDIX D - DAM SAFETY GUIDELINES UPLIFT PRESSURES

Canadian Dam Safety Association (CDSA 1995) Uplift Distributions

UPLIFT DISTRIBUTION - NORMAL LOADING COMBINATIONS

(A). FULL UPLIFT

(NO DRAINS OR EFFECTIVE RELIEF SYSTEM)

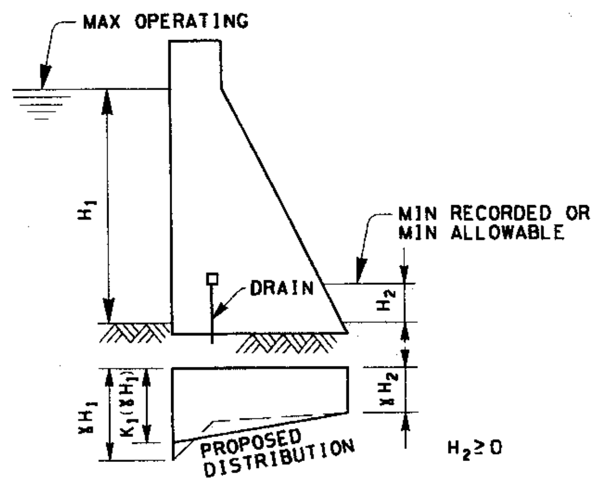


(B). REDUCED UPLIFT

(APPLICABLE ONLY IF REDUCED PRESSURE CAN BE MEASURED)

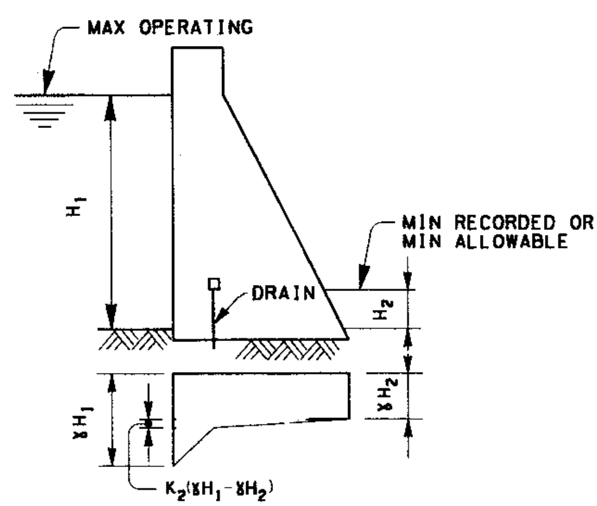
ALTERNATIVE 1

K1 = 0.67 OR TO BE DETERMINED FROM UPLIFT RECORDS



ALTERNATIVE 2

K2 = 0.33 OR TO BE DETERMINED FROM UPLIFT RECORDS



United States Army Corps of Engineers (USACE 1995) Uplift Distributions

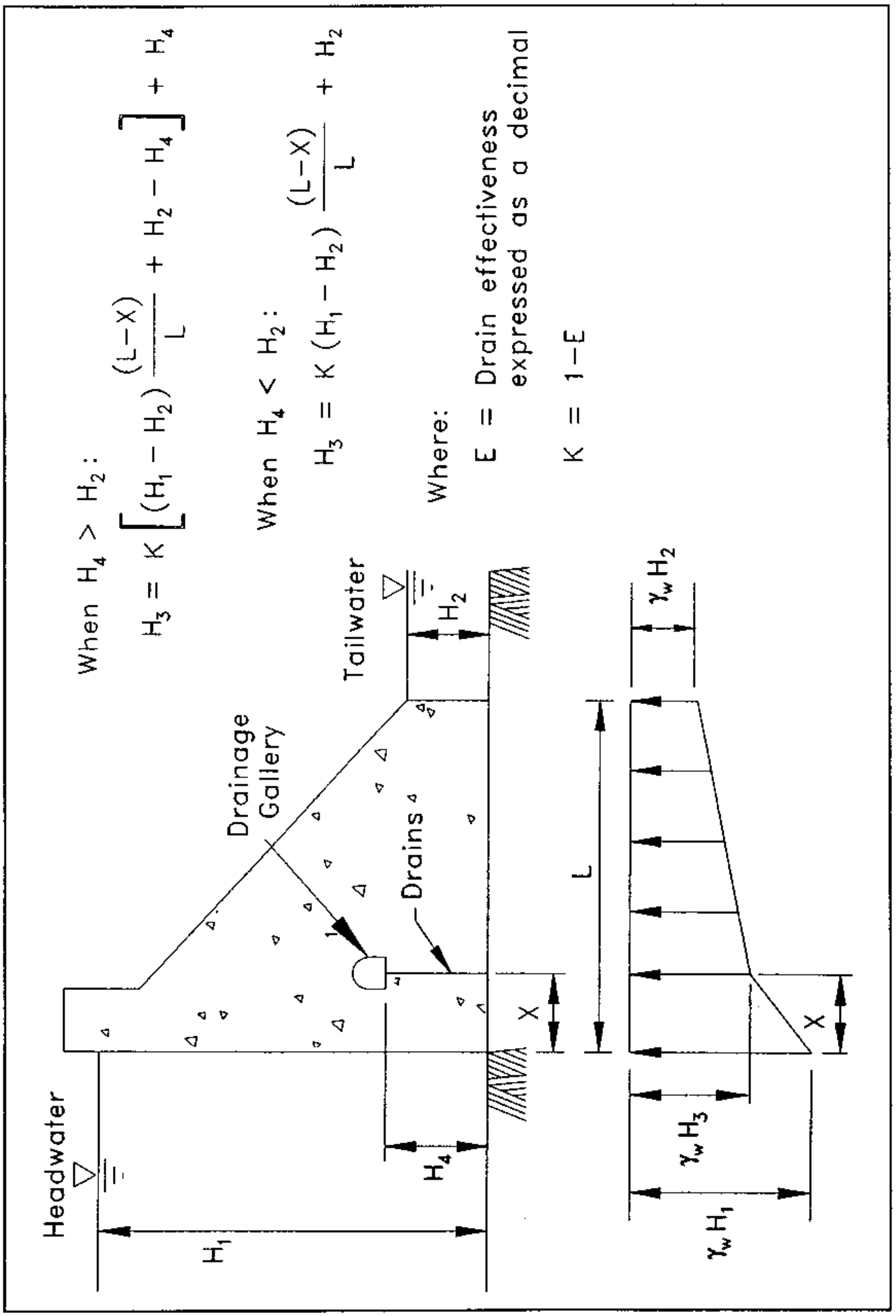


Figure 36 USACE uplift distribution with drainage gallery (no cracking).

