About CADAM

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CADAM: **C**omputer **A**nalysis of concrete gravity **DAM**s.
Version: **Educational release 1.4.3** (April 6, 2001).
NSERC / Hydro-Quebec / Alcan Industrial Chair on Safety of Concrete Dams.
École Polytechnique de Montréal, Canada.
Platforms: Windows 95, 98, NT, 2000, Me.
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Chairmans: Pierre Léger & René Tinawi.
Compiler: Delphi pro 5.

Legal Disclaimer

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INTRODUCTION

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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 (eg. 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 (CDA 1999, FERC 1999, USACE 1995, FERC 1991 & USBR 1987).
- To study different strengthening scenarios (post-tensioning, earthbacking, buttressing).

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.

System Requirements

CADAM runs under Windows 95, 98, NT, 2000 and Me. Your system must have the following:

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

Note: On Windows NT 4.0, Service Pack 3 must be applied before you install and use *CADAM*.

Installing/Uninstalling CADAM

To install or update CADAM from the web site: http://www.struc.polymtl.ca/cadam/

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

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 doesnt, run **setup.exe** (in your CD drive) 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. Depending on your system configuration, ***CADAM*** setup program may update the library COMCTL32.dll located in your Windows

You are now ready to run ***CADAM***!

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

To uninstall ***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 .**

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 Fig 2. Figure 3 shows the basic loading conditions supported for static analysis. Figures 4 and 5 show the basic loading conditions supported for the pseudo-static and pseudo-dynamic seismic analyses, respectively.

Basic Analysis Capabilities

The program supports the following analysis capabilities:

- Static Analyses: CADAM could perform static analyses for the normal operating reservoir elevation or the flood elevation including overtopping over the crest.
- Seismic Analyses: CADAM could perform seismic analysis using the **pseudo-static** method (seismic coefficient method) or the **pseudo-dynamic** method, which corresponds to the simplified response spectra analysis described by Chopra (1988) for gravity dams.

- Post-Seismic Analyses: 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.
- Probabilistic Safety Analysis (Monte-Carlo simulations): 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.
- Incremental Load Analysis: 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).

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:

- Section geometry: Specification of the overall dimensions of the section geometry. Inclined upstream and downstream faces as well as embedding in the foundation (passive d/s wedge) are supported.
- Masses: 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 wedge).
- Lift joints: Assign elevation and material properties to the lift joints. Inclined joints are supported.
- Pre-cracked lift joints: Assign upstream/downstream cracks in joint(s) as initial conditions.
- Reservoir, ice load and silt: Specification of water density, normal operating and flood headwater and tailwater elevations, ice loads and silt pressure (equivalent fluid, frictional material at rest, active or passive).
- Drainage system: Specification of drain location and effectiveness. The stresses computations be performed through linearisation of effective stresses (CDA 1999, FERC 1999, USACE 1985, USRB 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: Users defined horizontal and vertical forces can be located anywhere along the u/s face, the crest or the d/s face.
- Pseudo-static analysis: Specification of the peak ground horizontal and vertical accelerations as well as the sustained accelerations. Westergaards 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 Westergaards 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: Specifications 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.
- Probabilistic safety analysis: 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.
- Incremental Analysis: 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.

BASIC MODELLING INFORMATION

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.

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…).

1.3 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:

- A stress analysis to determine eventual crack length and compressive stresses,

- 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.

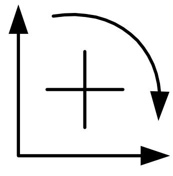
The gravity method is based (a) on rigid body equilibrium to determine the internal forces acting on the potential failure plane (joints and concrete-rock interface), and (b) on beam theory to compute stresses. The use of the gravity method requires several simplifying assumptions regarding the structural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

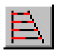
- The dam body is divided into lift joints of homogeneous properties along their length, the mass concrete and lift joints are uniformly elastic,
- All applied loads are transferred to the foundation by the cantilever action of the dam without interactions with adjacent monoliths,
- There is no interaction 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).

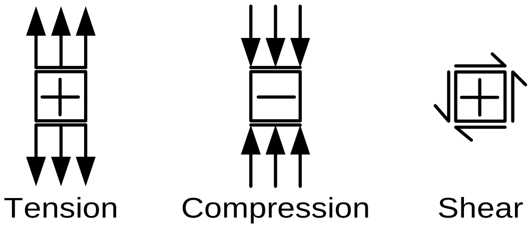
A special attention must be given to the interpretation of the computed magnitude and distribution of stresses along the dam-foundation interface while using the gravity method. The stresses and base crack likely to occur could be affected by the deformability of the foundation rock that is not taken 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).

Sign Convention

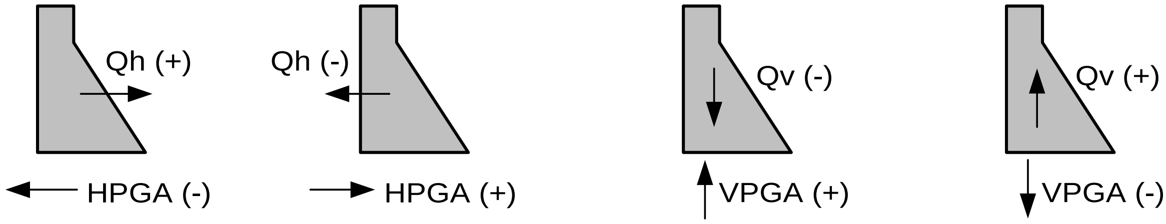
- Global system of axis: The origin of the global axis system is located at the heel of the dam. The global axis system allows to locate the coordinate of any point of the dam body along the horizontal "x =" direction, and the vertical "el.=" direction.
- Local Joint axis system: The dam base joint and 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 the figure below is used to define positive forces and moments acting in the global coordinate system.



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



<u>Positive direction of inertia forces:</u> According to dAlembert principle, the inertia forces induced by an earthquake are in the opposite direction of the applied base acceleration.



General Information

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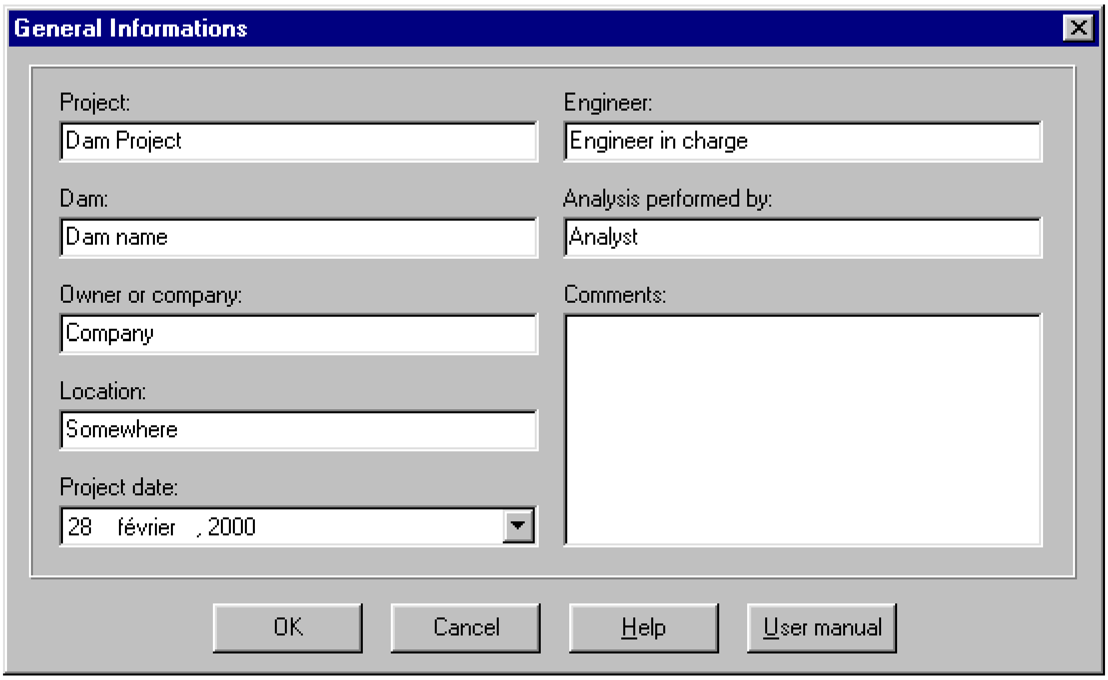

This window is to input general information about the dam analysed. This information appears in the reports displaying the results, except for the comments part. The comments are associated with a particular problem and allow the user to leave notes that will be accessible while reloading the problem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

Section geometry & Basic data:

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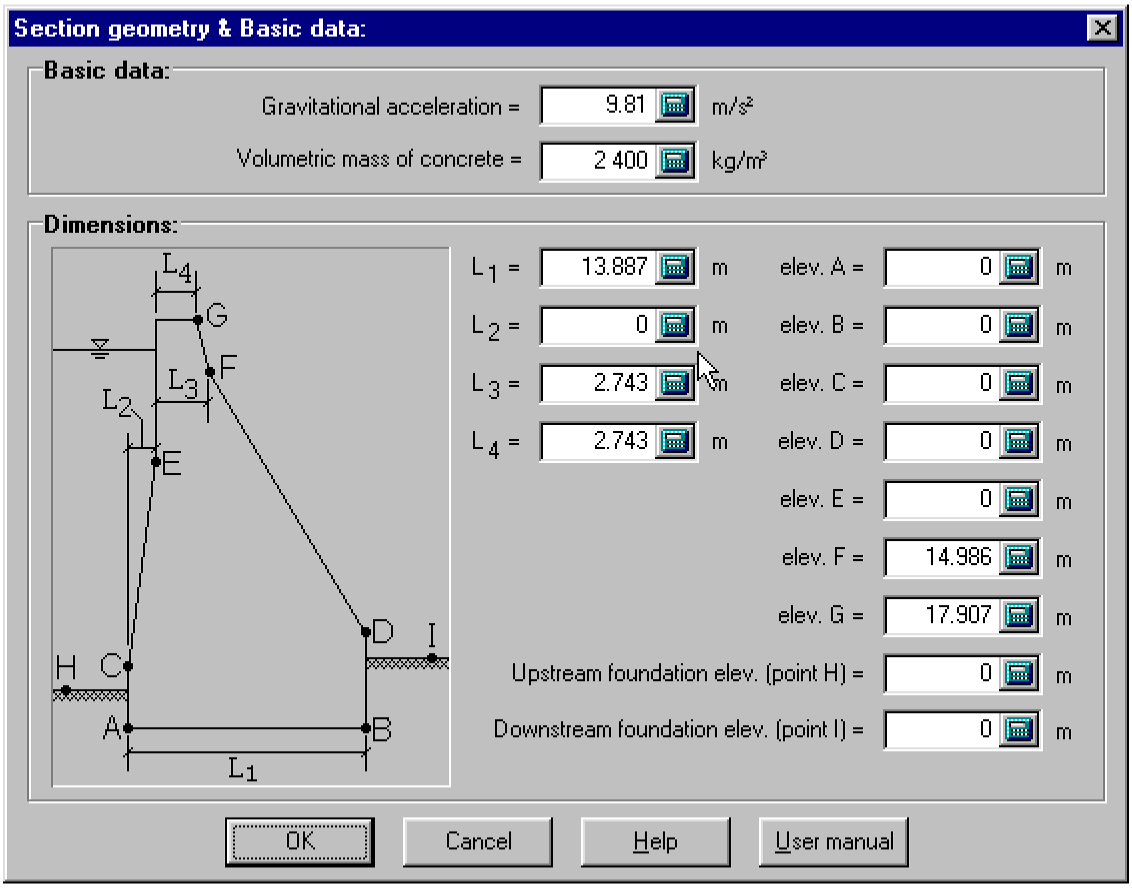

This window is to input the key points and basic geometrical dimensions to define the dam cross-section. The system of units, gravitational acceleration and volumetric mass of concrete are specified.

WARNING: Once the geometry is specified and if the user is comming back to this windows, CADAM will re-initialise the problem by erasing all data (materials, joints, reservoir, seismic inputs, etc...)

Concentrated Mass(es)

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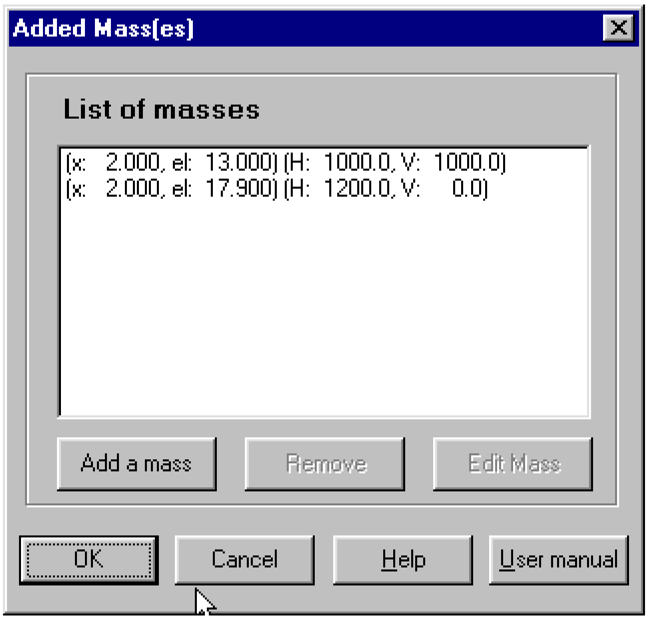


This window is used to add or subtract vertical and/or horizontal concentrated masses located arbitrarily within or outside of the dam cross-section. The masses could be used to represent fixed equipment located on the crest, or to introduce corrections to the basic cross section to represent holes or 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.

