

Notice to users:

Please print this User's Guide on

**A5 paper.**

The font sizes used in this document  
will look just right at the reduced  
size.

# WALLAP

Propped, Anchored and Cantilever  
Retaining Wall Analysis Program

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Distributed by **Geosolve**

User's Guide

Versions 5

for Windows 98, ME, NT, 2000, XP, Vista

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## **1.0 INTRODUCTION**

### **1.1 SCOPE OF THE PROGRAM**

WALLAP analyses a wide range of retaining wall problems including cantilever walls, anchored walls and strutted excavations. WALLAP is suitable for the analysis of both temporary works, such as sheet pile walls, and permanent works such as reinforced concrete diaphragm walls and contiguous bored pile walls.

#### **Single pile analysis**

WALLAP also has a facility for analysing single piles subject to horizontal and moment loads.

##### **1.1.1 Types of analysis**

WALLAP offers two separate types of analysis within the one program :

- Limit Equilibrium Analysis,
- Bending moment and Displacement Analysis:

#### **Limit Equilibrium Analysis:**

This is the calculation of Factors of Safety according to one of the following methods:

- CP2
- BSC Piling Handbook
- Burland-Potts
- Strength factor method

Limiting earth pressures are usually calculated using traditional active and passive earth pressure coefficients. An optional Wedge Stability analysis gives more accurate results for certain cases where the usual assumptions of earth pressure theory are not strictly applicable, such as:

- Sloping backfill with cohesion
- A berm or uneven ground on the active (or passive) side
- Intense surcharges over a limited width
- Ramp surcharges
- Weak soil layers at depth
- Non hydrostatic water pressures
- Seismic loading (earthquakes)

## **Bending moment and Displacement Analysis**

The stage by stage development of forces and wall movements is modelled as construction proceeds. The wall and soil are modelled as a beam and springs. Two spring models are available:

- Subgrade reaction analysis (for routine design)
- 2-D Finite element analysis (for a more rigorous approach)

The analysis includes the following features:

- Elastic soil behaviour
- Active and Passive limits
- Effect of construction sequence
- Strut pre-stressing
- Finite length of the wall
- Simple non-linear elastic soil model (optional)
- Soil below the wall (2-D FE analysis only)
- Soil arching (2-D FE analysis only)

The analysis produces an economical design which automatically takes account of any moment reduction due to fixed earth support.

### **1.1.2 The structure, soil, water and loads**

Composite walls (i.e. of non-uniform section) can be modelled.

#### **Struts and anchors**

Struts or anchors can be installed at up to 40 levels and may be pre-stressed. Struts can also be removed after installation.

#### **Soil properties**

Up to 40 soil strata may be defined. For each stratum the following parameters may be specified:-

- Unit weight.
- At rest earth pressure coefficient.
- Active and passive earth pressure coefficients.
- Consolidation state (OC or NC)
- Drained or Undrained soil type.
- Cohesion.
- Soil modulus.
- Poisson's Ratio.

The program offers advice on the selection of values of earth pressure coefficients and soil modulus. The program can calculate earth pressure

coefficients from values of soil friction, wall friction and backfill angle given by the user.

### **Water pressures**

Hydrostatic or non-hydrostatic Water Pressure Profiles may be defined on both sides of the wall. Thus it is possible to model a variety of complex conditions including: seepage, submerged ground, perched water tables and uplift pressures under structures.

### **Automatic water pressure balancing option**

This offers a convenient way of balancing water pressures in permeable at the toe of the wall by assuming a linear variation of piezometric head between the water levels either side of the wall.

### **Surcharges**

Surcharges can be applied at or below ground level on the active or passive side of the wall. All surcharges are defined as rectangular loaded areas. Ramp surcharges can be defined i.e. Surcharges may vary linearly with distance from the wall.

### **Loads applied to the wall**

Horizontal and moment loads may be applied to the wall.

### **Rotational Fixity**

Rotational spring restraints may be applied at any elevation. This facility may be used to model the effect of floor slabs which are built into the wall.

## **1.1.3 Construction sequence**

The following types of construction activity may be specified and combined in any order so as to model the construction sequence:-

- Excavation and Filling.
- Change water pressures.
- Installation and removal of struts or anchors.
- Application and removal of surcharges to the ground.
- Application of loads to the wall.
- Application of rotational restraints to the wall.
- Changes in soil properties.
- Change of wall stiffness.
- Seismic loading.

The Excavation Stage includes additional optional parameters for modelling berms.

### 1.1.4 Output

Printed output from the program consists of the following:

Listing of input data

Output at selected stages (by the user) of:

- Factors of safety
- Bending moments and shear forces
- Wall pressures
- Displacements
- Strut/anchor forces

Summary output (optional) of:

- Factors of Safety at each stage
- Strut forces at each stage
- Maximum/minimum moments and displacements at each stage
- Cumulative bending moment, shear force profiles
- Cumulative displacement profiles

### Graphics

Graphical display of the data shows the soil profile, water pressure profiles, surcharges, applied loads/restraints, strut positions and boundary conditions.

Results are displayed in the form of bending moment, shear force, wall pressure and wall displacement diagrams.

### Reports and output to Excel spreadsheets

You can create reports (in RTF format) containing text and graphical output for selected stages. Tabulated output to an Excel spreadsheet can also be created.

### 1.1.5 Units

Data may be entered in any consistent set of units e.g. (kN,m), (lb,feet). All print-out from the program is automatically annotated in the appropriate units.