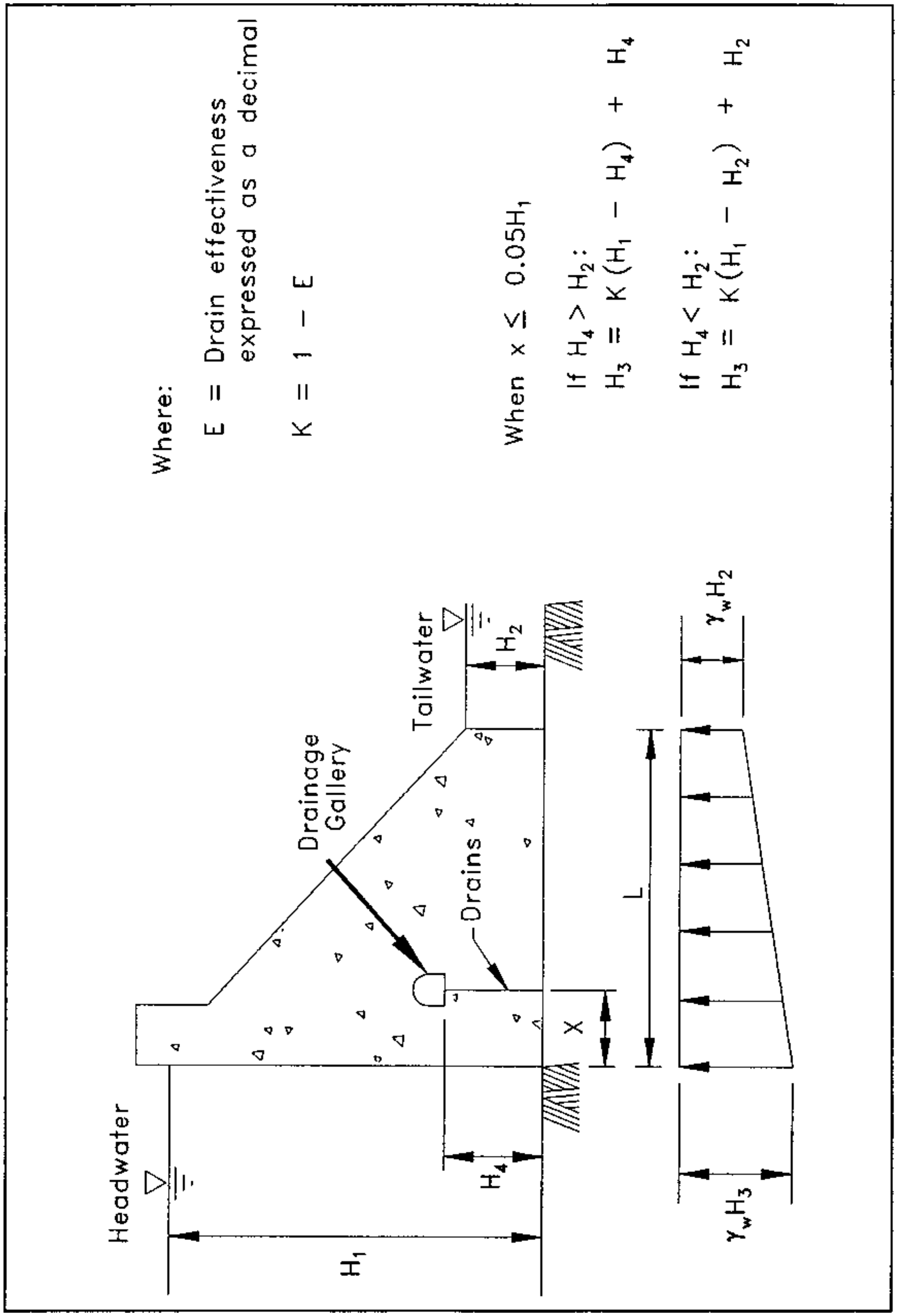


Figure 37 Usace uplift distribution with foundation drains near upstream face (no cracking).