To add a mass:

Press the button <**Add a mass**>, another dialog window will appear: click here to see this window

After filling the appropriate fields and by pressing the OK button, you will get back to the first dialog window. All your information entered will appear in a new line:
example: (x: 2.000, el.: 51.820, H: 1200.0, V: 1200.0)

To change a mass properties:
Select a mass from the list in the first dialog window and press <Edit mass>. The Mass properties dialog window will appear with the corresponding properties of the mass to edit. Simply change the parameter properties and press OK. Only one concentrated mass can be edited at the same time.

To remove one or many masses:

Select one or many masses (using CTRL+Left mouse button or SHIFT+Left mouse button) from the list in the first dialog window and then press <Remove>. Warning:

Once removed, masses are not retrievable.

How Concentrated masses are handled by CADAM:

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

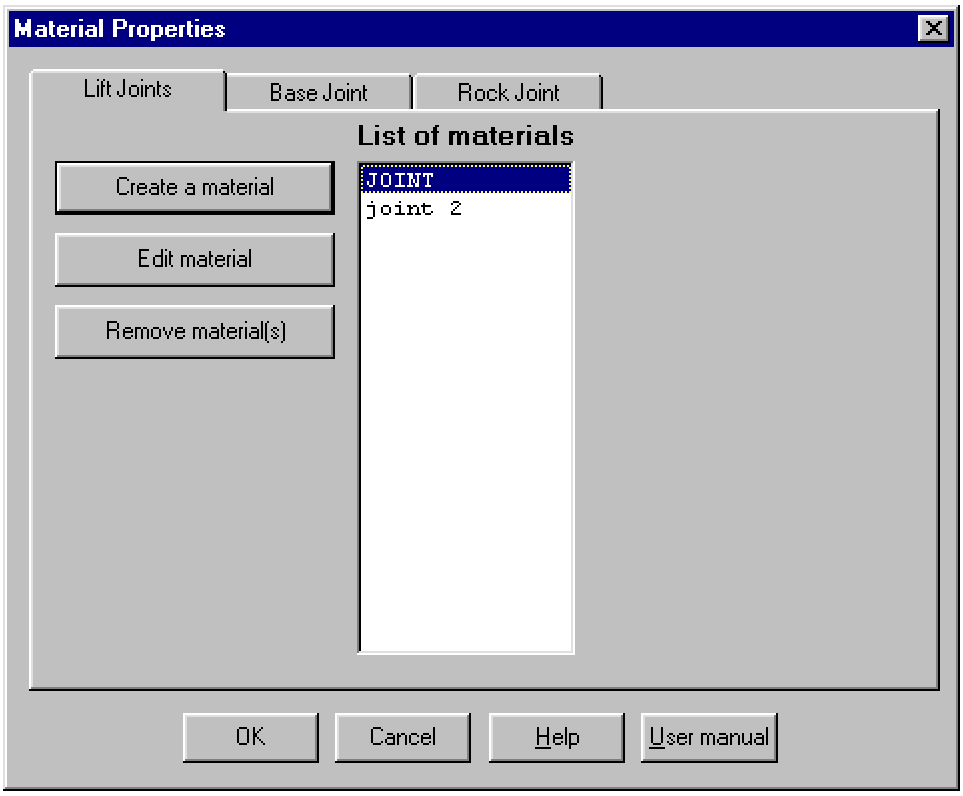
Pseudo-static seismic analysis: The inertia forces induced by concentrated masses are computed as the product of the mass and the specified seismic acceleration (either the peak ground acceleration or the sustained acceleration according to the analysis performed)

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 masses 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.

Material Properties

main page

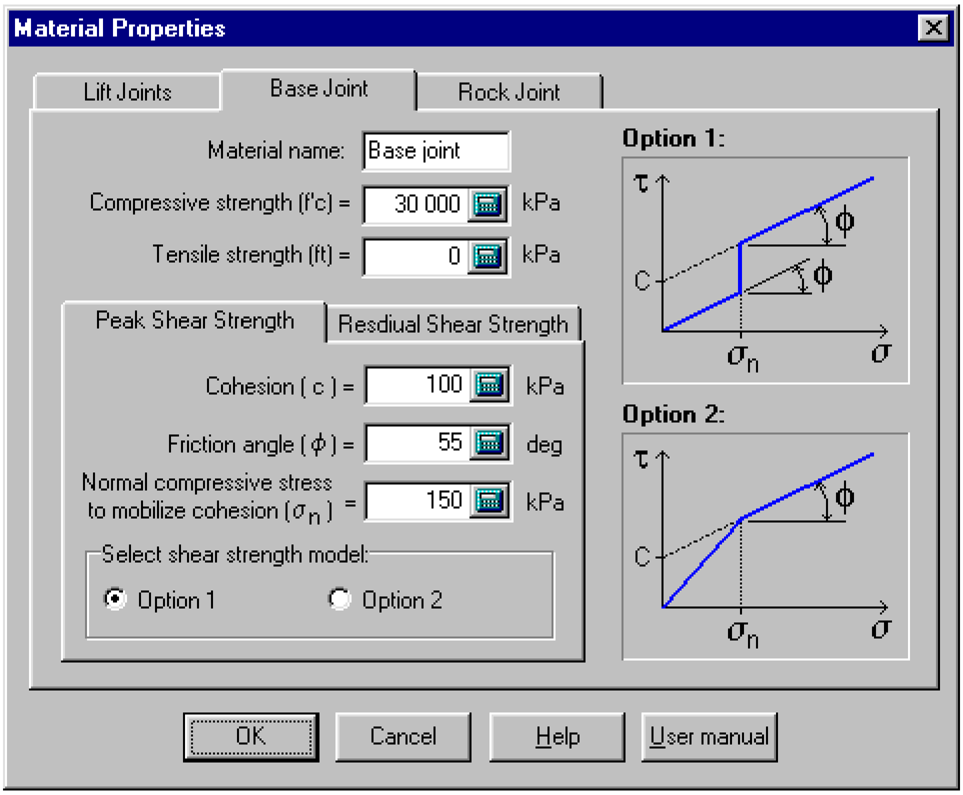
Lift Joints:



Specifying material strength properties:
This window is used to create a list of lift joint material properties. You can create new materials with different names. You could define as many as needed materials to describe variations of strength properties along the height of the dam.

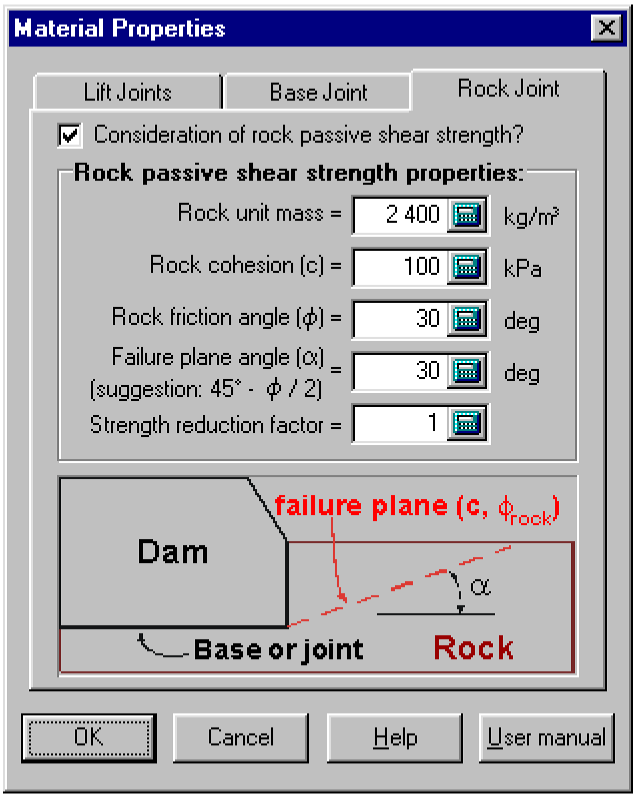
To create a new material: Press <Create a material> and a new dialog window will appear.

Base Joints:



The material strength properties at the concrete-rock interface are specified, using same models (options) as those for lift joints. click here for more informations

Rock Joints:



In the case where the dam is embedded in the foundation, this window allows the definition of parameters required to include the contribution of a passive wedge resistance to the sliding resistance of the dam. 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).

Lift joints

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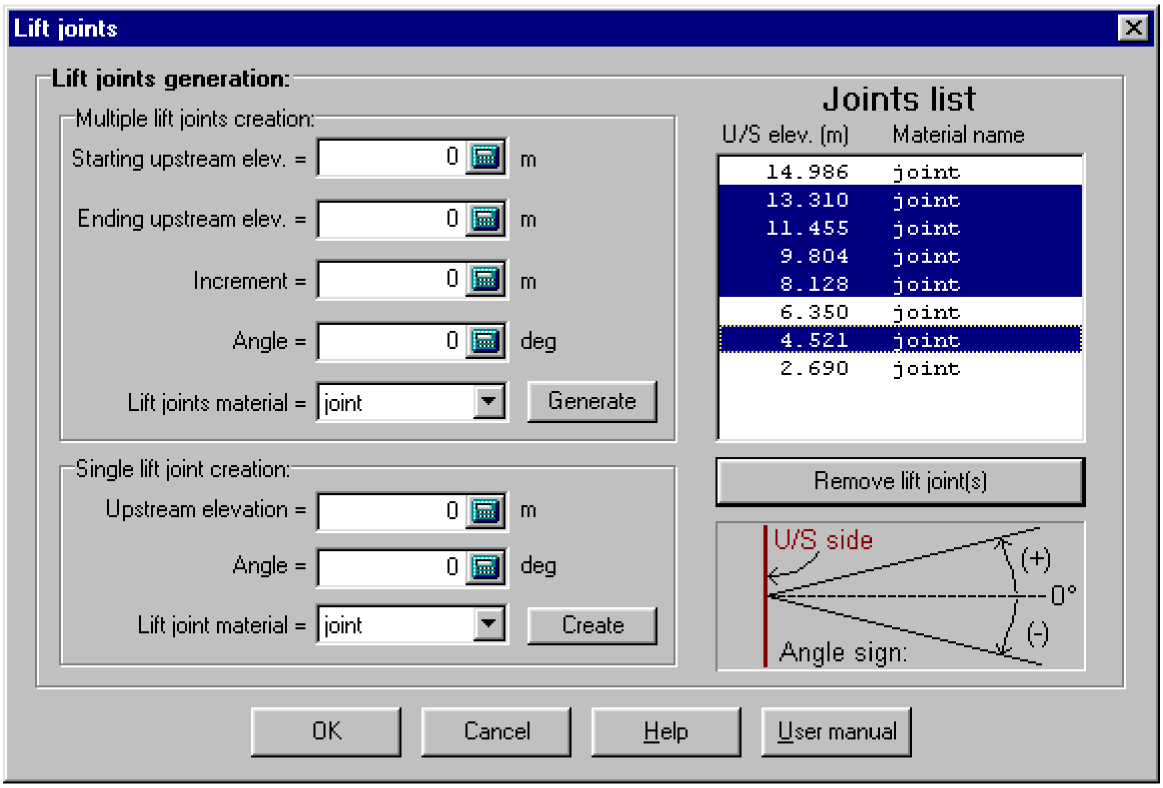

This window allows the automatic generation of lift joints along the height of the dam. The inclination angle of the joint could be specified. Material properties could be assigned to group of lift joints. Single lift joints could be added to the list of joints.

Lift joints are considered as failure planes for nonlinear calculations. No other failure planes are considered, except for the rock-concrete interface (base of the dam). This joint is automatically considered in the computational steps. You do not have to create the base joint.

To generate many lift joints:

- Enter the lowest upstream elevation of the lift joints in the field **Starting upstream ele. =**
- Enter the highest upstream elevation of the lift joints in the field **Ending upstream ele. =**
- Enter the increment in elevation in the field **Increment =**
- Enter the angle of inclination (optional) of the lift joints in the field **Angle =**. Refer to the drawing in the dialog window for the angle sign.
- Select a materail from the scroll list **Lift joints material =**. The material list is composed of all the material defined in the Material properties dialog window.
- Press the button **Generate.**

CADAM will automatically generates all the lift joints between the lowest and the highest elevation with a spacing equal to the increment. If the highest elevation is not a multiple of the increment, no lift joint is created at this elevation. *CADAM* automatically computes the upstream and downstream coordinates. The generated lift joints will appear in the Joints list, located on the right side of the dialog window.