## 1.2 WALLAP version 5 - RELEASE NOTES

WALLAP version 5 is the first windows version of WALLAP. The maximum numbers of data items (strata, soil types etc...) are now as follows:

Number of strata on either side of wall	= 40
Number of soil types	= 40

Number of struts and anchors	= 40
Number of moment and surcharge loads	= 40
Number of pore pressure points	= 20
Number of pore pressure profiles	= 20
Number of construction stages	= 80

These limits are larger than those of the standard version 4.10 program and correspond to the limits of the "large" version 4L.10 program. Old data files of all version 4.10 programs can be read by version 5.01

The maximum number of nodes which the program may generate for the analysis is now 80. The number of nodes generated is not directly controlled by the user but is a combination of the number of different strata elevations, struts, water pressure profiles, and applied loads. The increased limit gives greater flexibility to model complex problems.

### **Format of output**

The title block has been reorganised to accommodate the increased length of Filenames/Run Identifiers. Soil and wall friction parameters are now displayed explicitly. All other output is virtually identical to WALLAP version 4.

### **1.3 WALLAP VERSION COMPATIBILITY**

WALLAP Version 5 has been designed to provide a high degree of compatibility with its predecessor, version 4.10 at many levels:-

- Version 4 data files (both Standard and Large versions) can be read and processed by Version 5.
- The definition and usage of all engineering parameters is preserved in version 5
- The methods of calculation are identical apart from:-  
Revised criterion for maximum water filled tension crack depth.  
Revised arching active pressure calculation
- The formatting of printed data and results is preserved virtually unchanged.

To summarise, you should be able to read and process your version 4 data files and obtain virtually identical output using WALLAP version 5.

WALLAP version 5 cannot read data files created by WALLAP version 3.43 or earlier.

## 2.0 GETTING STARTED

Before attempting to install or execute the program you should read the README.RTF file on the master disk. This file contains important information about the program and how to install it.

## 2.1 SYSTEM REQUIREMENTS

### 2.1.1 Memory requirements

WALLAP requires about 10Mb of RAM.

### 2.1.2 Disk Space Requirements

Disk space requirements for WALLAP version 5 are as follows:

	Disk space
Program files	4Mb
Each data file	25kb
Matrix storage	5kb per construction stage. (2D F.E. solution only)
Output files	.OUT file ~10kb per construction stage
	.BIN file ~10kb per construction stage
Report files	.RTF file 20 kb
	+5 kb per stage (text only)
	+100 kb per stage (b/w graph)
	+2 Mb per stage (colour graph)

The temporary matrix files store intermediate results in the creation of the stiffness matrix for each stage. They speed up program operation by re-using matrices from previous stages or runs (when the data match). Their filenames are of the form:-

xxxxxxx.nnL                      xxxxxxxx.nnR

where xxxxxxxx is the Run name, nn is the stage number and L, R indicates left or right hand soil block.

You are responsible for removing old or unwanted files which will otherwise occupy valuable disk space.

### 2.1.3 Screen resolution

WALLAP requires a screen resolution of 800x600, 1024x768 or greater.

### 2.1.4 Printed output

Printed output from the program is in lines up to 78 characters long. A choice of fonts and point sizes is available. Pagination of the output is designed for printing on A4 paper.

Printer options are selected at print time using a standard windows printer dialog box.

## Font selection

The default font is Courier New 9pt. Alternatives are available under the **Format|Font selection** menu

## 2.2 PROGRAM INSTALLATION

Please read the README.RTF file on the master diskette before installing.

To install the program run SETUP.EXE.

## 2.3 STARTING THE PROGRAM (stand alone PC's)

If the installation routine has created a Geosolve program group you can click Start and select

**Programs|Geosolve|WALLAP 5.xx**

If the installation routine has created a WALLAP icon on the Windows Desktop you can double click on that.

Otherwise use Windows explorer to view the WALLAP 5 folder and double click on the WALLAP.EXE application.

## 2.4 BEGINNERS GUIDE

Please read the release notes for WALLAP version 5.

The following sequence of steps will familiarise you with the basic operations of WALLAP:-

1. Using Windows explorer create a folder called MyData (or other suitable name)
2. Copy the demonstration data files DEMO???.DAT from the WALLAP folder to your data folder.
3. Run WALLAP and after the opening screen press **Ctrl+O** or select **File|Open** from the main menu.
4. Use the Open file dialog box to select MyData as your current data folder
5. Select DEMO1.DAT.
6. Note the graphical display in the bottom right corner which shows the ground profile at Stage 1. This includes the surcharge applied at Stage 1.

7. To view the data at other stages press the construction stage selection arrows next to the green box at the top right of the screen.
8. Use the "plus" and "minus" buttons in the corner of the graphic box to increase and decrease the size of the box.
9. Select Stage No. 8
10. From the data edit tabs select the **Struts** tab.
11. Edit the elevation of strut no.2 to a value of 7.50 - observe the change in elevation on the data plot.
12. From the data edit tabs select the **Wall/Pile** tab.
13. Edit the elevation of toe of wall to -3.00m.
14. Select **File|Save As** and save the data as Demo1A.dat and note the **Data last modified** time change to the current date and time.
15. Press **Alt+A** to enter analysis mode.
16. While the analysis is in progress, click and drag the scroll bar in the progress summary box in order to view the complete summary. Note that the analysis pauses while the scroll bar is clicked.
17. Allow the analysis to finish normally and then view the output for successive stages by pressing **Alt+Right**. Observe the tabulated results and the graphics change as you move through the stages. Type **Alt+W** to toggle between bending moment and soil pressure display in the graphical output.
18. Press the Report button or type **Alt+T** to create and print a report or alternatively (but more cumbersome)

Use the copy and paste facilities to copy data and results to a separate (Word) document:- Display the Summary results; select the tabulated text by typing **Ctrl+A**; copy it to the windows clipboard using **Ctrl+C**; paste it into the Word document. Now click on the summary graphics; copy the graphics to the windows clipboard using **Ctrl+C**; paste the graphics into the Word document.