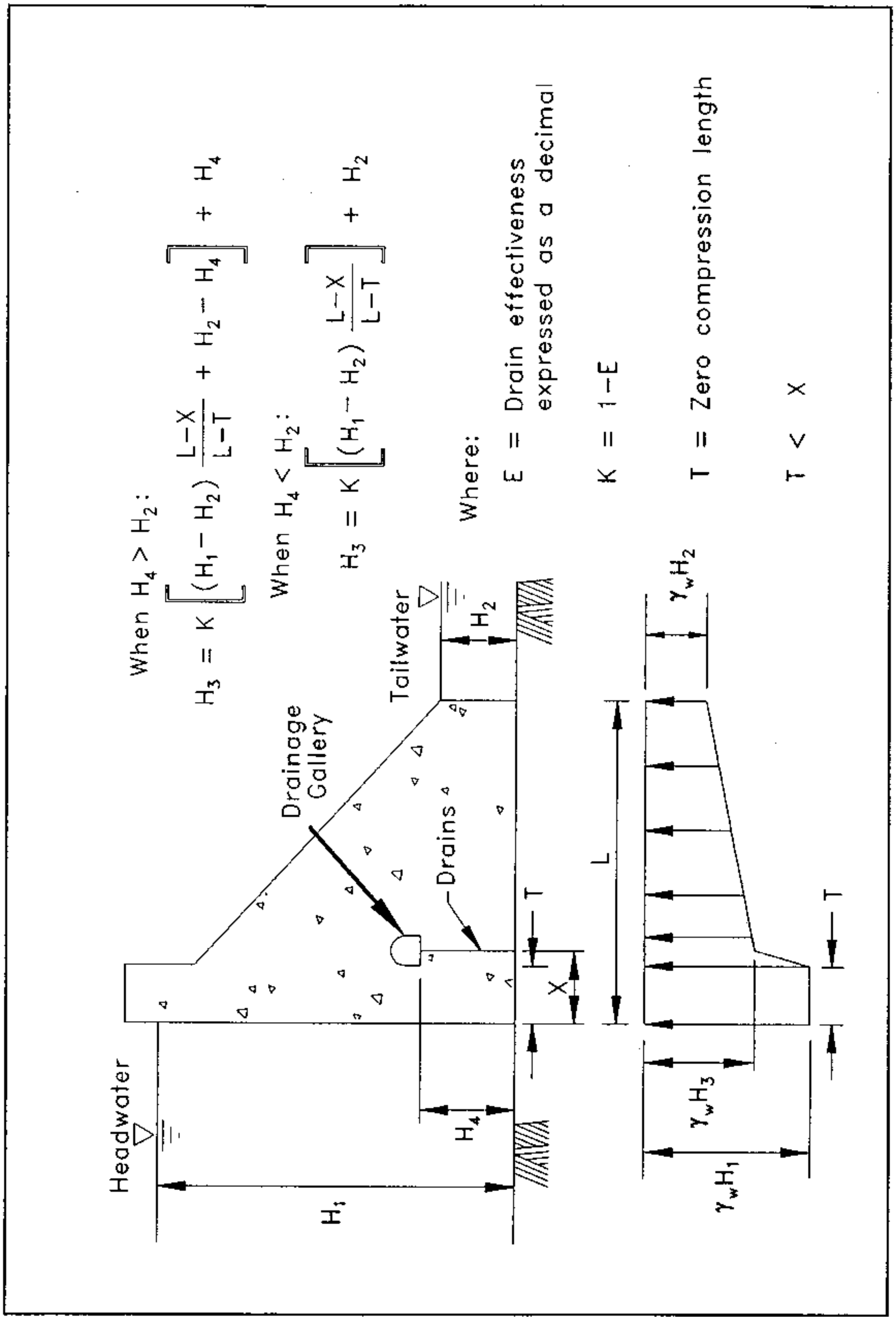


Figure 38 USACE uplift distribution with cracking not extending beyond drains

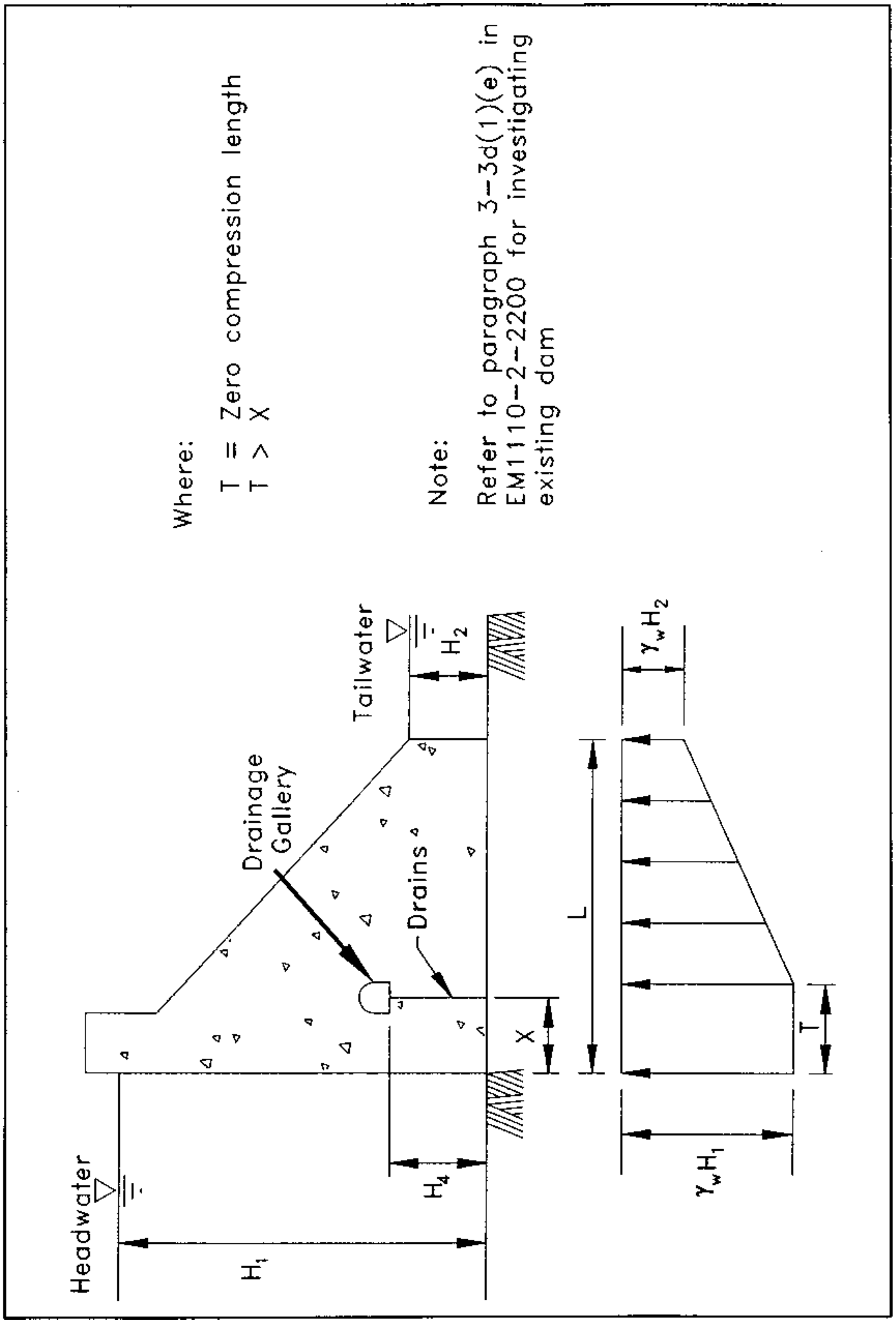


Figure 39 USACE uplift distribution with crack extending beyond drains

Department of the Interior – Bureau of Reclamation (USBR 1987) Uplift Distributions

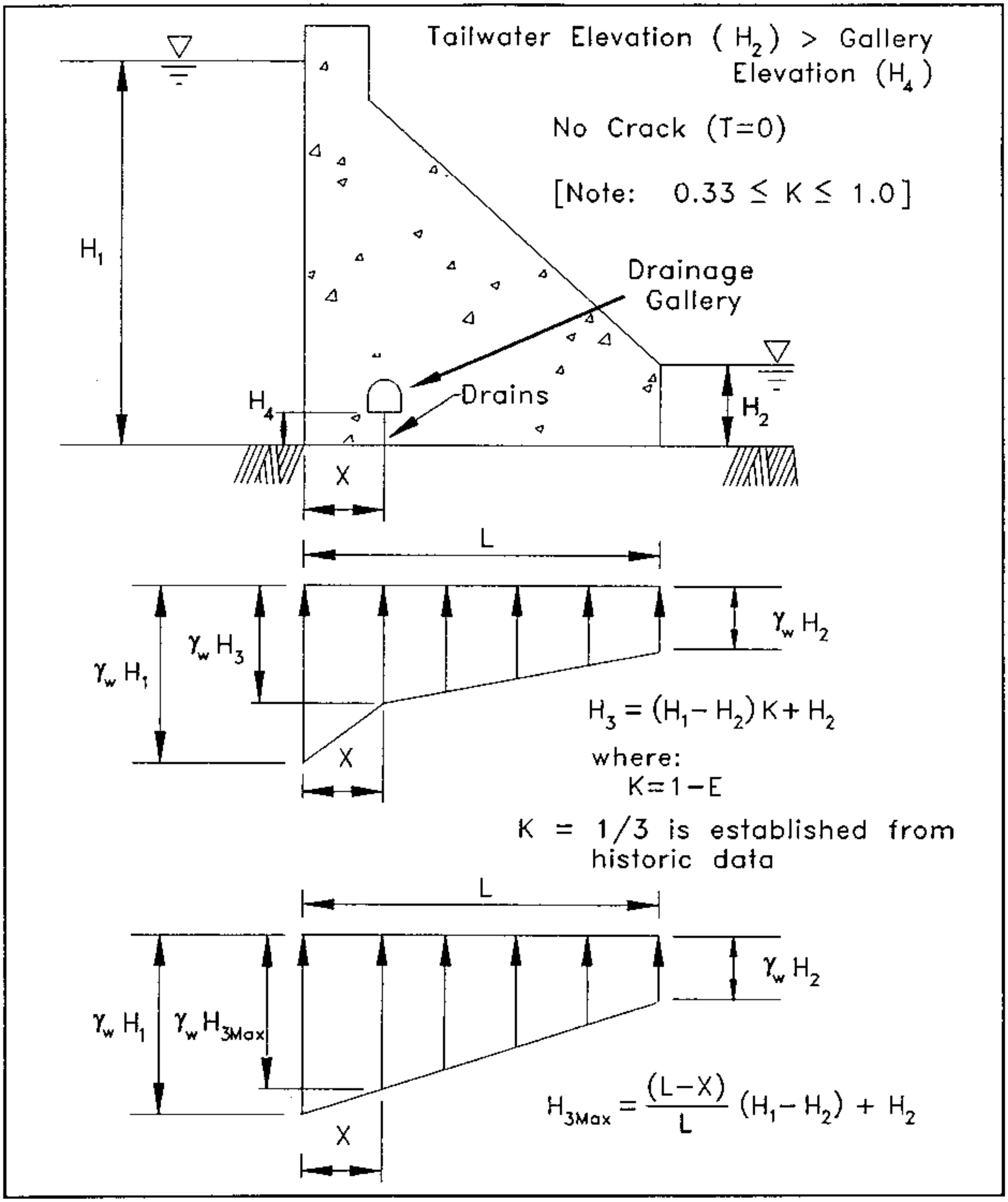


Figure 40 USBR uplift distribution with drainage gallery below tailwater (no cracking).