To generate a single lift joint:

- Enter the upstream elevation of the lift joint in the field **Upstream ele. =**
- Enter the angle of inclination (optional) of the lift joint in the field **Angle =**. Refer to the drawing in the dialog window for the angle sign.
- Select a materail from the scroll list **Lift joint material =**. The material list is composed of all the material defined in the Material properties dialog window.
- Press the button **Create.**

To delete one or many lift joints from the Joints list:

- Select the lift joints to be deleted from the **Joints list** (using CTRL+Left mouse button or SHIFT+Left mouse button).
- Press the **Remove lift joint(s)** button.

Pre-cracked lift joints

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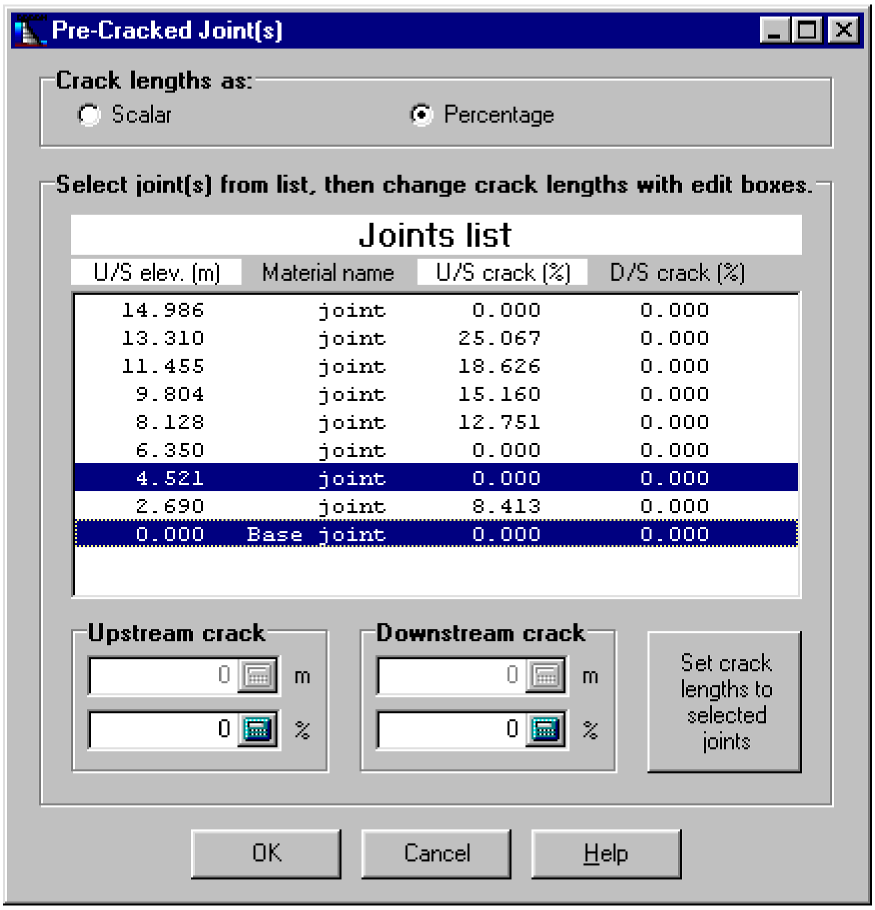


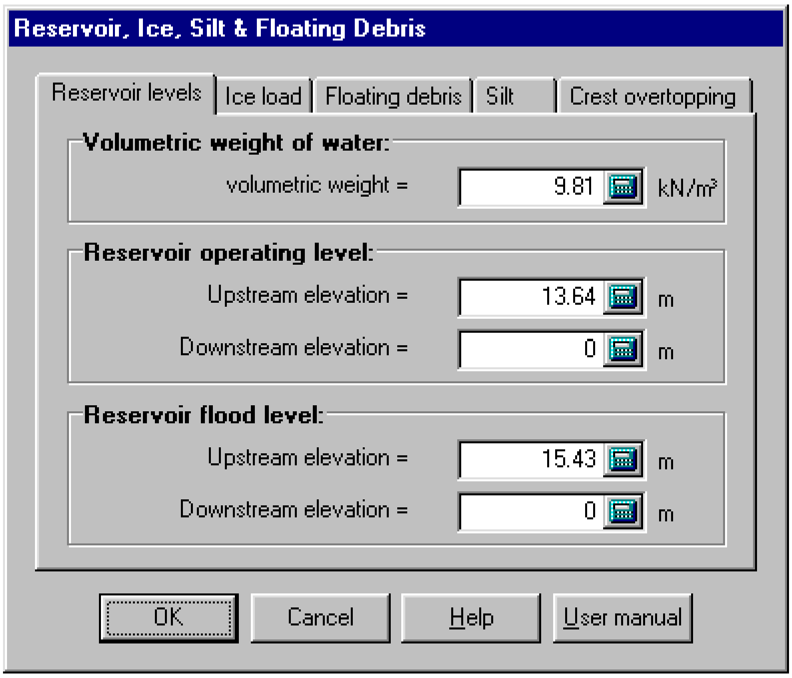
This window allows the user to assign existing cracks to lift joints along the height of the dam. These cracks and related uplift pressures are considered as initial conditions and will always be considered in all load combinations. Cohesion is set to zero along a crack. Moreover, these cracks will be 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.

Reservoir, Ice, Floating Debris & Silts

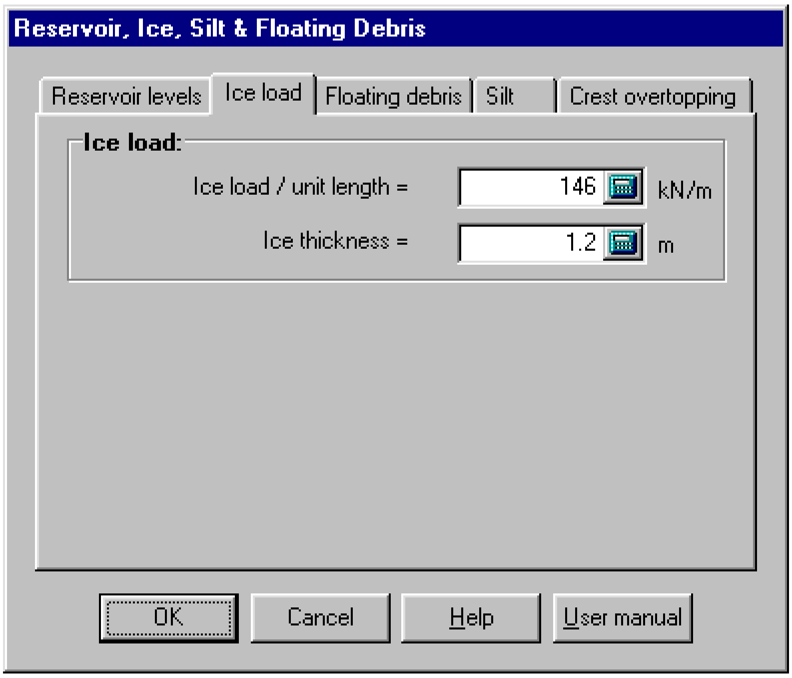
Main page

Reservoirs:



This window allows the specification of the volumetric weight of water, as well as the normal and flood headwater and tailwater elevations. Water levels below the foundation surface are possible and handle by CADAM. The default elevations for empty reservoirs are the foundation elevations. **WARNING**: In the case where the dam is embedded in the foundation, special attention should therefore be taken into account regarding all water elevations.

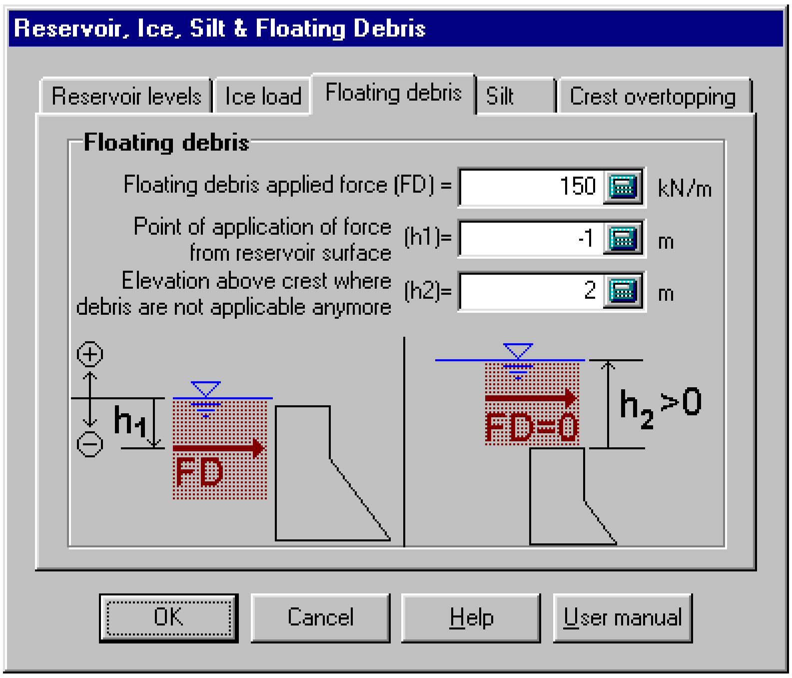
Ice Load:



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.

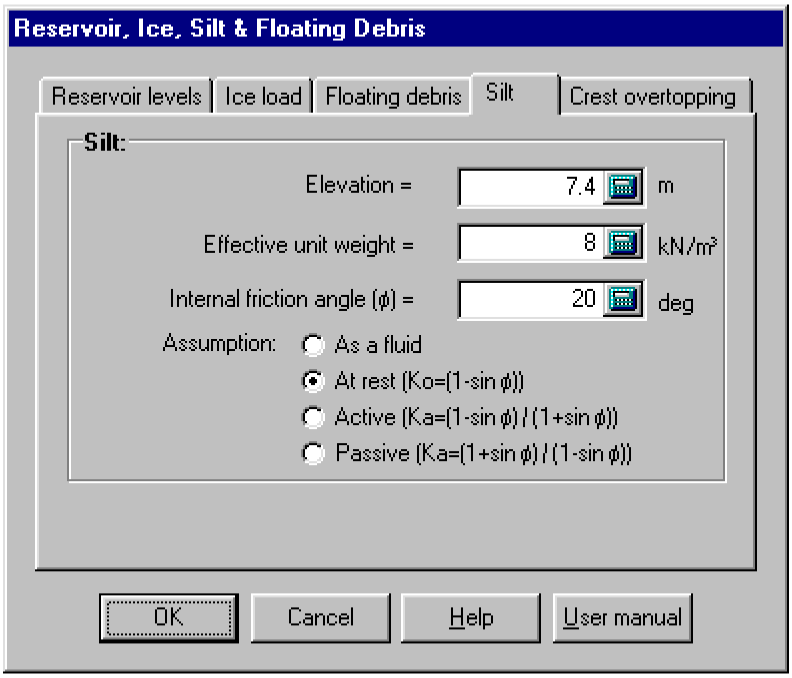
Note: Ice load will be ignored upon an overtopping of the reservoir greater than the ice thickness.

Floating Debris:



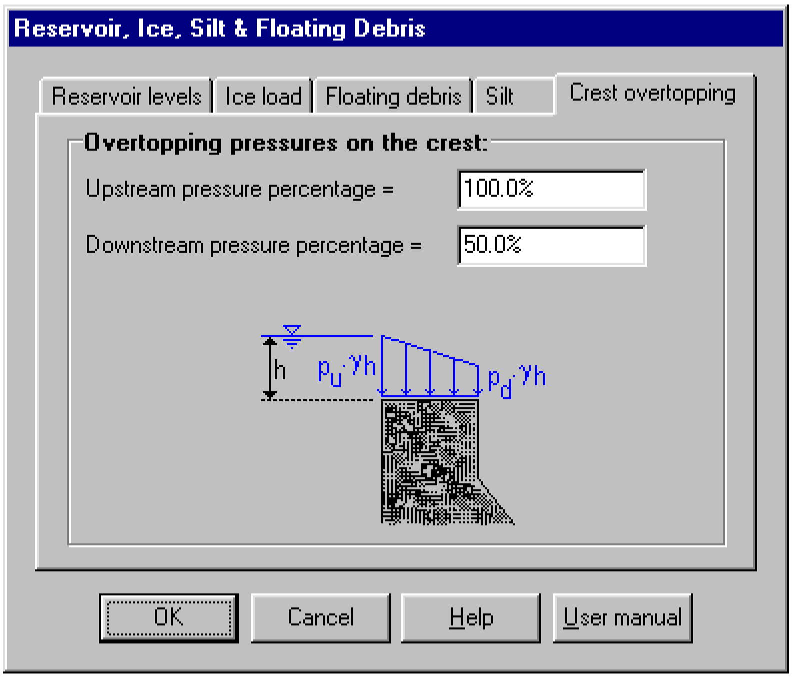
This window allows the specification of the properties of floating debris accumulated on top of the upstream reservoir. Floating debris are considered only in the flood case. The point of application of the force is taken from the reservoir surface. Moreover, upon overtopping of the reservoir, a maximum 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.