Before going on to explore further you might like to read the General rules for data entry (Section 3.9).

### **3.0 GUIDE TO PROGRAM OPERATIONS**

#### **3.1 THE WALLAP DESKTOP**

Wallap always runs 'maximized'. The program can be minimized but not 'normalized'. The Main menu contains the following items

**File Edit View Format Analysis Help**

Beneath the Main Menu the Titles of the current data set are displayed. A yellow box in the top right corner displays the Current data file name and its folder. Beneath the yellow box is the date/time stamp of the current data set i.e. the time the data was last saved to disk or edited. A green box in the top right corner shows the currently displayed construction stage (data or results, according to whether you are in Data input mode or View Results mode). The arrow buttons next to the green box are used to move backward and forward through the construction sequence. Alternatively, click on the green Construction stage selection button/indicator to see a list of stages and select one for viewing.

The four Mode buttons are located under the Main Menu and Titles in the top left corner of the screen. The Graphics display (data or results) can be made larger or smaller using the [+] and [-] buttons in the lower right corner of the screen.

##### **3.1.1 Data graphics - description**

Strata boundaries are shown as horizontal solid black lines. Ground level on either side of the wall is indicated by hatching. The width of the excavated/filled area is shown.

Vertical surcharges (at or below ground level) are indicated by vertical (red) arrows. Where possible the surcharge arrows are drawn to scale so the length of the arrows corresponds to an equivalent height of soil which would exert the same pressure.

Strut and anchor elevations are indicated by (purple) arrows. Horizontal and moment loads applied to the wall are shown by (red) arrows in the appropriate direction. Rotational restraints are indicated by a double ended semi-circular (purple) arrow.

The water tables on either side of the wall are shown as horizontal (blue) dashed lines. Water pressures are plotted in (blue) dashed lines. The water pressure scale is drawn at the bottom of the plot.

For Stage 0 (initial conditions) the plot also includes the total  $K_0$  soil pressure (red). Soil pressures are plotted to the same scale as the water pressures.

### 3.1.2 Results graphics – description

The graphical display shows either:-

- Bending moment, shear force and displacement profiles.  
Shear force and bending moment are plotted on one diagram with shear force shown in dashed lines.
- Active, passive and nett earth pressures.  
Active pressures (left) and passive pressures (right) are plotted on one diagram. Total pressure (soil + water) is shown in solid lines and water pressure in dashed lines.

Type **Alt+W** to toggle the display between the two sets of graphs. You may find that not all construction stages are available for selection because not all stages were analysed.

Use the construction stage selection button to display results for a particular stage.

**Summary graphical output** consists of two diagrams:-

- Bending moment, shear force envelopes on one diagram.
- Displacement envelopes.

## 3.2 THE MAIN MENU

### 3.2.1 'File' menu

Menu item	Shortcut	Description
New Data Set		Start a new data set
Open	Ctrl+O	Open an existing file
Save	Ctrl+S	Save the current data file
Save As		Save the current data under a new name
-----		
Print Setup		Select printer options
Print		
Data listing		Print current input data
Current stage - tabulated results		Print numerical output for current stage
Current stage - graphical results		Print graphical output for current stage
Report		
Print report		Print the current report
Review options		Review selections for creating report
-----		
1.		Quick file open
2.		.
3.		. list of recently
4.		. opened data files
etc. . .		
-----		
Exit	Alt+X	Terminate Wallap execution
-----		

### 3.2.2 'Edit' menu

Menu item	Shortcut	Description
New	Ctrl+N	Insert new data item
Delete	Ctrl+X	Delete data item
Copy	Ctrl+C	Copy data item to WALLAP clipboard
		or Copy text/graphics to Windows clipboard
Paste	Ctrl+V	Paste data item from WALLAP clipboard
Undo	Ctrl+Z	Undo data edits
Redo	Ctrl+R	Redo data edits
-----		
Factor all soil moduli	Ctrl+F	Factor all soil moduli
Factor all soil strengths	Ctrl+F	Factor all soil strengths
-----		
Reverse coordinates	Ctrl+K	see Section 13.3.7

### 3.2.3 'View' menu

Menu item	Shortcut	Description
Select Stage	Alt+L	Select a construction stage for viewing
Previous Stage	Alt+Left	Select previous construction stage for viewing
Next Stage	Alt+Right	Select next construction stage for viewing
-----		
Graphics	Alt+G	Move focus to the graphical display
Zoom Plus	Alt+Up	Increase size of graphical display
Zoom Minus	Alt+Down	Decrease size of graphical display
Plot Options		
Bound. Conditions	Alt+B	Toggle display of FE boundary conditions on data plot
Soil Descriptions		Toggle display of soil descriptions on data plot
BM or Soil pressures		Toggle display of Bending Moment or Soil pressures
-----		
Data	Alt+D	Select Data input mode
Previous Data Block		Display previous data block for editing
Next Data Block	Ctrl+Tab	Display next data block for editing
-----		
Summary Results	Alt+S	View Summary output
Detailed Results	Alt+R	View Detailed results for one stage
Messages		View messages generated during analysis
Data Listing	Alt+N	View complete data listing
-----		
View Report	Alt+T	View Report
-----		

### 3.2.4 'Format' menu

Choose **Format|Font** from the main menu or type **Alt+O** to select a new font, style or size. The new font will be applied to all subsequent analyses and their results. The new font will also be remembered the next time the program is executed. Old output files will be displayed and printed in the font prevailing at the time they were created.

To revert to the default font (Courier New, 9pt) choose **Format|Default font** from the main menu.

It is assumed that output will be printed on A4 paper and the results are paginated accordingly.