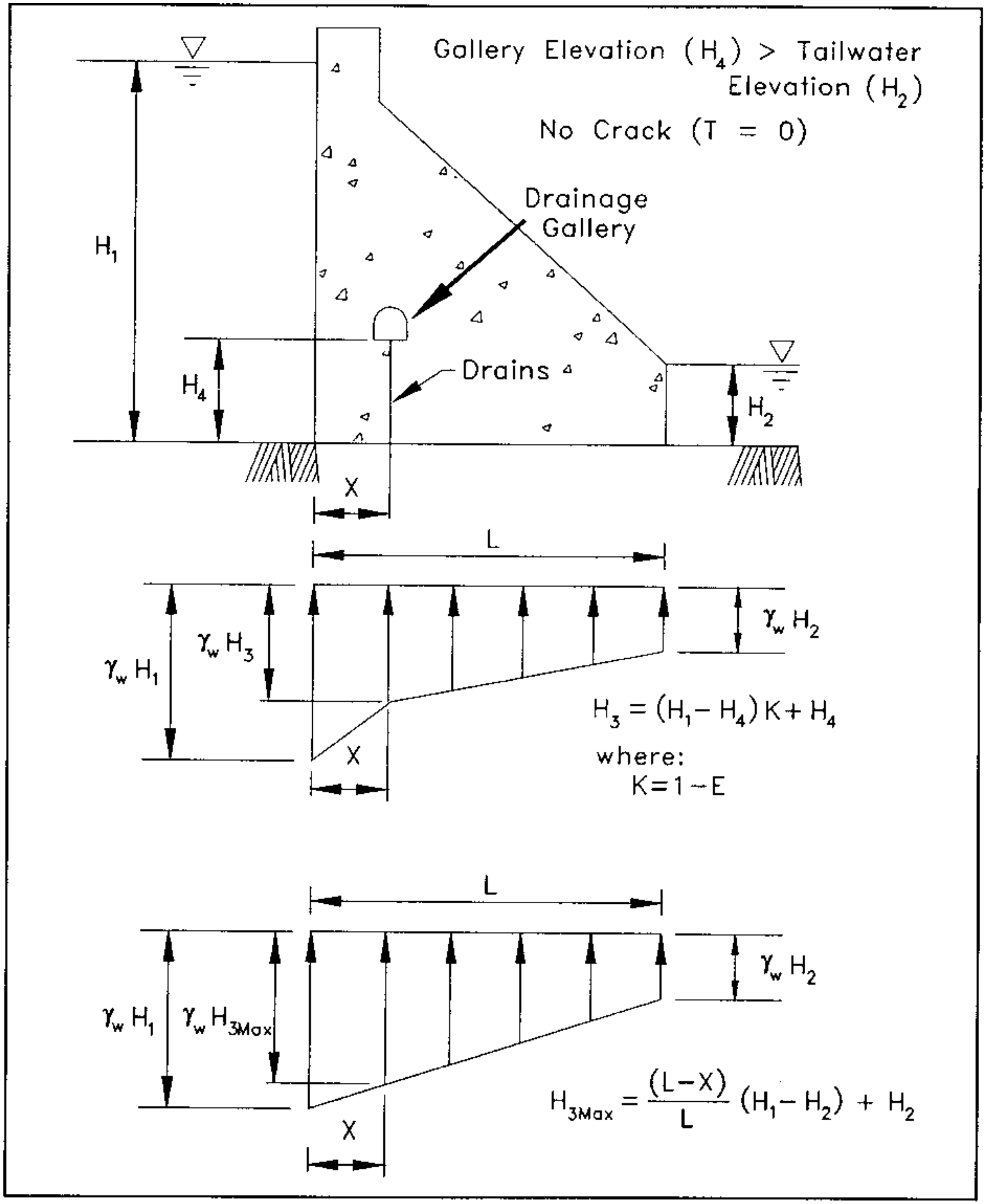


Figure 41 USBR uplift distribution with drainage gallery above tailwater (no cracking).

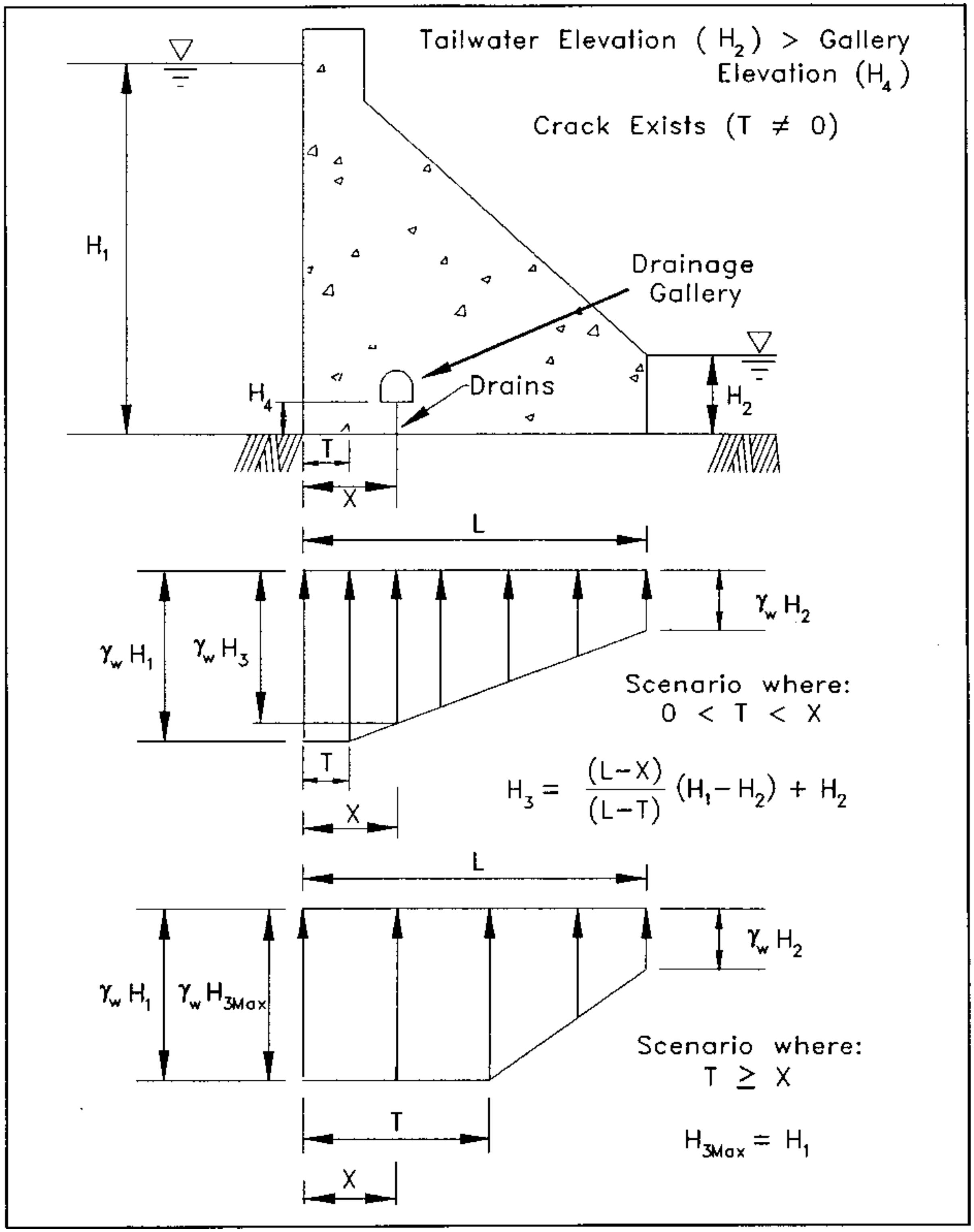


Figure 42 USBR uplift distribution with drainage gallery below tailwater and partial cracking.