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, 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.

Crest overtopping:



During a severe flood it is possible that non-overflow section of the dam be overtopped. This window allows a users 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 pu and pd, respectively. Negative crest pressures are allowed if sub-atmospheric pressures could be developed.

Uplift pressures

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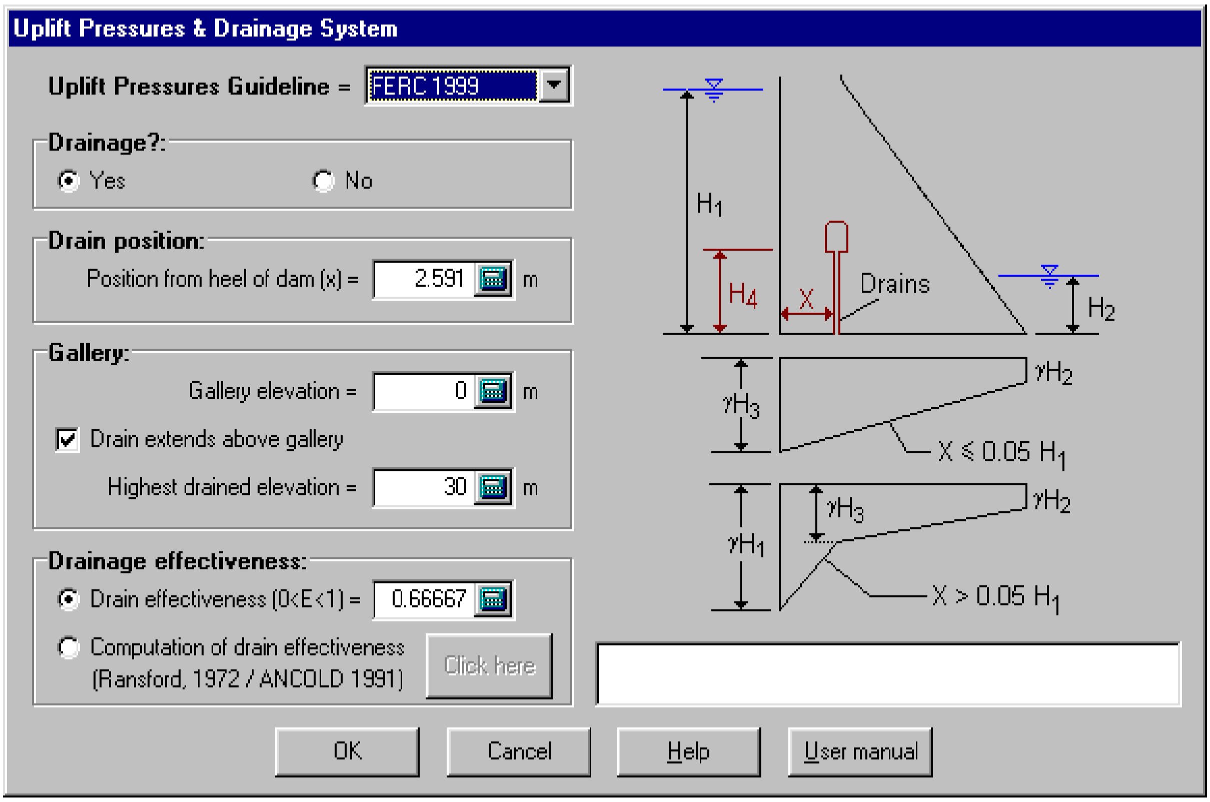


Uplift Pressures Computation of "Effective Stresses":

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

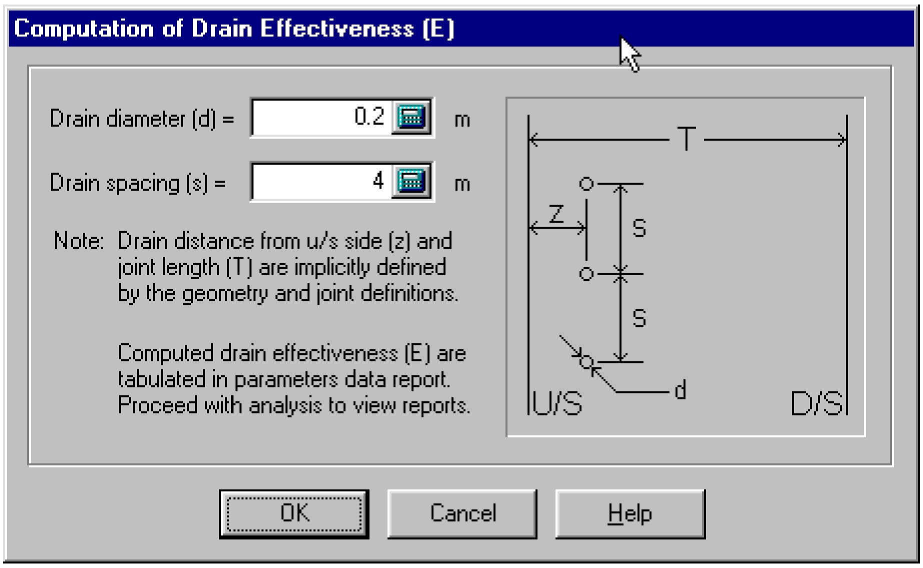
- As an external load acting on the surface of the joint (USACE 1995, CDSA 1995, USBR 1987): In this case, normal stresses are computed using beam theory considering all loads acting on the free-body considered (including the uplift pressure resultant). The computed "effective" normal stresses then follow 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.

- As an internal load along the joint (FERC 1991): 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.

Drain Effectiveness - Users specified value

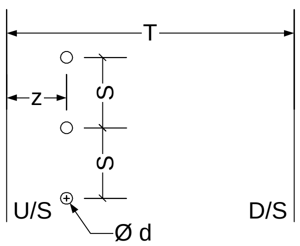
A series of windows could be activated to specify the position of the drains, the drain effectiveness and the elevation of the drainage gallery according to particular versions of Dam Safety Guidelines (USACE 1995, USBR 1987 for uplift pressures considered as external loads, FERC 1991 for uplift pressures 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).

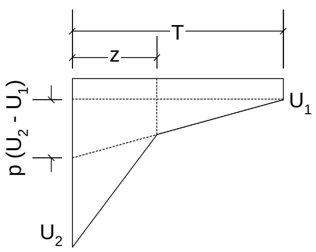
Drain Effectiveness Simplified seepage analysis



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:

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





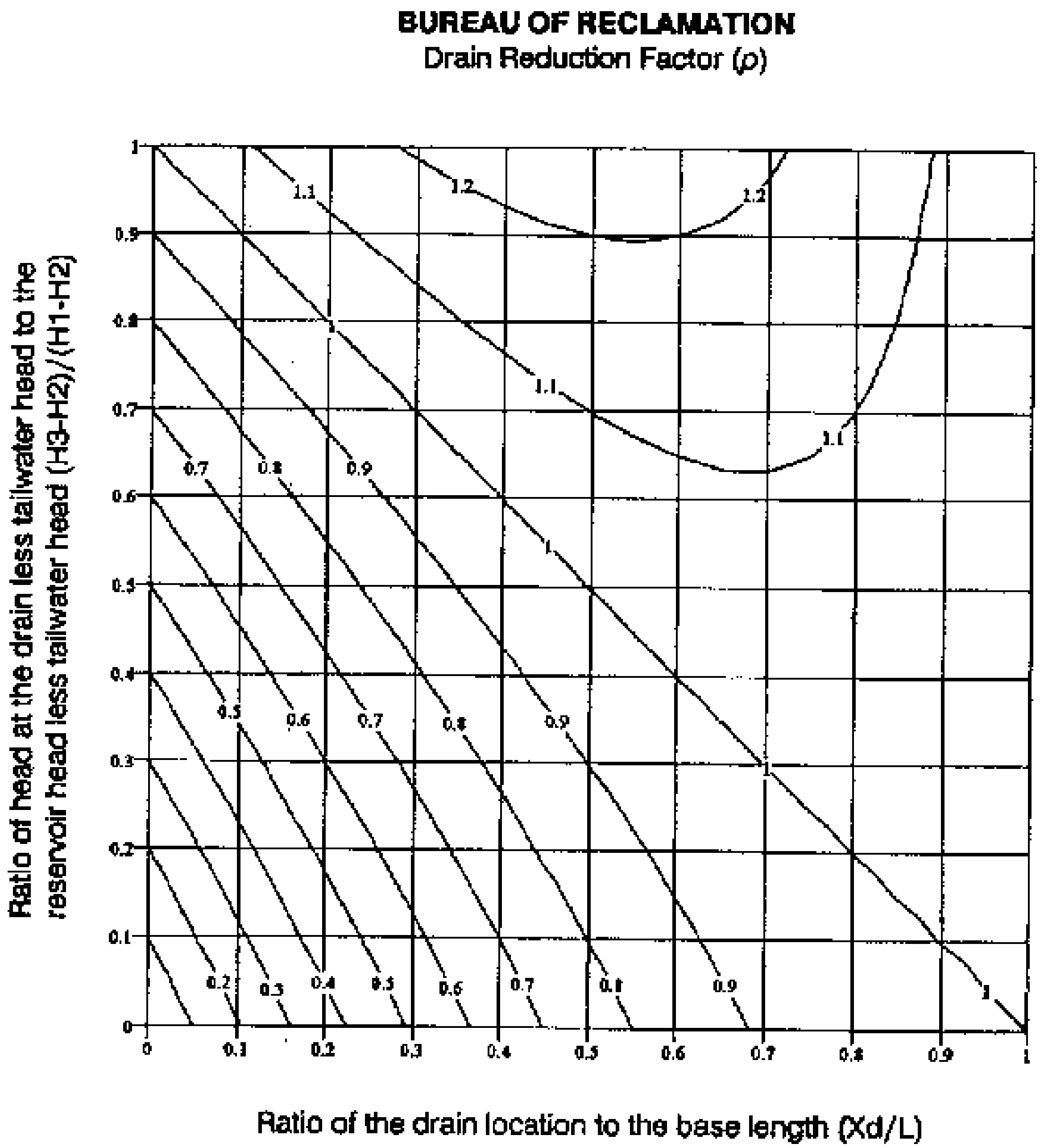
This simplified seepage analysis is applicable for a wide section where numerous drains, evenly spaced, having the same diameter. Moreover, the simplified seepage analysis is computed under no cracking and the resulting drain effectiveness will be used as initial conditions for all subsequent calculations.

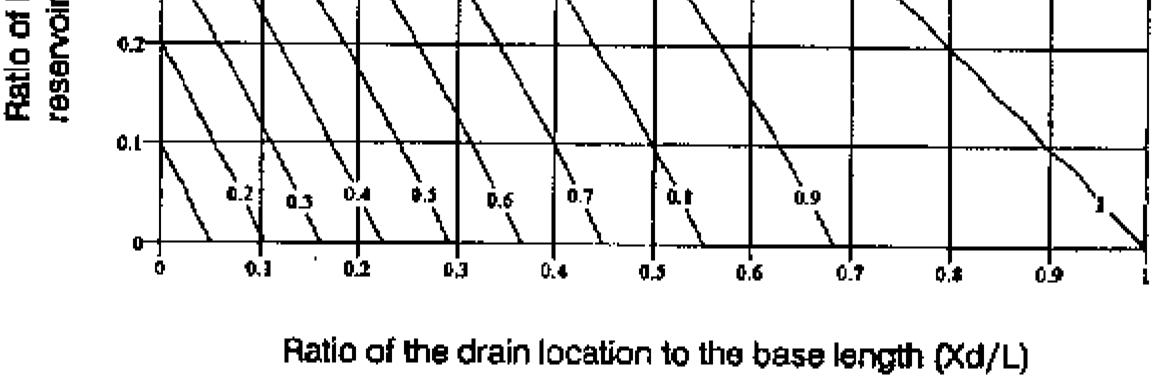
USBR guidance on crack initiation

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

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

where σzu is equal to the absolute value of the stress at the upstream face induced from uplift forces minus the allowable tensile stress. *ft* 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 σz does not achieve the minimum compressive stress σzu 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.