### 3.2.5 'Analysis' menu

**Analyse (Alt+A)** starts analysis of the current data. Clicking this option is equivalent to clicking the Analysis mode button.

**Interrupt analysis (Alt+I)** allows you to interrupt an analysis while it is in progress - see Section 3.3.2.

### 3.2.6 'Help' menu

There are 5 items, **Context sensitive help**, **Help Contents**, **Help Index**, **E-mail to Geosolve**, **Geosolve help line**. See Section 3.4 for details.

### 3.3 MODE BUTTONS

#### 3.3.1 'Data input' mode button

Click the **Data** input mode button or select **View|Data** from the main menu or press **Alt+D** to enter Data input mode.

In Data input mode a set of 13 data edit tabs is visible. Click one of the tabs to display the associated data block e.g. Titles, Strata, Soil types etc...

Beneath the box displaying the data there is the **Data errors and warnings** box. If not all the data or errors/warnings can be displayed at once, scroll bars appear at the sides of the boxes. You can also move the splitter bar between the data and the error/warnings listings to view more or less of one box or the other.

During data input the graphical display in the lower right corner of the screen shows the data for the currently selected construction stage including all surcharges, struts, water pressures and excavation level at the currently selected stage. Stage 0 refers to the initial conditions before the first construction stage.

#### 3.3.2 'Analyse' mode button

Click the **Analyse** mode button to commence the analysis of the current data. Alternatively choose **Analysis|Analyse** from the main menu or type **Alt+A**. It is good practice to save newly edited data before analysing it.

On entering analysis mode the data edit display is hidden and a progress summary box appears together with a progress bar at the bottom of the screen.

The progress bar shows the stage number, iteration count and convergence progress within the current construction stage. The progress summary shows the factors of safety and maximum and minimum bending moments, shear forces and displacements at each completed stage. To view the progress summary, click and drag the slider of the progress summary box. The analysis is suspended while the mouse button is held down on the slider.

At the end of the analysis the program enters **View results** mode.

### **Interruption of analysis**

During an analysis it may become apparent that the data is unsuitable and that time will be wasted by allowing the analysis to proceed to completion. To interrupt the analysis at any stage choose **Analysis|Interrupt Analysis** from the main menu or type **Alt+I**. After a short pause the program will display the question:-

Interrupt run?

If the response is N (no) the analysis will proceed as if nothing had happened. If the response is Y (yes) the run is interrupted and the program displays whatever results have been calculated so far.

### **3.3.3 'View Results' mode button**

Click the **View Results** mode button to view the results of an analysis. The display shows 4 pages which can be viewed by clicking the tab at the top of the page, via the main menu or via a shortcut key.

<b>Page</b>	<b>Shortcut</b>	<b>Description</b>
Data listing	Alt+N	View a complete listing of the current data set.
Detailed results	Alt+R	View detailed results for the currently selected stage.
Summary results	Alt+S	View summary results for all stages
Messages	-	View messages generated during the analysis

If the data file has been edited since the results file was created then a 'Data modified' warning is issued.

The Detailed results box displays the results for one stage at a time. Use the construction stage selection button to display results for a particular stage. Information on these pages may be copied to the windows clipboard for use in other documents.

The display on the right hand side of the screen shows a graphical representation of the tabulated results.

### **View stored output**

To view the results of a previous analysis, read the data file from disk and then follow the procedure above for viewing results.

### 3.3.4 'Report' mode button

To create a report for printing or output to disk file, click the Report mode button, choose **ViewReport** at the main menu or type **Alt+T**.

Details of the report options are given in Section 3.11

## 3.4 HELP FACILITIES

### 3.4.1 Context sensitive help

Press **F1** at any time to obtain help on the currently selected menu or data item. This help includes advice and suggestions on appropriate values for data items.

### 3.4.2 Help Contents

Press **Alt+C** at any time to access the Contents page of the WALLAP help system.

### 3.4.3 Help Index

Press **Alt+H** at any time to access the complete Help Index.

Then click the **Find** tab of the Help Topics window and type a word or phrase to obtain Help on a topic of your choice. The help index covers most topics related to operation of the program, data input and interpretation of output.

You may browse through the complete index or a selection of the index topics. For example if you enter 'modulus' you will see a list of all index items containing the text string 'modulus'. The 'topic' need not be a complete word e.g. 'constr' will suffice for 'construction stages'.

### 3.4.4 E-mail to Geosolve

Selecting this option will cause your e-mail system (probably Outlook Express) to open up ready to send an e-mail to Geosolve. Please paste in relevant bits of WALLAP data listings or output and add a message or question.

### 3.4.5 Geosolve help line

For rapid assistance, or to report any quirks or bugs to Geosolve, please contact:

Daniel Borin	Tel	+44 20 8674 7251
Geosolve	Fax	+44 20 8674 9685
e-mail		support@geosolve.co.uk
web site		http://www.geosolve.co.uk

### 3.5 POPUP MENUS AND HOTKEYS (SHORTCUTS)

A **right-click** of the mouse button on any part of the WALLAP desktop will display useful Popup menus. These popup menus provide convenient access to many features available from the main menu or via Hot keys. Here is a summary of all the shortcut keystrokes (Hot Keys) available in WALLAP