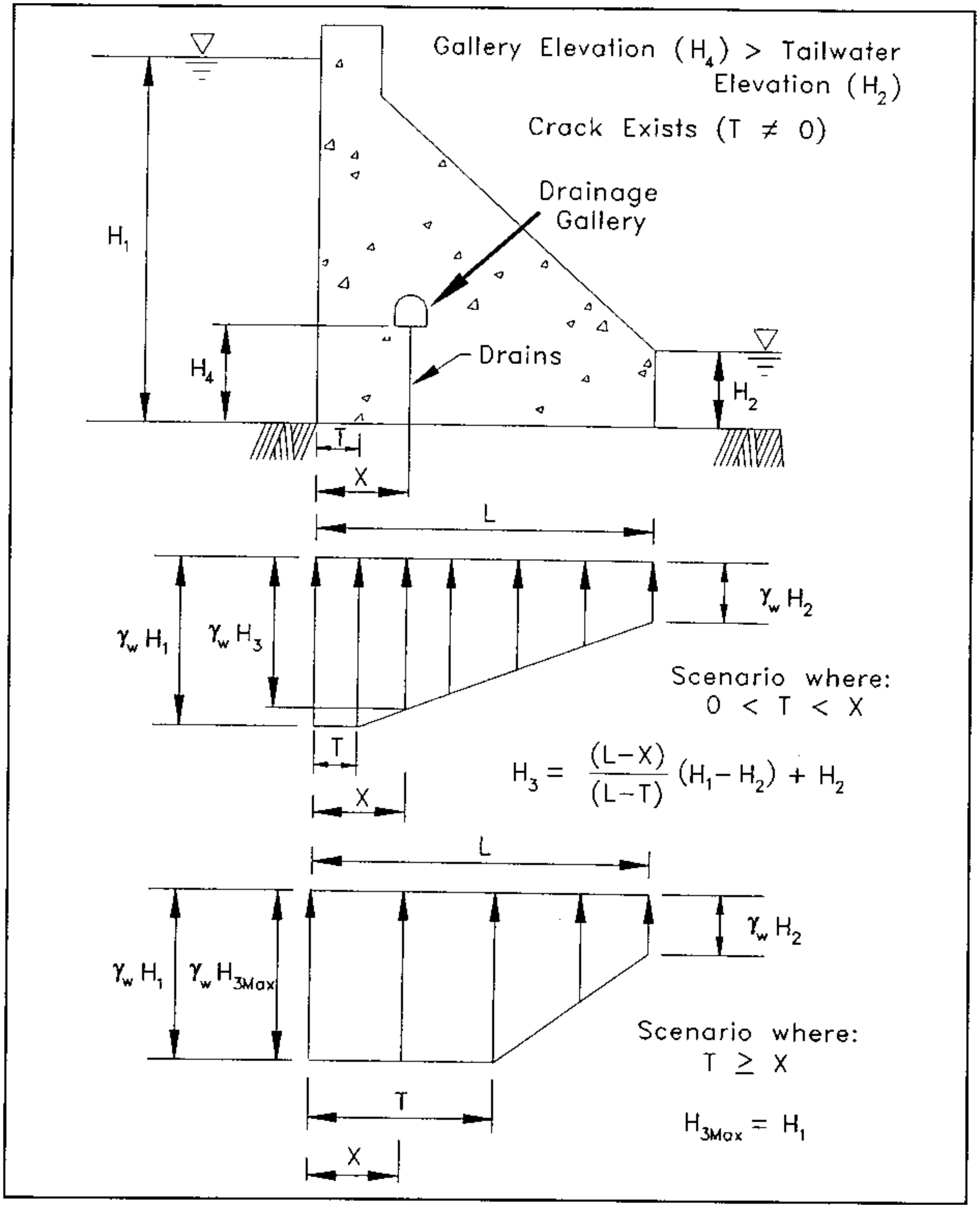


Figure 43 USBR uplift distribution with drainage gallery above tailwater and partial cracking.

Federal Energy Regulatory Commission (FERC 1999) Uplift Distributions

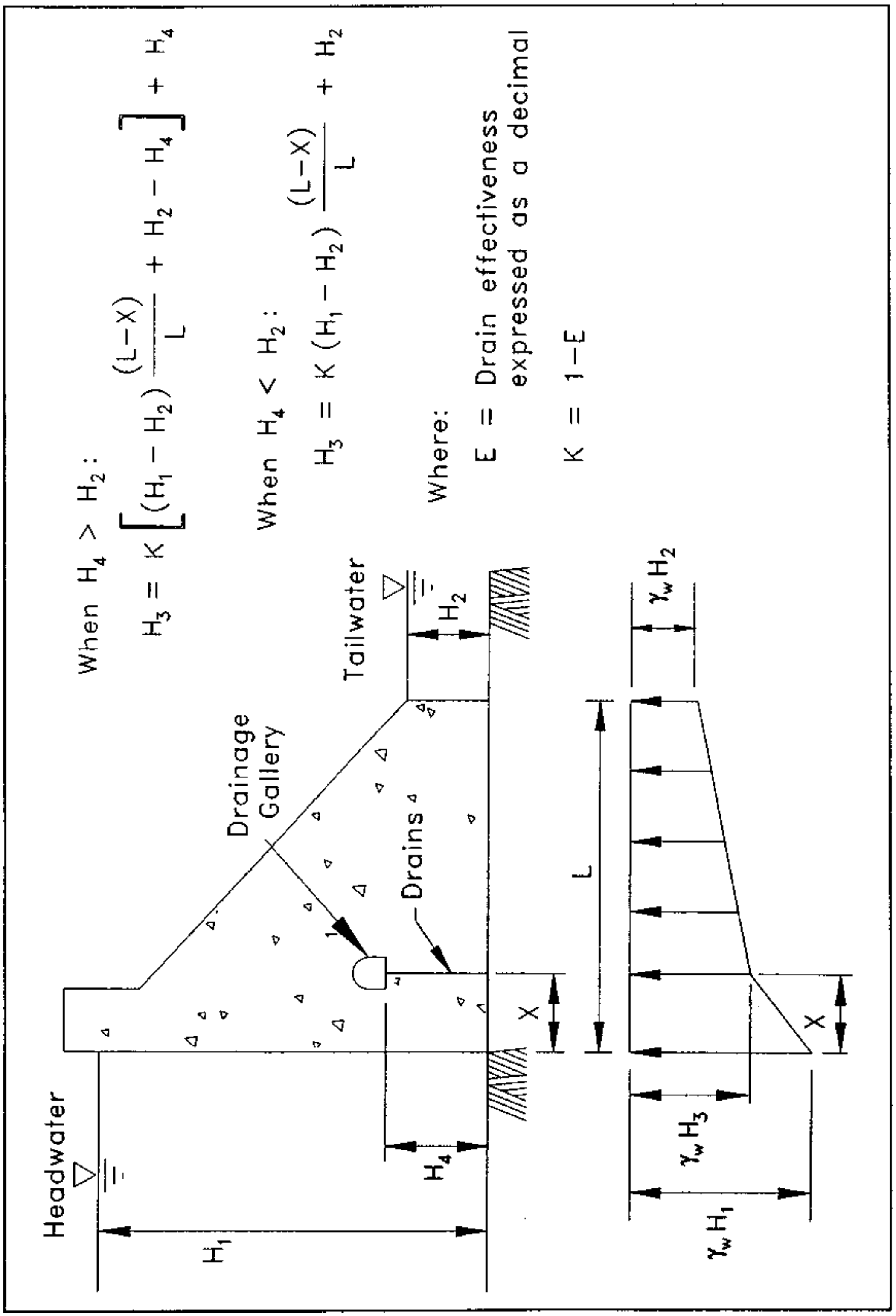


Figure 44 FERC uplift distribution with drainage gallery (no cracking)