Post-tensioning cables

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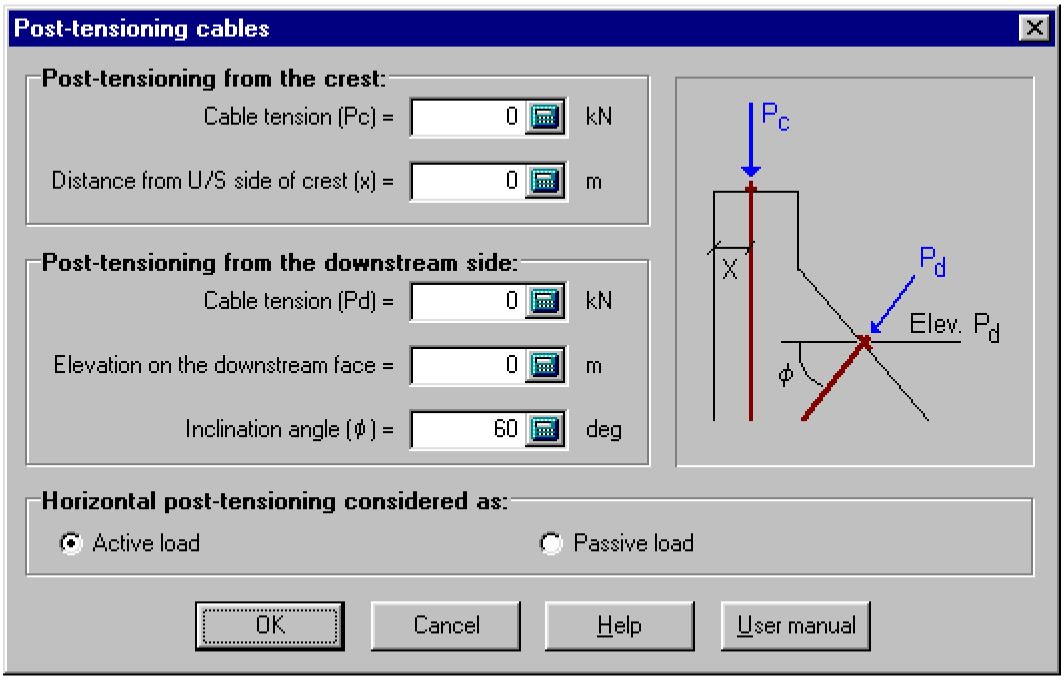

This window allows the specification of post-tension anchor forces applied either from the crest or from the d/s face. The horizontal force components induced by inclined post-tensioned cables could be treated as active forces being deducted from other applied horizontal forces such as the u/s reservoir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

Applied forces

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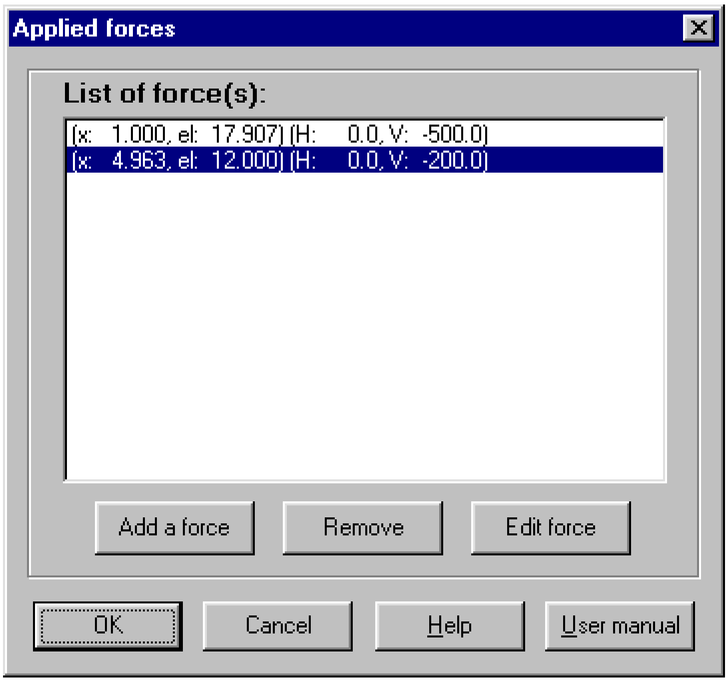

This window allows the consideration of arbitrarily defined active external forces acting within or outside the dam body. To add a force, just click the button Add a force To edit an existing force, click on the force description in the list and then click the button Edit Force . There is no limit in the number of forces that can be created. A force will act on a joint only if its point of application is set above the joint plane.

Pseudo-static method (seismic coefficient)

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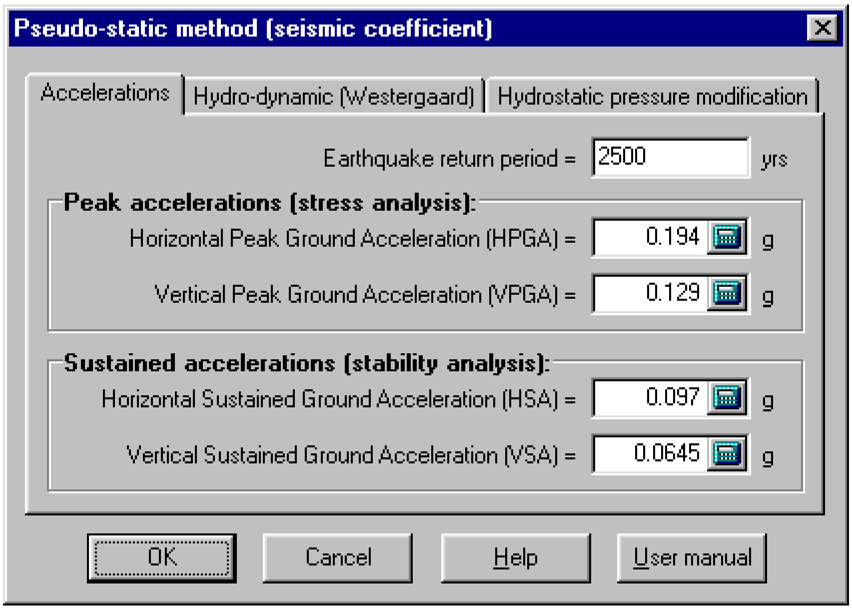
Basic Assumption - Rigid Body Behaviour:

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.

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.

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.

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

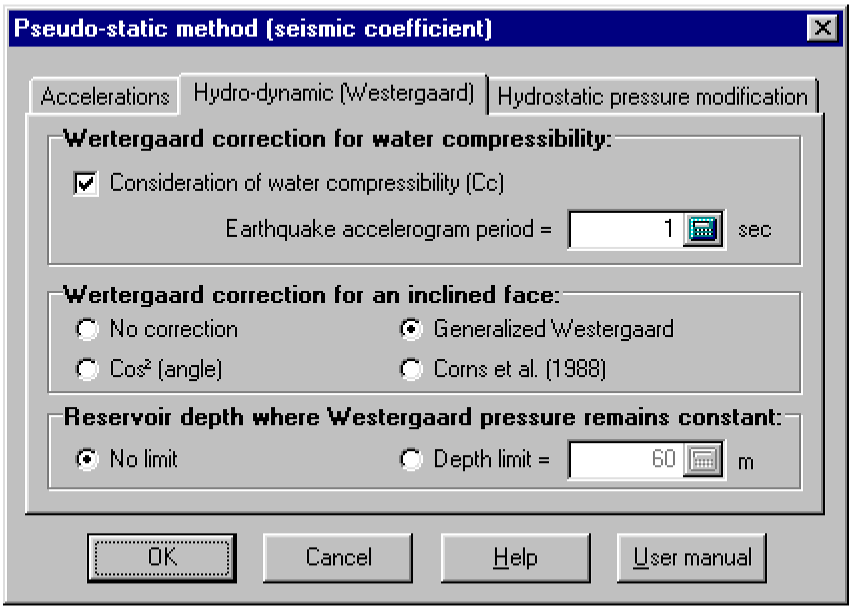
Earthquake return period: The earthquake return period is specified. This value is not used in the computational algorithm of the program. It will be reported in the output results as complementary information.

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.

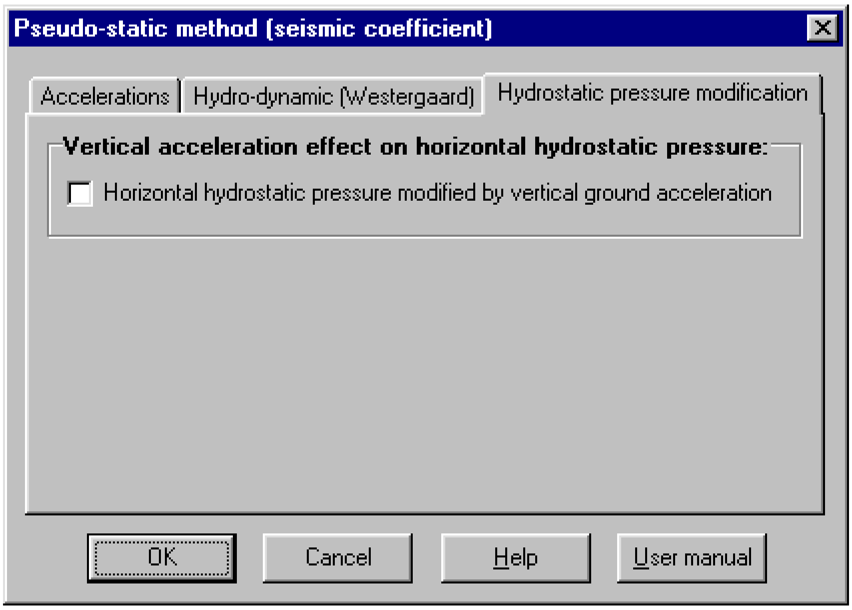
Hydro-dynamic (Westergaard):



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).
- 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 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.

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.

Pseudo-dynamic method (Chopra)

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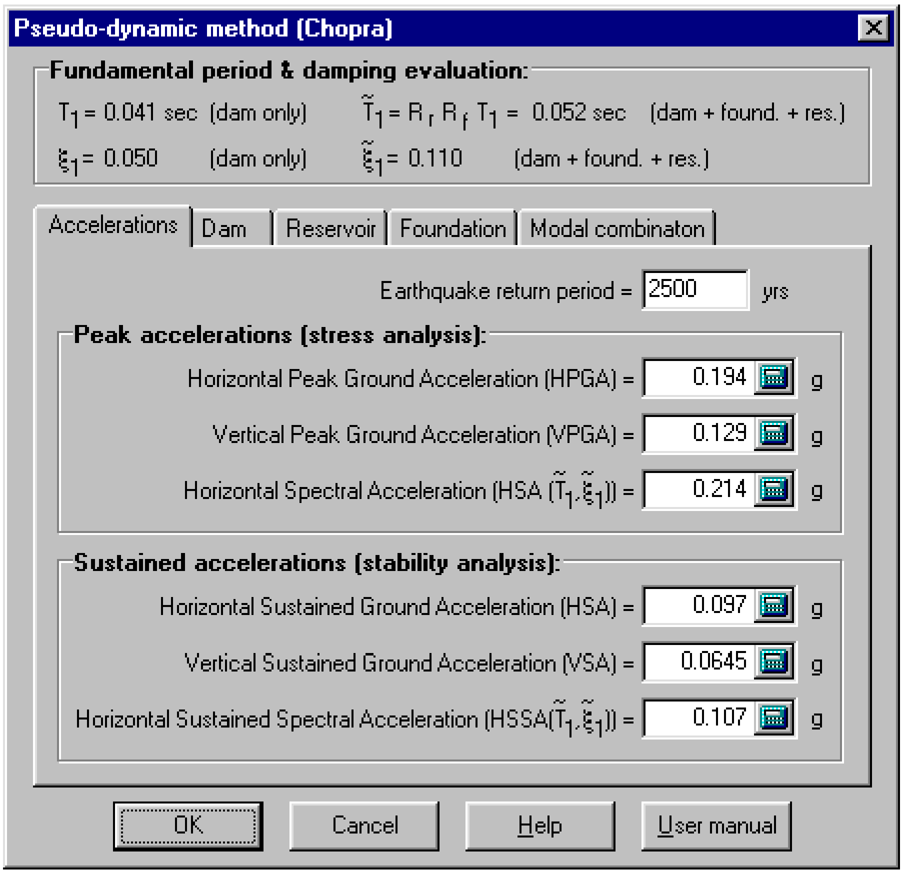
Basic Assumption Dynamic Amplification:

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.

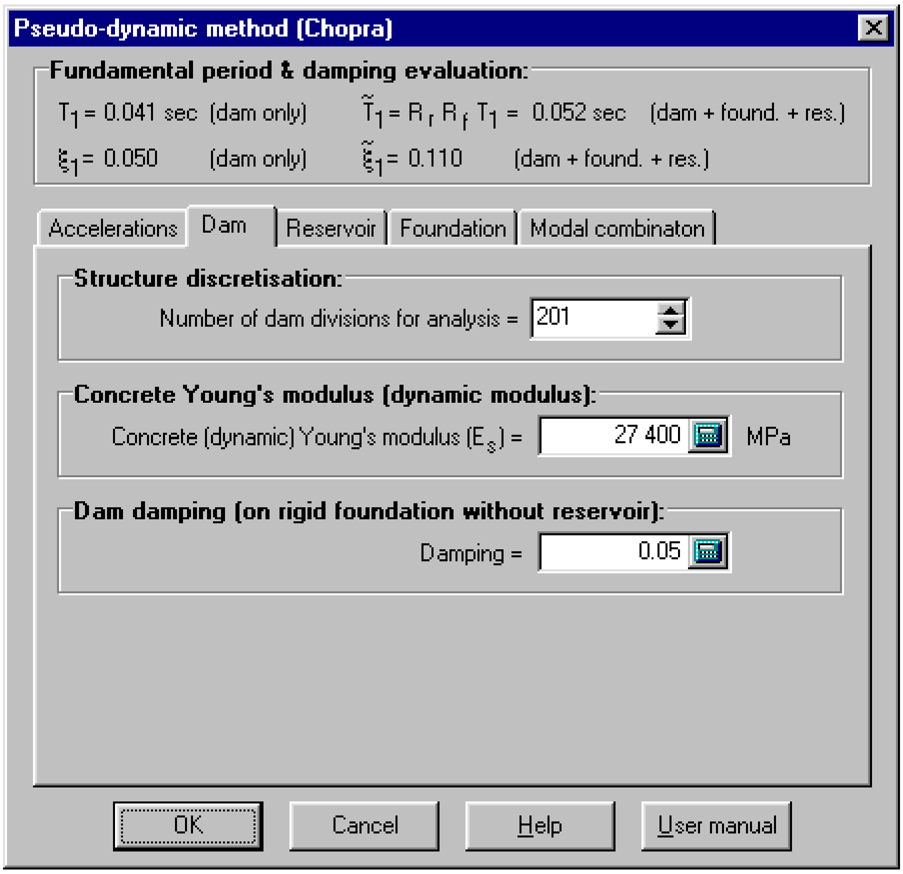
A pseudo-dynamic seismic analysis is based on the response spectra method. A pseudo-dynamic analysis is conceptually similar to a pseudo-static analysis except that it recognises the dynamic amplification of the inertia forces along the height of the dam. However, the oscillatory nature of the amplified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

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) the stress analysis using peak spectral acceleration values, and (b) the stability analysis 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.