<b>Key</b>	<b>Action</b>
F1	Context sensitive help
Ctrl+C	Copy Data / Results to clipboard
Ctrl+F	Factor all soil moduli
Ctrl+E	Factor all soil strengths
Ctrl+K	Reverse coordinates – see Section 13.3.7
Ctrl+N	New data item
Ctrl+O	Open file
Ctrl+P	Print
Ctrl+R	Redo
Ctrl+S	Save
Ctrl+V	Paste data item
Ctrl+X	Delete
Ctrl+Y	reserved as alternative to Ctrl+R
Ctrl+Z	Undo
Ctrl+Tab	Move focus to Next block (data or results)
Shift+Ctrl+Tab	Move focus to Previous block (data or results)
Alt+A	Analyse
Alt+B	Show/Hide boundary conditions
Alt+C	Help contents
Alt+D	View data
Alt+E	'Edit' menu
Alt+F	'File' menu
Alt+G	View graphics
Alt+H	Help index
Alt+I	Interrupt analysis
Alt+L	Select a stage
Alt+M	View messages
Alt+N	View data listing
Alt+O	Select font
Alt+R	View detailed results
Alt+S	View summary results
Alt+T	Enter report mode
Alt+V	'View' menu
Alt+W	Swap display of Bending moments / Earth pressures
Alt+X	Exit
Alt+Left	Previous stage
Alt+Right	Next Stage
Alt+Up	Zoom + (enlarge graphical display)
Alt+Down	Zoom - (reduce graphical display)

### 3.6 CONSTRUCTION STAGE SELECTION

The green button in the top right corner of the WALLAP desktop shows you the number of the 'current construction stage'. The current stage may be selected in one of the following ways:-

- Click on the green button or type **Alt+L** and select from the dropdown menu
- Use the hot key combinations **Alt+Left** or **Alt+Right** to move backward or forward through the construction sequence a stage at a time.
- Right click anywhere and select one of the options **Alt+L**, **Alt+Left** or **Alt+Right**.

During data input the graphical display in the lower right corner of the screen shows the data for the currently selected construction stage including all surcharges, struts, water pressures and excavation level at the currently selected stage.

Stage 0 refers to the initial conditions before the first construction stage.

While viewing results, you may find that not all construction stages are available for selection because not all stages were analysed. The graphical display in the lower right corner of the screen shows the results for the currently selected construction stage. At the same time the tabulated results for the current stage are shown in the panel on the left hand side of the screen.

When viewing **detailed results** the graphical display shows either:-

- Bending moment, shear force and displacement profiles, or
- Active, passive and nett earth pressures.

Type **Alt+W** to toggle the display between the two sets of graphs.

### 3.7 DATA FILES

A data file contains one data set.

If several data sets containing different versions of a problem are to be stored on disk, they must be stored in files with different names. If you attempt to store a data set under an existing filename, the program will print the warning:-

C:\...\filename.dat exists. Over-write?

#### Filenames

A filename consists of any sequence of up to 45 letters or numbers. You will not normally have to type the file extension (.DAT or .OUT). The program automatically gives data and output files the appropriate file extension. The following characters should not be included in filenames:

[ ] \ . < > ? : ; /

#### Data folders

When data files are accessed, the program assumes that they are stored in the current folder on the currently logged drive as displayed in the yellow panel at the top of the screen. Use the **Open** and **Save As** dialog boxes to select a new folder.

#### 3.7.1 Opening an existing data file

Choose **File|Open** from the main menu or type **Ctrl+O**. Use the dialog box to select a data file. While browsing the data files, the title and subtitle of the currently highlighted file are displayed in a box at the top of the screen to assist in selecting the correct file. If the highlighted file is not a WALLAP data file a warning is displayed.

You may use the dialog box to access data on other drives and folders. The newly selected folder becomes the current folder and the data are read into memory and become the current data set.

#### Quick file open

To re-open a recently accessed data file choose **File** from the main menu and select one of the files listed.

#### 3.7.2 Starting a new data set

Choose **File|New** from the main menu. You will be prompted to save your current data if it is not already saved. The program creates a complete skeleton data set including one stratum, one soil type and a dummy excavation stage.

Soil types may be imported from other data files by copying their properties via the WALLAP clipboard (Section 3.9.3).

On completion of data entry, the data are stored in memory and are referred to as the current data set. The new data must be stored in a disk file if they are not to be lost at the end of the session.

### **3.7.3 Saving data on disk**

Choose **File|Save** or type **Ctrl+S**. The current data are saved to the current filename. Existing data in that file will be overwritten.

#### **Saving to a new file**

Choose **File|Save As** from the main menu. Use the dialog box to enter a new filename or select an existing file which will get overwritten. Use the dialog box to select a different folder or create a new folder for saving your data. You can access data in any folder on any drive. The folder containing the selected file becomes the current data folder.

### **3.7.4 Where to store your data**

Store your data in folders set aside specially for WALLAP data. Never store your data in the WALLAP program folder. Data for different projects should be kept in separate folders to facilitate archiving and retrieval of data and results.

## **3.8 DATA STRUCTURE**

### **3.8.1 Data sets**

A data set contains all the data necessary to carry out one analysis. The data in a data set are grouped into 13 data blocks. When a data set is stored on disk it occupies one file.

When a data set is entered for the first time via the keyboard, or read from a disk file, it is stored in memory (RAM) and becomes the current data set.

### **3.8.2 Run Identifiers and data file names**

The Run ID which appears in the title block is always the same as the last data filename which was read or stored on disk. In order to maintain the correspondence between RunID and Data filename, you should always store newly edited data before carrying out an analysis. This will enable you to trace printed output to a particular data file.

You should choose a convenient mnemonic and numbering system to identify the various data files and the corresponding analyses which are generated during a job.

## **File maintenance**

You are responsible for removing old or unwanted files which will otherwise occupy valuable disk space.

## **3.9 GENERAL RULES FOR DATA ENTRY**

### **3.9.1 Selecting a data block**

Click the Data input mode button or select **ViewData** from the main menu or press **Alt+D** to enter Data input mode. In Data input mode a set of 13 data edit tabs is visible. Click one of the tabs to display the associated data block e.g. Titles, Strata, Soil types etc...