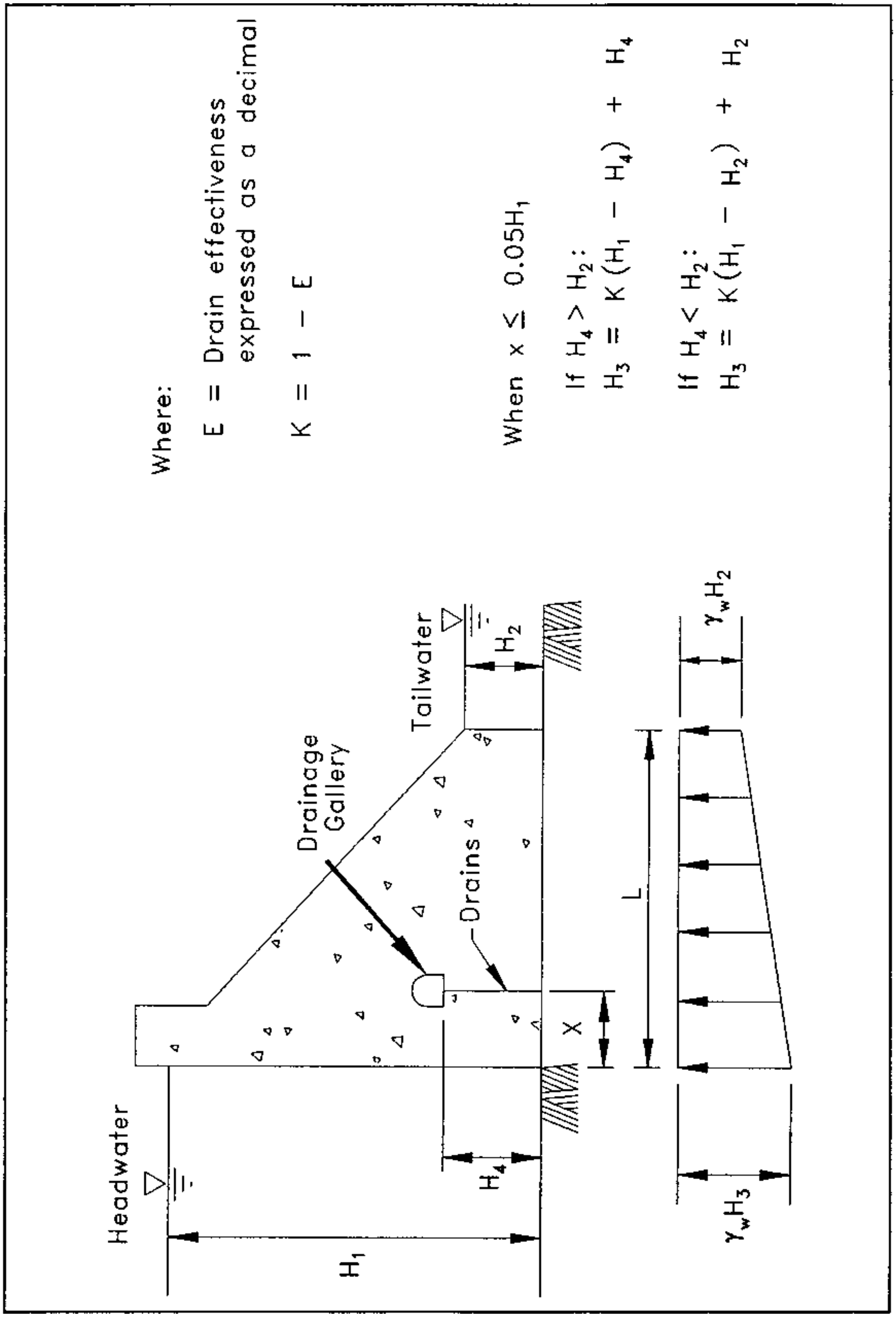


Figure 45 FERC uplift distribution with drains near upstream face (no cracking).