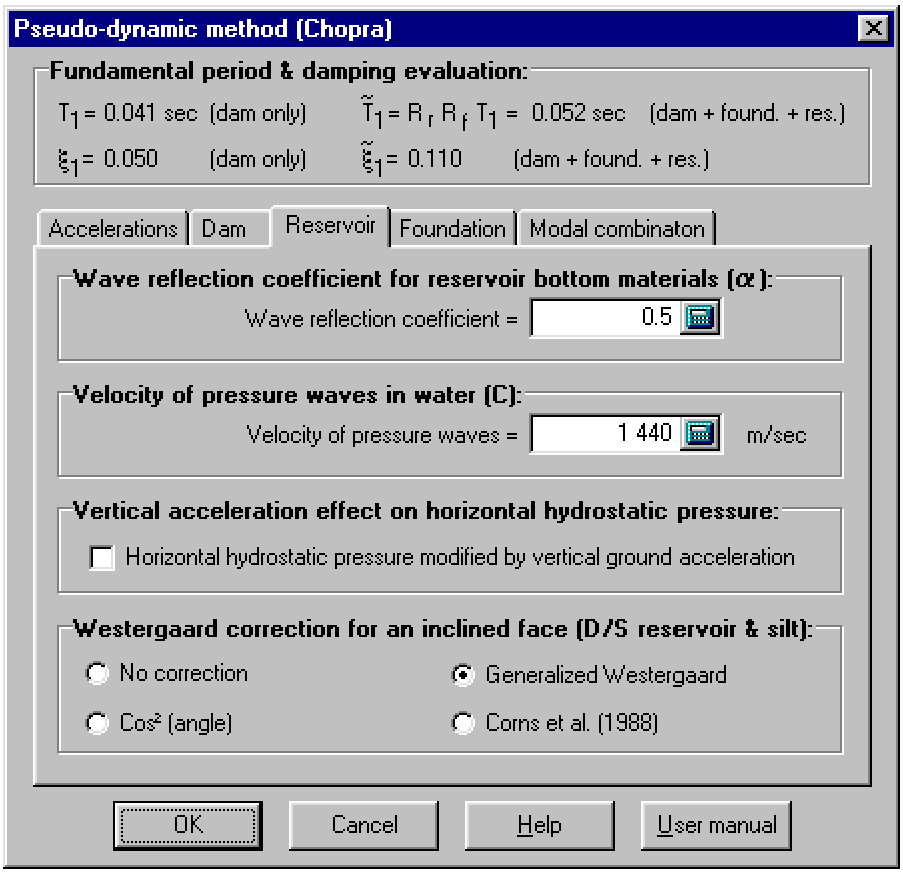
Dam:



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 Youngs modulus (Es). The dam damping (ξ1) on rigid foundation without reservoir interaction is necessary to compute the dam foundation reservoir damping (ξ1).

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.

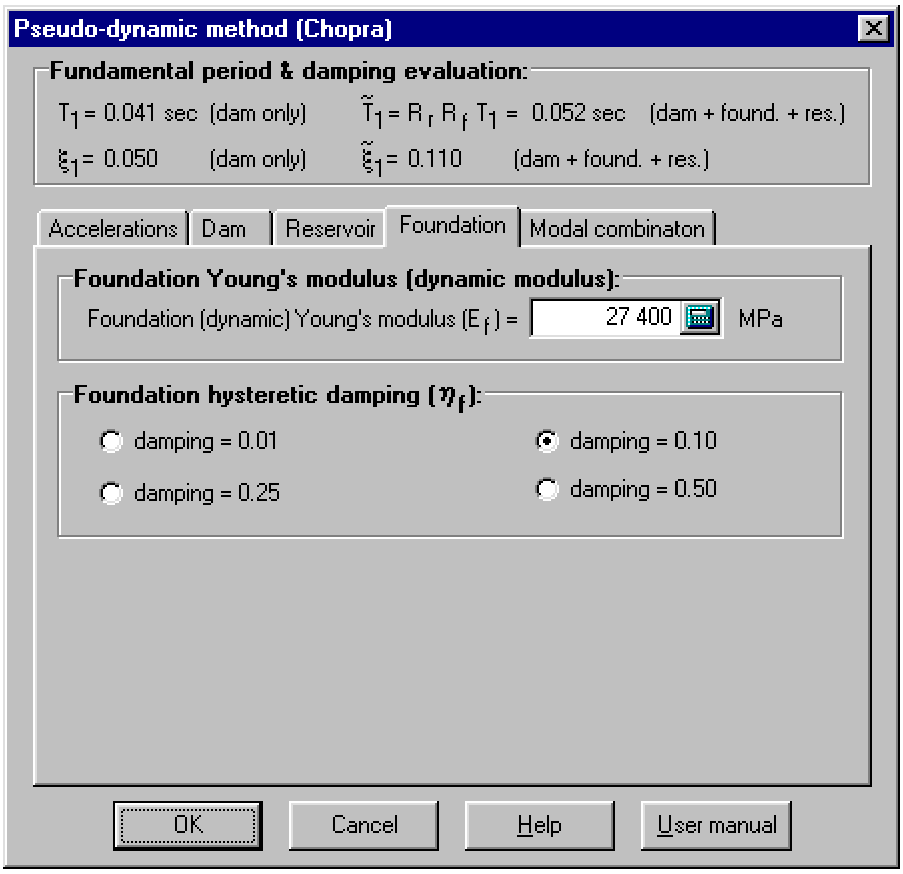
Reservoir:



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).

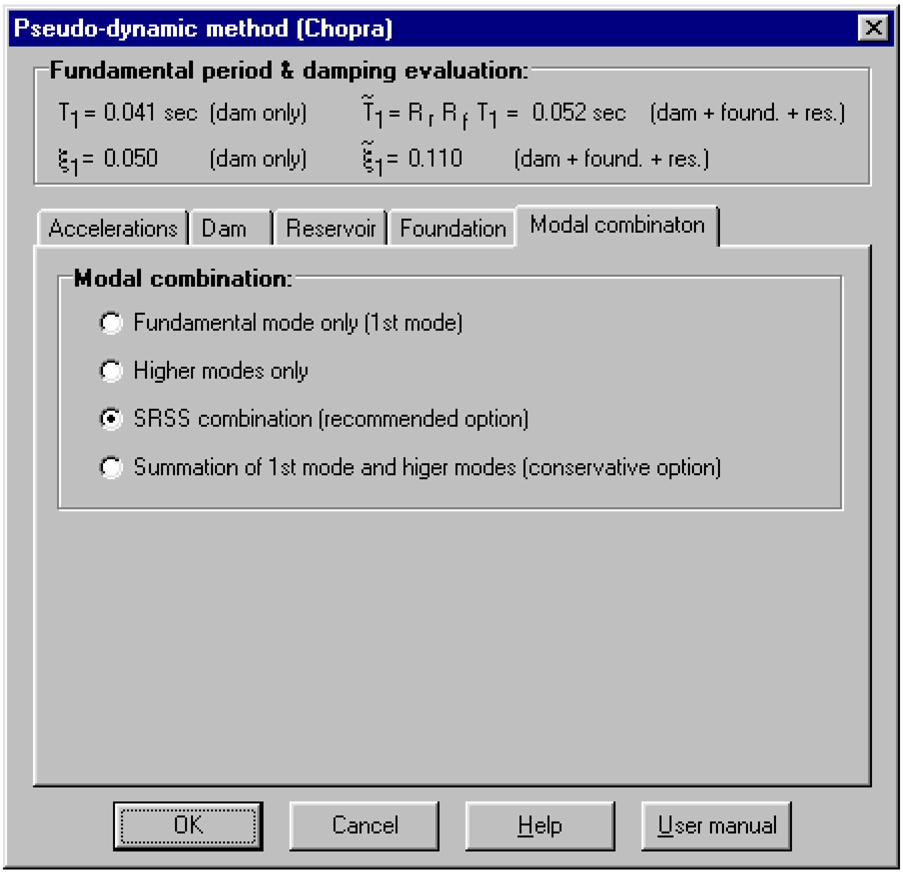
<u>Foundation:</u>



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 (ηf) will affect the damping ratio of the dam foundation reservoir system.

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.

Probabilistic safety analysis (Monte-Carlo simulations)

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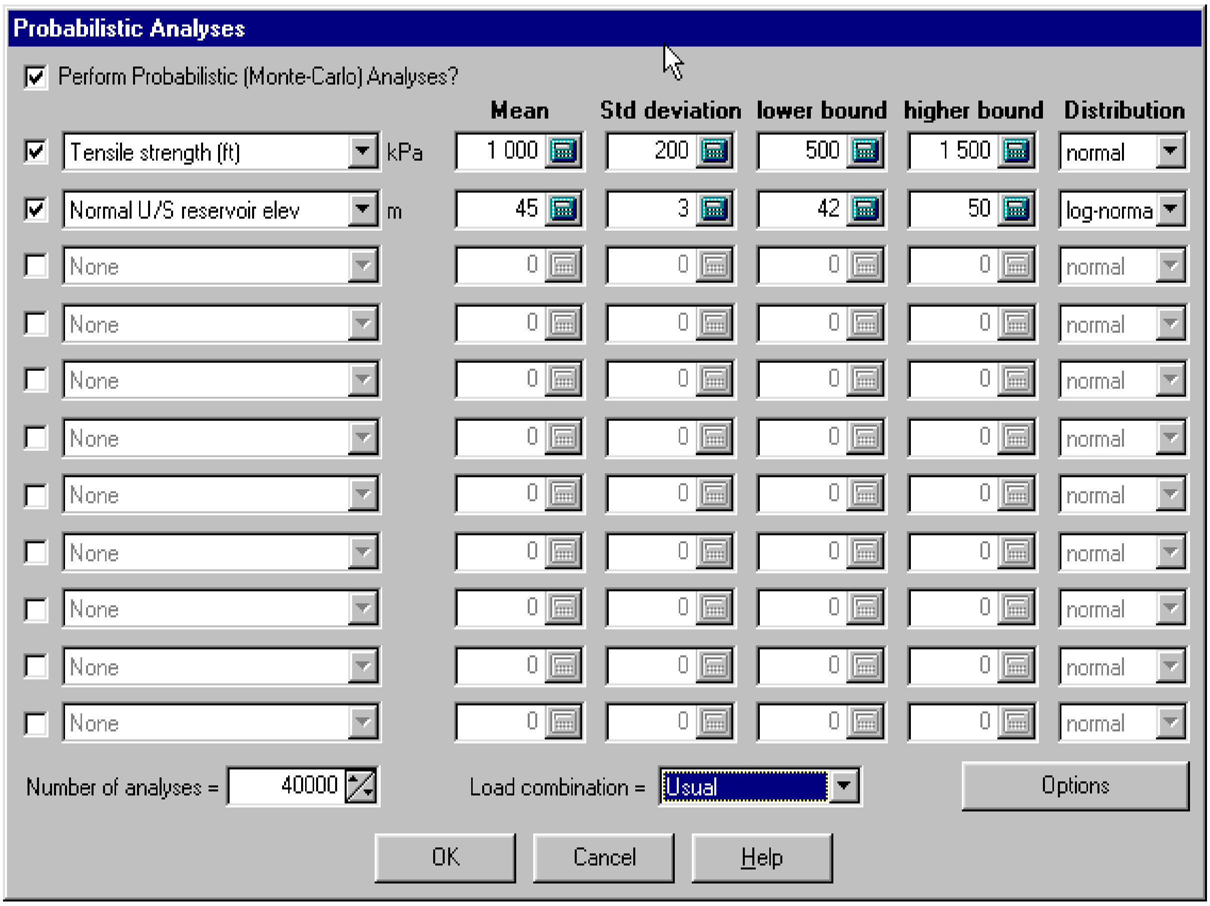


This window allows the specification of input parameters for a probabilistic analysis. The first step is to select the random variables by checking the check boxes to enable the controls beside it. Then select the variable parameter from the scroll list. This list is composed of five strength parameters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

Strength Variable Parameters:

- Tensile strength;
- Peak cohesion;
- Residual cohesion;
- Peak friction coefficient (tanϕ);
- Residual friction coefficient (tanϕ);

Loading Variable Parameters:

- 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.