### **3.9.2 Selecting and editing a cell**

Use the mouse or keypad arrows to highlight the item to be edited. Obtain help on the currently selected item by pressing **F1**.

### **Numeric and Text data**

To edit Numeric data or Text data press **Enter** or click on the item to open the item for editing. To overwrite the existing value simply start typing at the highlighted box. Conclude the data entry by pressing the Tab key, Up arrow, Down arrow or Enter, or by clicking on another cell.

### **Options data** (e.g. yes/no, drained/undrained)

Where a data item is selected from a series of options you can:-

- Click on the option and select from the dropdown menu, or
- Press the space bar to cycle through the various options, or
- Type the initial letter of the option, Y, N etc... ( this only works where there is a choice of 2 options)

### **Insert New data item**

To define a new soil type, strut etc..., highlight the undefined item or the position in the sequence where the new item is to be inserted and:-

- Press **Ctrl+N**, or
- Choose **EditNew** from the main menu, or
- Right click and choose **Insert at cursor** from the popup menu.

The exact usage depends on the data type being added. For struts, surcharges, pwp profiles, and loads you can simply move to the undefined item and press **Enter**.

### Delete data item

To delete a soil type, strut etc..., highlight the item and:-

- Press **Ctrl+X**, or
- Choose **Edit|Delete** from the main menu, or
- Right click and choose **Delete at cursor** from the popup menu.

### 3.9.3 Clipboard operations

Groups of data can be copied and pasted via the WALLAP clipboard.

The following example illustrates the procedure for soil properties but the same steps can be applied to Struts, Surcharges, Water pressure profile etc....

To copy the properties of soil type **i** to soil type **j**

1. Select the **Soil types** tab
2. Move the cursor to soil type **i**
3. Type **Ctrl+C** or right click within the soil properties menu and select **Copy**. This copies the properties of soil type **i** to the WALLAP clipboard
4. Move the cursor to soil type **j**
5. Type **Ctrl+V** or right click within the soil properties menu and select **Paste**. This pastes the properties of soil type **j** from the WALLAP clipboard

Soil types can be copied and pasted from one data file to another via the windows clipboard.

See Section 3.12 for clipboard operations on results listings and graphics.

### 3.9.4 Undo and Redo data edits

Data edits can be undone up to a 100 steps. Type **Ctrl+Z** or choose **Edit|Undo** from the main menu.

Edits which have been undone can be redone provided no other changes have been made in the mean time. Type **Ctrl+R** or choose **Edit|Redo** from the main menu.

### **3.9.5 Moving focus**

During data input, focus is either on the Main form, the Current data block (left side of screen) or the Graphics box (lower right) corner of screen. In general the Current data block may obscure part of the Graphics box or vice versa. Click on the visible part of either box to bring it to the front.

## **3.10 VIEWING RESULTS**

Refer to Section 3.3.3 for a description of the **View Results** mode button. There are 4 tabs in View Results mode. Select the item you wish to view.

### **3.10.1 Data listing**

This is a complete listing of the input data. This item can be viewed even when no analysis has been done and there are no results to view. Type **Alt+N** or choose **View|Data Listing** from the main menu.

### **3.10.2 Detailed results for each stage**

The output for each stage begins with the title block and the stage description (Fill, excavate etc.). The results of the stability analysis are shown first, followed by the bending moments and displacements. Detailed descriptions of the output are given in Chapter 15.

Use the (green) stage selection button to select a particular stage for viewing. The tabulated figures are also shown in graphical form in the plot on the right side of the screen.

### **3.10.3 Summary results**

Detailed descriptions of summary output are given in Section 15.4. The tabulated figures are shown in graphical form in the plot on the right side of the screen.

### **3.10.4 Messages**

These are progress messages generated during the analysis. They are generally not of interest but may be useful in certain circumstances where a problem has been encountered in achieving convergence of the bending moment and displacement calculation.

### 3.10.5 Formatting output

The font size and style of the results listings can be controlled using the Format option in the main menu. Click **Format|Font selection** or type **Alt+O** to bring up the font selection box. Font selection must be done before the analysis. Results cannot be reformatted after the analysis.

The default font is Courier New 9pt.

## 3.11 CREATING AND PRINTING REPORTS

To create a report for printing or output to disk file, click the **Report** mode button, choose **View|Report** at the main menu or type **Alt+T**. The following options control the information included in the report.

To leave Report mode, click **Close**, type **Esc** or close the form. No other WALLAP processing is possible while in Report mode.

### 3.11.1 Stage selection

#### Automatic stage selection

Use this option to include output for all stages of certain types, according to the **Automatic output selection options** in the top right corner of the form e.g. all Excavation and Load Application stages. The Output Options in the data file (Section 14.0) will be ignored.

For **Automatic stage selection** you must also decide whether you want detailed listing of **Active/passive pressures for all selected stages**. If this option is not selected, output for the selected stages will consist only of Factor of Safety, Bending moments and Displacements.

#### Last construction stage only

The report will contain results for the last stage only plus optional summary output.

#### Custom stage selection

Use this option to make stage selections in accordance with the Output Options in the data file. Click **Check custom selections** to review or change the Output Options in the data file (Section 14.0).

### 3.11.2 Graphical output

#### Data graphics

Choose **Data graphics for all selected stages** to include a picture of the data at each selected stage. Alternatively choose **Data graphics for last stage** to include a picture of the data at the last stage only.

#### Results graphics

If you have chosen **Automatic stage selection** you must decide whether you want graphical output of bending moments etc. at all selected stages or none. If you want Results graphics at some stages and not others then choose **Custom stage selection** and make your choices in the **Output options** data.