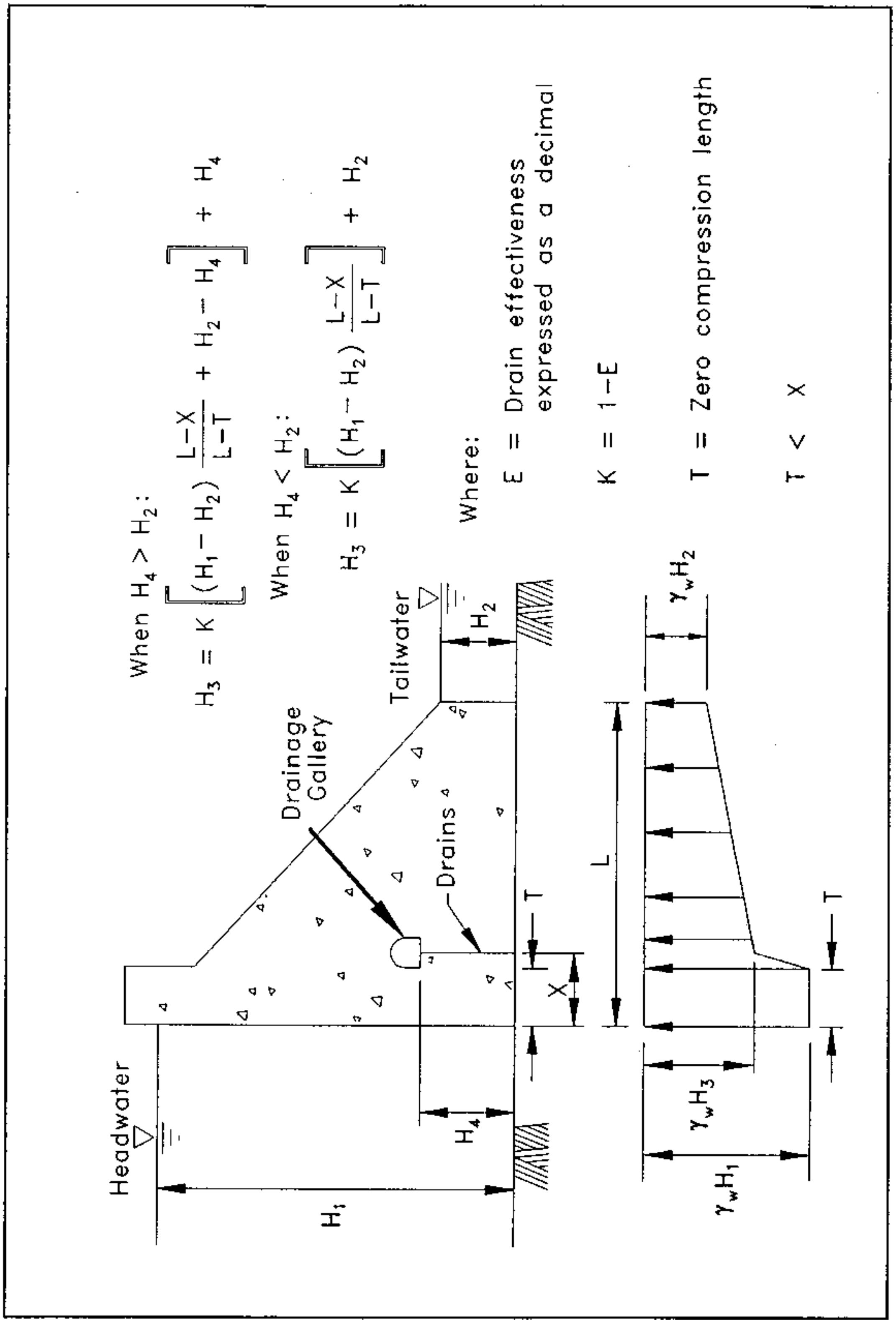


Figure 46 FERC uplift distribution with cracking not extending beyond drains

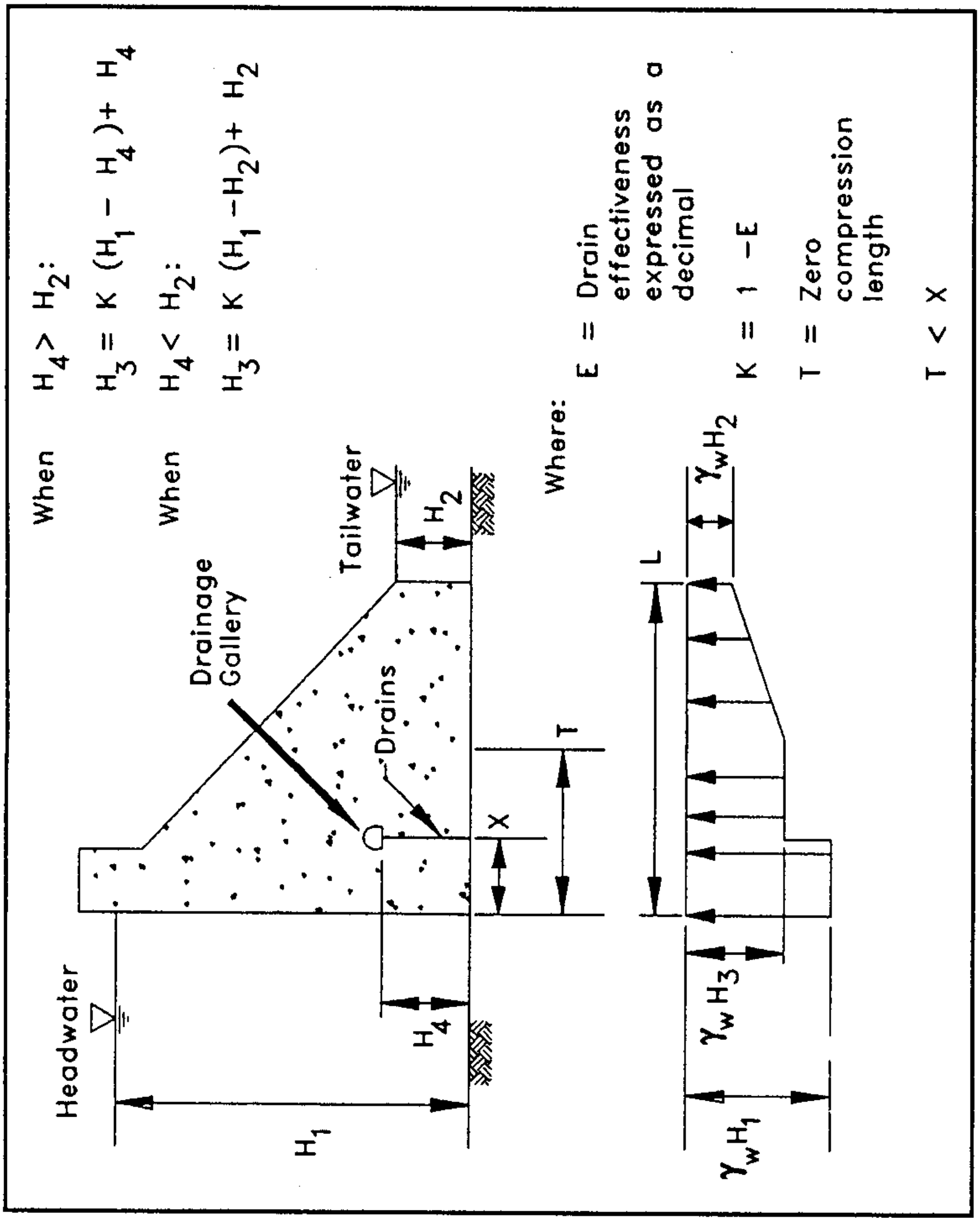


Figure 47 FERC uplift distribution when crack extends beyond drain line and measurements indicate drains are still effective.