Monte-Carlo simulations require that random variables 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.

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.
  - 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
  - If the initial upstream reservoir is set over 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 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.

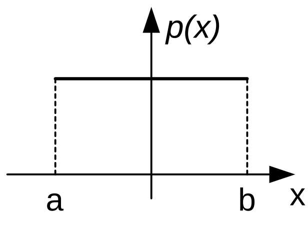
The **horizontal peak ground acceleration** will change the following parameters:

- All dependent accelerations (VPGA, HSA, 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.

Probability Distribution functions available in CADAM:

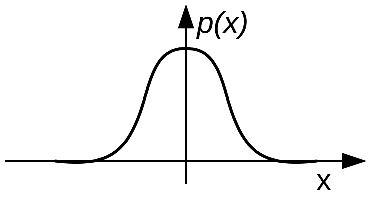
- **Uniform distribution:**

$$p(x) = \frac{1}{b-a}$$



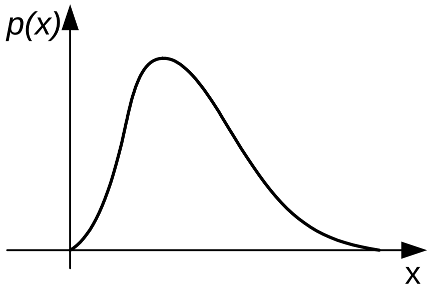
- **Normal distribution:**

$$p(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2}$$

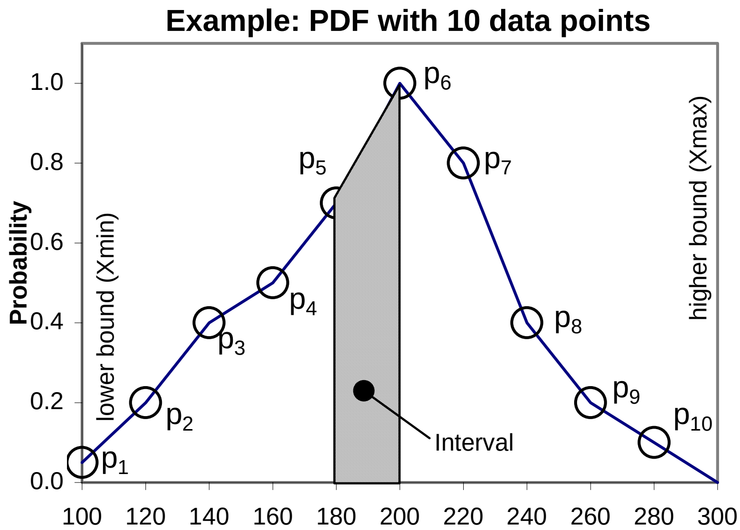


- **Log-normal distribution:**

$$p(x) = \frac{1}{x\sigma_Y\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{\ln x - \mu_Y}{\sigma_Y}\right)^2}$$



- **User defined distribution**:



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.

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 (Xmin) and upper bound (Xmax) 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. For any normal distribution, 68.27% of the values of x lie within one standard deviation of the mean, 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.

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 Pf . For example, more than 3000 simulations are required for a 95% confidence level and Pf=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 Pf could be plotted as a function of N as the calculation proceeds.

See also: Probabilistic Analyses - output parameters

Incremental load analysis

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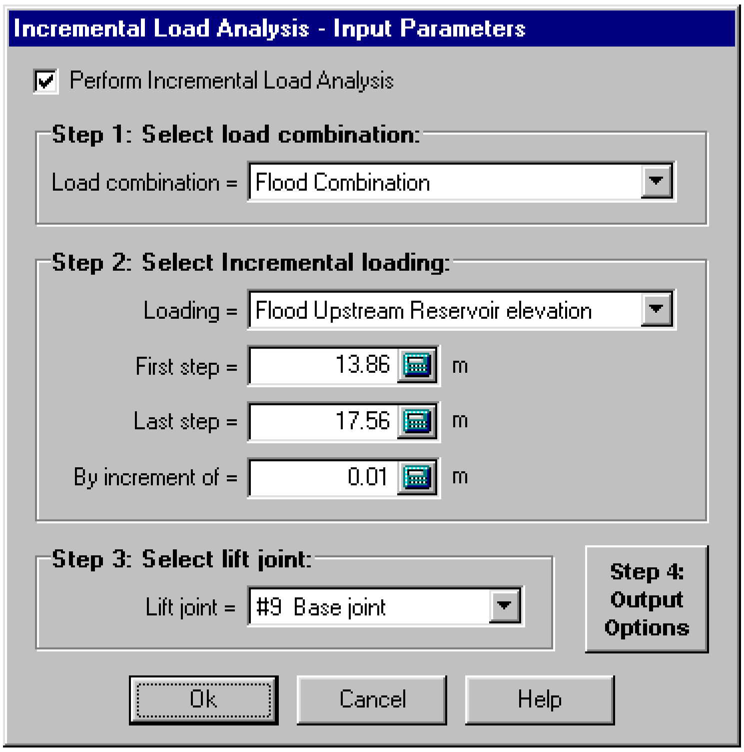

This window allows the specification of incremental load analysis parameters. The procedure consists of selecting a load combination, then a loading condition to be incremented for this combination, and finally a lift joint to be considered for the computation.

Seven types of load condition could be incremented:

- Normal upstream reservoir elevation
- Flood upstream reservoir elevation
- Horizontal peak ground acceleration
- Ice load
- Last applied force
- Post-tensioning
- 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 important 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.

Increasing an “independent” load condition might involve changing certain dependent variables that are a function of the independent the 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:

Upstream reservoir elevation (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.
- Downstream reservoir elevation: The elevation of the downstream reservoir will follow these rules:
  - 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.
  - 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).

Horizontal peak ground acceleration will change:

- All accelerations (VPGA, HSA, 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.

Cracking options

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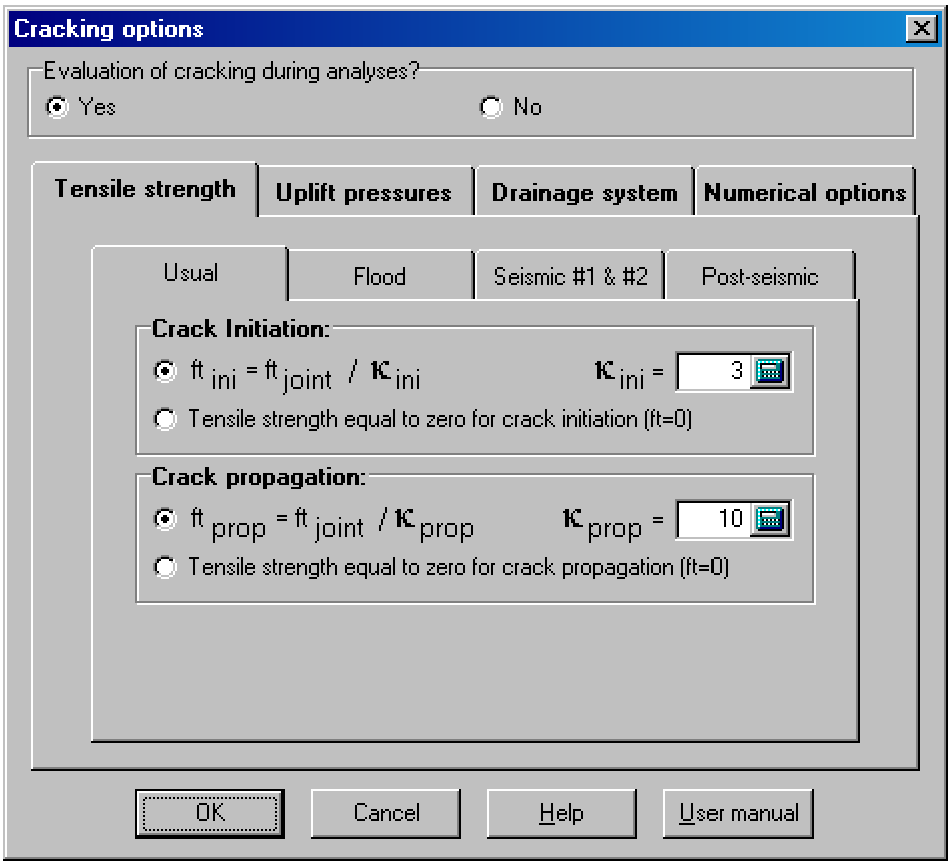
Tensile strength



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.

No cracking possible: 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?).

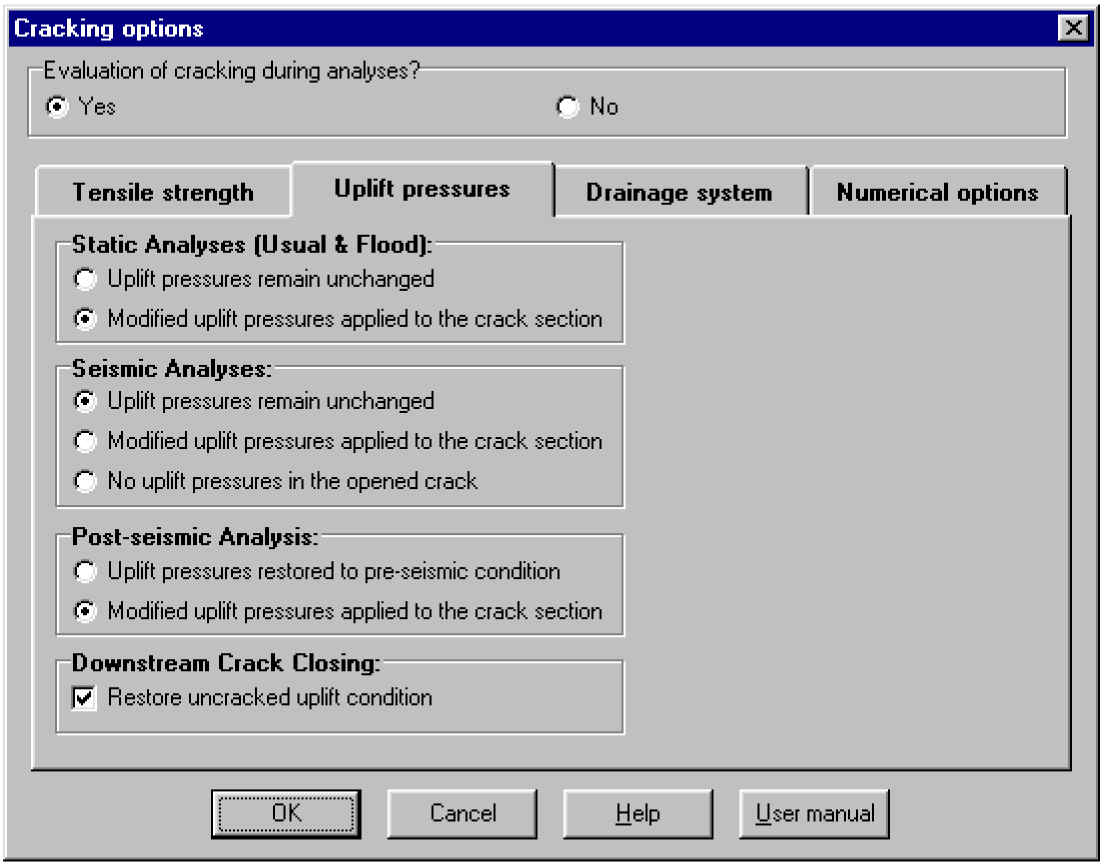
When cracking is allowed, a distinction is made between the criteria for crack initiation and crack propagation. After crack initiation, say at the u/s end of a joint where stress concentration is minimal, it is likely that stress concentration will occur near the tip of the propagating crack (ANCOLD 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.

Crack initiation: 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.

Crack propagation: 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.