#### Summary graphics

Select this option to include plots of the Bending moment, shear force and displacement envelopes.

#### Common scale for all stages

As for the on-screen results display, you can choose to have all bending moment, shear force and displacement diagrams plotted to a common scale or to have each diagram plotted to the largest scale that will fit the box.

### 3.11.3 Create report

Click **Create report** to begin creation of the report using the options selected above. The report will be created in an RTF (Rich Text Format) file in the same folder as that in which the data and results files are stored. An RTF file can be viewed and printed using MSWord, WordPad and many other non-Windows word processing programs.

### 3.11.4 View report

Click **View report** to open the report file using your default word processing package (usually MSWord). You are free to edit the report file and add comments or other information.

To return to WALLAP, close MSWord or click on the WALLAP icon on the Windows taskbar.

### 3.11.5 Print report

Click **Print report** to print the report on your default printer. To print to another printer or select non-standard printer options, use **View report** and use the print facilities in MSWord.

### 3.11.6 Output to an Excel spreadsheet

Tabulated output to an Excel spreadsheet allows you to carry out further processing on tabulated results. On the Report menu, click **Excel spreadsheet options**. The parameter and stage selection options are the same as described above for the reports. There are no options for graphical output to an Excel file.

## 3.12 USING THE WINDOWS CLIPBOARD

Data and results listings may be copied to the windows clipboard as follows:-

1. Select all or part of the text box. This may be done by clicking and dragging or by typing **Ctrl+A** to select all text in the box.
2. Copy the selected text to the windows clipboard using the standard keyboard shortcut, **Ctrl+C** or by choosing **Edit|Copy** on the main menu.

Graphical output may be copied to the windows clipboard as follows:-

1. Display the required graphic (data or results).
2. Click in the graphics box.
3. Copy the graphic to the windows clipboard using the standard keyboard shortcut, **Ctrl+C** or by choosing **Edit|Copy** on the main menu.
4. The graphic will be scaled to occupy a fixed area suitable for an A4 page in the destination document.

## 3.13 TERMINATING PROGRAM EXECUTION

Type **Alt+X** or choose **File|Exit WALLAP** from the main menu or close the main form. Any unsaved data will be lost.

## 4.0 TITLE BLOCK and FORCE, LENGTH UNITS

I.K.BRUNEL and PARTNERS	Sheet No.
Program: WALLAP Version 5.04	Revision A28.B42.R35
	Licensed from GEOSOLVE
Run No. DEMO1	Job No. ABC/123
Portsmouth dockyard	Made by : DLB
Sheet pile wall with two levels of anchors	Date:06-07-2007
	Checked :
-----	
	Units: kN, m

### 4.1 TITLES

'Titles' comprises six items of information which are printed in the title block at the top of the input data and at the top of each section of output. They are:-

	<b>Maximum permitted no. of characters</b>
Main title	60
Sub-title	60
Job number	7
Engineer's initials	4
Force units	2
Length units	2
Unit weight of water	-

The text may contain any characters. The Date is set by the system clock and cannot be changed within the program. Blank entries are accepted except for the Units.

### 4.2 FORCE AND LENGTH UNITS

The Force units and Length units entered by the user are used by the program to prompt data entry in the correct units and also to annotate the output. The suggested style is:-

**kN, m or kg, cm or lb, ft**

Data can be entered in any consistent set of units. It is up to you to ensure that the values entered for strength, density, etc., correspond to the given units.

## 5.0 STRATA PROFILE - INITIAL CONDITIONS

The section should show original ground level (at the time of installing the wall) and the boundaries between the different soil strata.

The strata and the boundaries between them are numbered from ground level downwards as shown in Figure 2. Thus the number of each soil stratum is the same as the number of its upper boundary so that boundary No.1 corresponds to ground level. There is no lower boundary to the section and the program assumes that the lowermost stratum extends downwards indefinitely.

Each stratum should be allocated a 'soil type'. Different soil types may be allocated to the ground on either side of the wall within a single stratum; for example when there are different ground conditions on either side of the wall.

The same soil type can be assigned to more than one stratum as shown in Figure 2.

A maximum of 40 soil strata is permitted. At least one stratum must be defined. The y coordinates of the strata may be entered in any order.

### 5.1 COORDINATE SYSTEM

The vertical axis has the positive direction pointing upwards. There is no restriction on the use of negative coordinate values except that all values must lie between -10000 and +10000. It is often convenient to use O.D. levels for the vertical coordinates.

### 5.2 STRATA ELEVATIONS

Enter the elevation (y coordinate) of the **upper** boundary of the stratum. The elevation of the top stratum is the initial GL. The lowermost stratum is assumed to extend downwards indefinitely.

Two strata cannot have the same elevation.

### 5.3 ASSIGNING SOIL PROPERTIES TO A STRATUM

Define the soil properties of a stratum by assigning it a Soil Type(s). You can assign different soil types to the active and passive sides.

The actual properties of the Soil Types are defined in the Soil Properties (Section 6).

### 5.4 EDITING THE STRATA PROFILE

The following edit menu is displayed

Strata Profile				
Stratum no.	Elevation of top of stratum	----- Soil types -----		
		Active side		Passive side
1	11.00	1	Sand	1 Sand
2	6.00	2	Soft clay	2 Soft clay
3	1.00	3	Stiff clay	3 Stiff clay

#### Edit y coordinate or soil type of a stratum

Move the cursor to the value to be edited and enter a new value. The new elevation (y coordinate) of the stratum cannot lie above or below its neighbours. If you want to change the strata sequence, delete a stratum and insert a new stratum at the required elevation.