Federal Energy Regulatory Commission (FERC 1991) Uplift Distributions

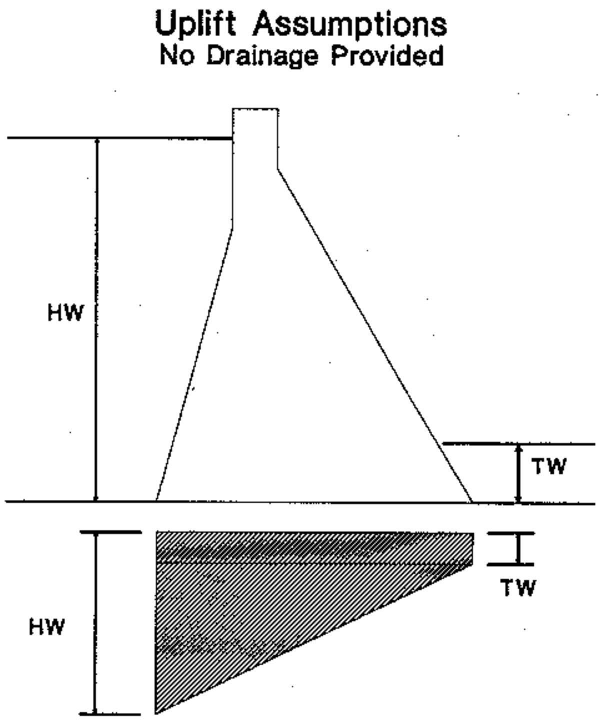


Figure 1

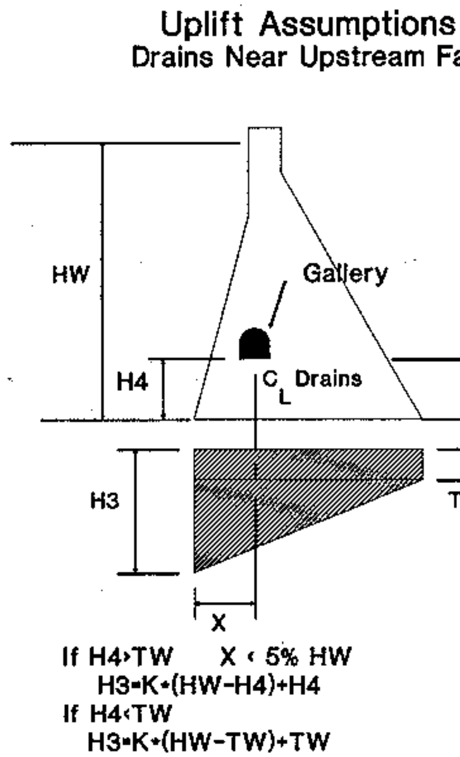


Figure 3

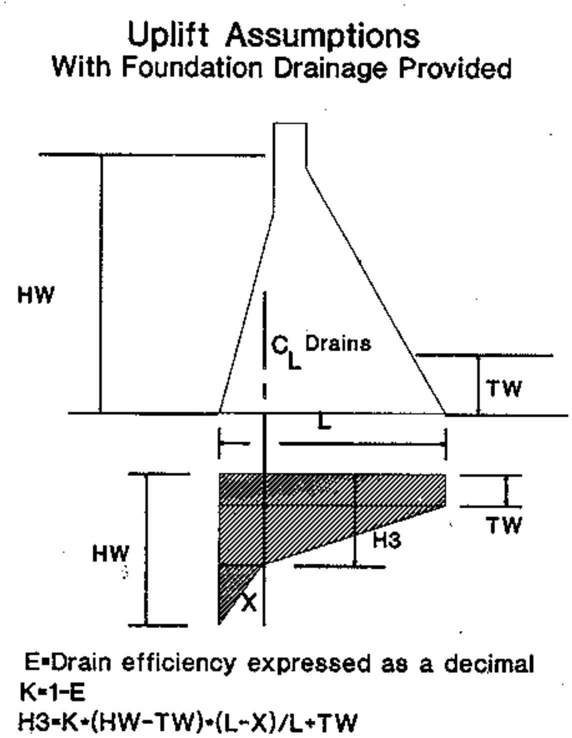


Figure 2

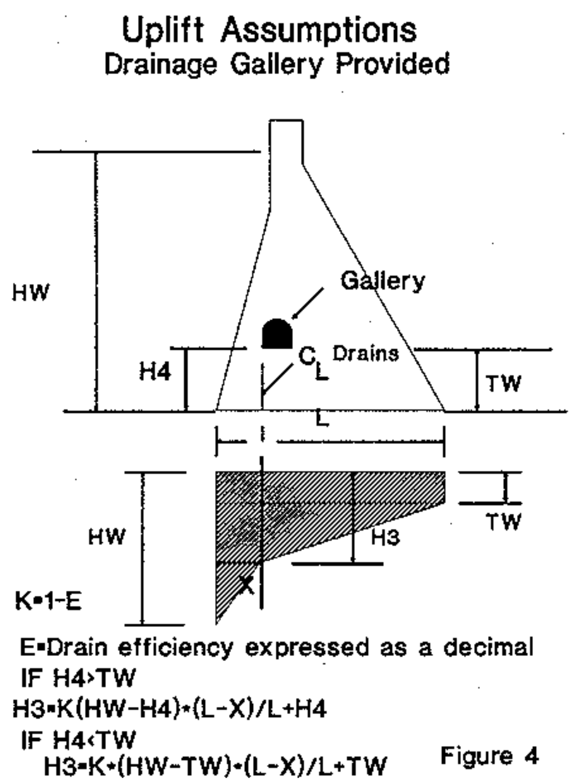
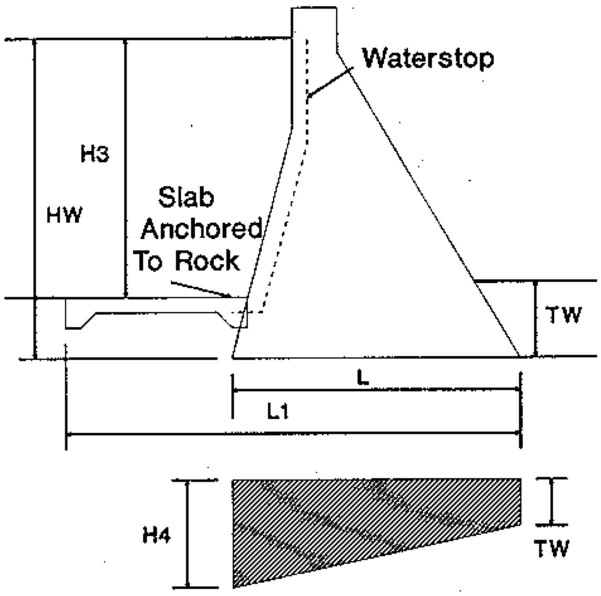


Figure 4

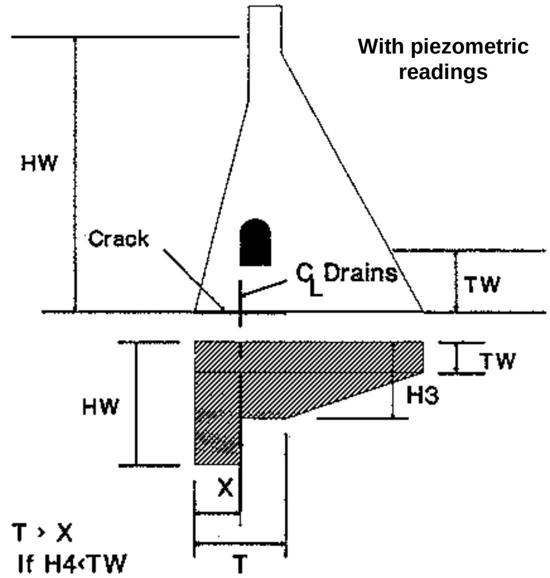
Uplift Assumptions
Upstream Cutoff



H4= (HW-TW)*L/L1 + TW

Figure 5

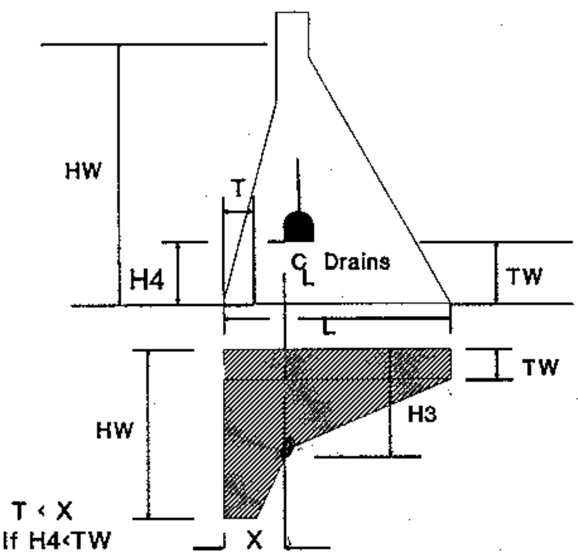
Uplift Assumptions
Cracked Base, With Drains



T > X
If H4<TW
H3=K*(HW-TW)+TW
If H4>TW
H3=K*(HW-H4)+H4

Figure 7

Uplift Assumptions
Cracked Base, With Drains



T < X
If H4<TW
H3=(HW-TW)(K*(L-X)/L+(T/X)*(1-K*(L-X)/L))+TW
IfH4>TW
H3=(HW-TW)(K*(L-X)/L+(T/X)*(1-K*(L-X)/L))+H4
T=Crack Length

Figure 6

Uplift Assumptions
Cracked Base, With Drains

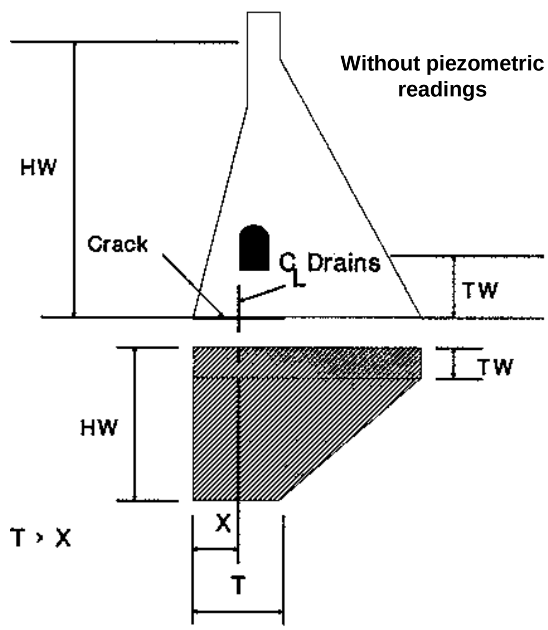


Figure 8