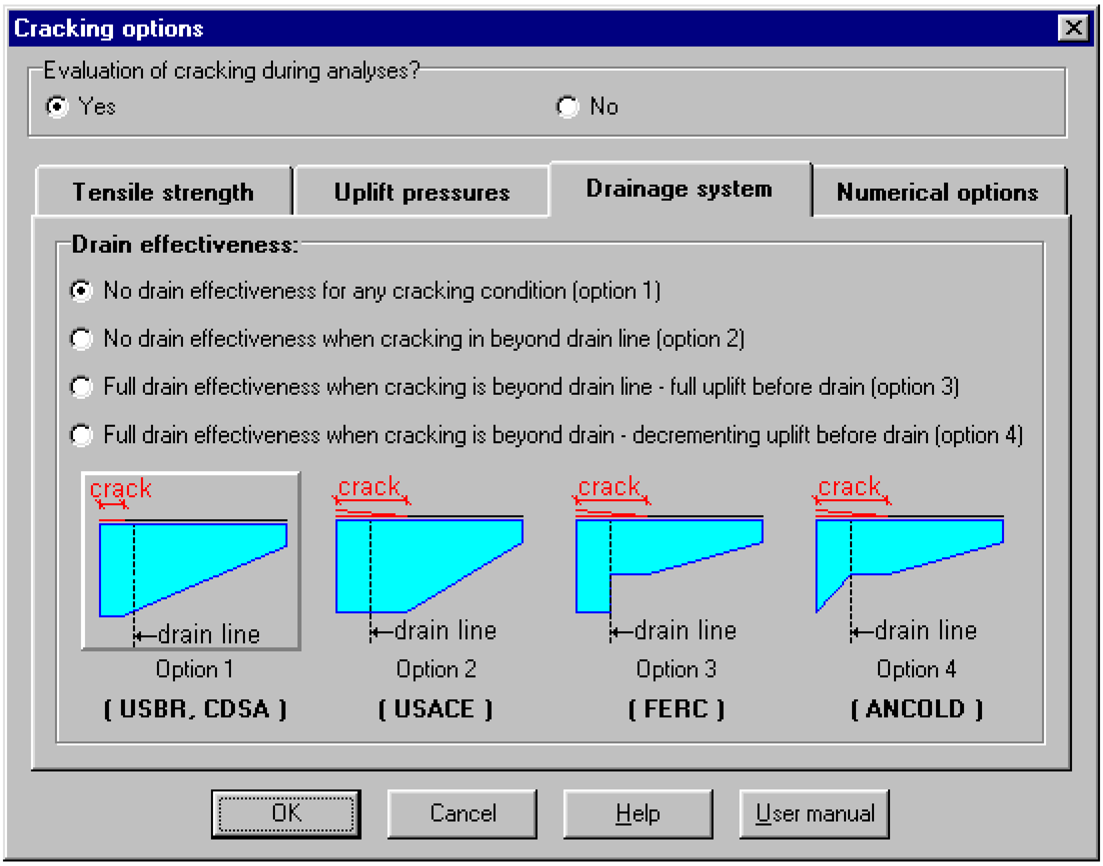
Dynamic magnification of tensile strength: Under rapid loading during a seismic event the tensile strength of concrete is larger that under static loading. A dynamic magnification factor could be specified to increase the tensile strength used for seismic crack initiation and propagation criteria.

Uplift pressures



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.

Drainage system

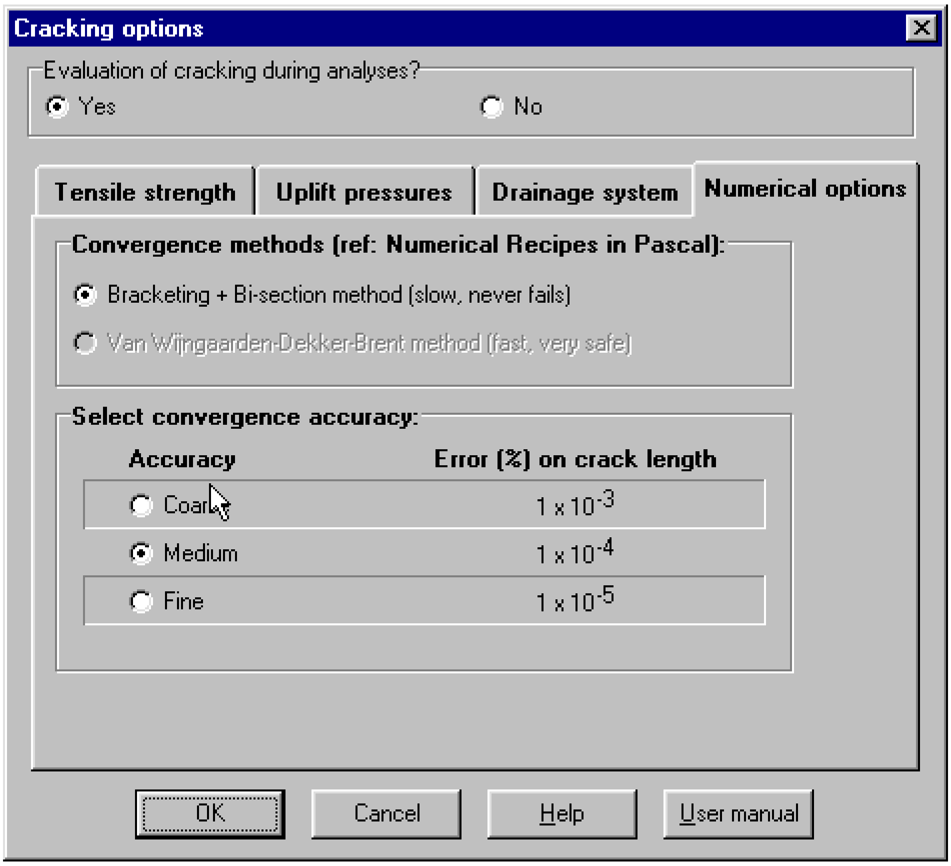


Upon cracking passing the drain, four options are offered to the user:

- No drain effectiveness under any cracking conditions (CDSA, USBR)
- No drain effectiveness when the crack reaches the drain line (USACE);
- Full drain effectiveness, but with full uplift pressures applied between the reservoir and the drain line (FERC);
- Full drain effectiveness with a linear decrementing uplift pressure starting from full reservoir pressure at the reservoir level to the drainage pressure at the drain line (ANCOLD).

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

Numerical options



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 (%).

Load Combinations

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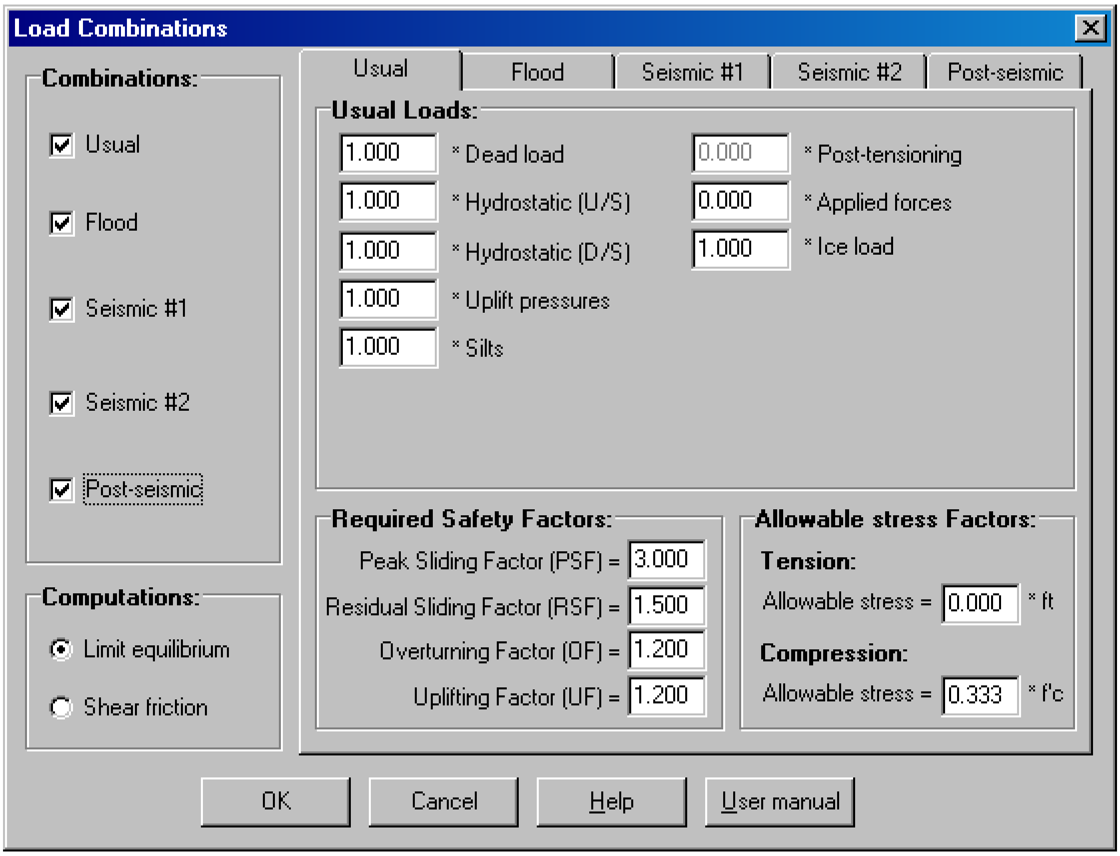

Load Combination and Load Conditions:

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.

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.

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.

PERFORMING THE STRUCTURAL ANALYSIS

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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:

- The stress analysis is first performed to compute the potential crack length and compressive stresses along each joint;
- The sliding stability is performed along each joint considering the specified shear strength joint properties;
- The overturning stability is performed by computing the position of the resultant of all forces along each joint;
- Additional performance indicators such as the floating (uplifting) safety factor are computed.

Chapter 17 of the user's manual presents a brief review of the key computational procedures used in CADAM. Appendix D of the user's manual, presenting flowcharts related to structural safety evaluation of concrete dams, should be consulted in complement to chapter 17. 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.

STRESS ANALYSIS AND CRACK LENGTH COMPUTATIONS

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CADAM is based on the gravity method using beam theory to compute normal stresses to the crack plane. Shear stresses are computed assuming a parabolic distribution for the uncracked section (USBR 1976). For a cracked section, 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.

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. 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. 1998a, 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 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 of the user's manual, two different crack criteria (initiation and propagation) are supported by CADAM.

The uplift pressures could be considered as an external force and the **effective stress** at the crack tip, σn, is computed while including uplift pressures in the force resultant (USACE 1995, USBR 1987 (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, sn, to be used in the crack initiation (propagation) criteria (FERC 1991).

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

ΣV = Sum of all vertical load **excluding** uplift pressures

A = Area of uncracked ligament

ΣM = 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.

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

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

CADAM

SLIDING STABILITY ANALYSIS

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Basic formula for horizontal sliding plane (static loads)

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

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

ΣV =	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, σn, to determine the compressed area upon which cohesion could be mobilised could be specified - see section 7.1 of user's manual)
AC =	Area in compression
ΣM =	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:

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

ΣV =	Sum of vertical static forces excluding uplift pressure
QV =	Vertical concrete inertia forces
U =	Uplift pressure force resultant
ΣHd =	Sum of horizontal concrete inertia forces
Qh =	Horizontal hydrodynamic forces
φ =	Friction angle (peak value or residual value)
c =	cohesion (apparent or real)
Ac =	Area in compression
ΣH =	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).

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

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

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

Inclined Joints (ex. static loads)

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:

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

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)

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

W = Saturated weight of the rock wedge;
A2 = 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.

OVERTURNING STABILITY ANALYSIS

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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, LFR 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:

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

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

UPLIFTING (FLOATING) STABILITY ANALYSIS

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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:

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

ΣV =	Sum of vertical loads excluding uplift pressures (but including the weight of water above the submerged components);
U =	Uplift force due to uplift pressures.

SAFETY EVALUATION FOR STATIC LOADS

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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:

$$Sh = \frac{1}{2} K \gamma'_S h^2_{silt}$$

K = Earth pressure coefficient

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. Brand (1999) and Léger et al. (2000) have presented further discussions of water pressure acting on overflow sections.

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.

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).

Increasing applied load to induce failure: 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 D 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.

Reducing material strength to induce failure: 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).

SAFETY EVALUATION FOR SEISMIC LOADS

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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:

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

Hd(y)= Additional total hydrodynamic horizontal force acting above the depth y for a unit width of the dam;

Kθ = Correction factor for the sloping dam faces with angle θ from the vertical. To compute the horizontal force KθH = cos 2θ can be used as a first approximation, while the vertical force can be estimated from Kθ V = sinθ cosθ ; Alternatively, USBR (1987) present a detailed formulation for Kθ

Ce = 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.

USBR (1987) considers the following for inclined faces:

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.

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 Ce coefficient is:

Metric:

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

Imperial:

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

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

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

<u>Generalised Westergaard Formulation sloped u/s face</u>

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, Pni, acting at any point i on the u/s face is expressed as:

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

Hi = Water depth at the vertical section containing point i;
H = Total depth of reservoir;
yi = Height of the point i in this section;
rni = Normal acceleration component at point i.

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. According to dAlembert principle, an upward vertical acceleration of the rock is going to produce an increase in the effective volumetric weight of water ($\gamma e = \rho w (g + accV)$) 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 ($\gamma e = \rho w (g - accV)$) and related initial hydrostatic pressures. These considerations are independent of the Westergaard hydrodynamic pressure computations.

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 during earthquakes: (a) no uplift pressures in the opened crack, (b) uplift pressures remain unchanged, (c) full uplift pressures applied to the crack section.

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.

SAFETY EVALUATION FOR POST-SEISMIC CONDITIONS

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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.

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