#### Add a stratum

A new stratum can be inserted anywhere in the existing profile. Move the cursor to the position where the new stratum is to be inserted and

- Type **Ctrl+N**, or
- Click **EditNew** on the main menu, or
- Right click and select **Insert at cursor** from the popup menu

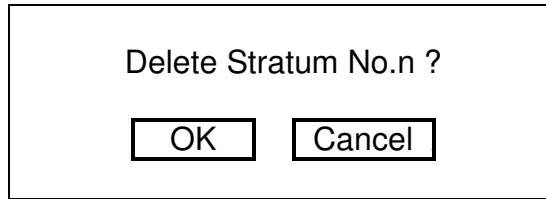
Remember that the new y coordinate defines the upper boundary of the new stratum.

#### Delete a stratum

Move the cursor to the Stratum to be deleted and

- Type **Ctrl+X**, or
- Click **EditDelete** on the main menu, or
- Right click and select **Delete at cursor** from the popup menu

The program requests confirmation:-



where n is the currently selected stratum. After each deletion the strata below the deleted stratum (if any) are re-numbered automatically and the revised profile is displayed.

### 5.5 MODELLING OF SLOPING BACKFILL

All strata in WALLAP are defined essentially as horizontal. The effects of sloping ground are modelled by use of equivalent surcharges **or** adjustments to soil properties. Sloping backfill can be modelled in one of two ways:

#### a) **Surcharge method**

Impose one or more surcharges to represent the weight of soil above the top of the wall. Ground which slopes downwards away from the wall can be modelled by the use of negative surcharges. Surcharges must be used in conjunction with the **Wedge Analysis** option (Section 13.3.6) if the results are to be reliable. The surcharge method of modelling sloping backfill is to be preferred because:

- It takes full account of the backfill profile at all stages of the calculation.
- It can model the exact ground profile

#### b) **Modified earth pressure coefficients**

Enter values of  $K_a$  and  $K_p$  corresponding to the sloping backfill condition. This method is simpler but has limitations:

- It takes account of the backfill profile only in respect of the limiting active pressures but not in respect of  $K_o$  soil pressures.
- The adjusted  $K_a$  values are strictly only correct for infinite uniform slopes without cohesion.

### 5.6 MODELLING OF BERMS

Berms are modelled as a special form of Excavation Stage. Additional optional parameters specify the dimensions of the berm. Details are given in Section 12.1.1 and Figure 11. See Data File DEMO6.DAT for a worked example.

## 6.0 SOIL PROPERTIES

Soil Strata are allocated properties via Soil Types in the Soil Properties section. The properties of a stratum can be changed during construction (e.g. from undrained to drained) by substituting one soil type for another (Section 12.1.7). The following sections describe the items of data which make up the definition of a Soil Type.

### 6.1 SOIL DESCRIPTION

A text of up to 20 characters. Soil descriptions are shown on the graphical output of the soil profile.

### 6.2 BULK UNIT WEIGHT

Many soils have different bulk unit weights above and below the water table. Thus for each soil type, two values of bulk unit weight may be specified, one for material above the water table (partially saturated or dry) and one for material below the water table (saturated bulk unit weight).

**Saturated Bulk Unit Weight is therefore usually greater than Dry Bulk Unit Weight.**

The program automatically uses the appropriate values in the analysis according to the position of the water table.

The units of bulk unit weight must be consistent with those used for cohesion and surface loads:-

<b>Cohesion</b>	<b>Corresponding units of</b>
<b>Units</b>	<b>bulk unit weight</b>
kN/m <sup>2</sup>	kN/m <sup>3</sup>
kg/cm <sup>2</sup>	kg/cm <sup>3</sup>
lb/ft <sup>2</sup>	lb/ft <sup>3</sup>

**Submerged** unit weights must **not** be specified; water pressures on submerged ground are taken account of in the analysis.

### 6.3 COHESIONLESS OR COHESIVE SOIL TYPE

All soil types are defined as Cohesionless or Cohesive. The following restrictions apply:

Category	Restrictions	Typical soil types
Cohesionless soil	Always "drained". Cohesion value is zero. $K_{ac}$ and $K_{pc}$ are zero	Sand, gravel, Cohesionless silt
Drained Cohesive soil	No restrictions	Medium / long term Behaviour of clays
Undrained Cohesive soil	$K_a = 1$ $K_p = 1$ Poisson's ratio = 0.49	Short / medium term Behaviour of clays

### 6.4 NORMALLY- OR OVER-CONSOLIDATED SOIL TYPE

All soil types are defined as Normally Consolidated or Over-Consolidated (NC/OC). The modulus of NC cohesionless soils is defined in a different way from the other types:

	Modulus model	Typical soil types
NC cohesionless	Modulus = 0 at GL increasing linearly with depth	Uncompacted hydraulic fill
OC cohesionless	Constant modulus, With optional linear Variation with depth	Compacted granular fill
NC cohesive	ditto	V.soft clay ( $c_u < 10$ kPa)
OC cohesive	ditto	Firm / stiff clay

## 6.5 DRAINED OR UNDRAINED SOIL TYPE

Cohesive soils are defined as behaving in either a Drained or Undrained manner. Drained and Undrained analyses are applicable as follows:-

Type of analysis	Applicability
Drained analysis	Medium / long term behaviour
Undrained analysis	Short / medium term behaviour

### 6.5.1 Drained soil

The analysis of Drained cohesive soil is carried out in effective stress terms i.e. pore pressures are assumed to have time to reach equilibrium.

### 6.5.2 Undrained soil

The analysis of Undrained cohesive soil is carried out in total stress terms - there is insufficient time for pore pressures to reach equilibrium. Limiting active pressures in Undrained soil take account of the "minimum equivalent fluid density" criterion (Section 13.3.4) and the "maximum water filled tension crack depth" criterion (Section 13.3.5). Soil pressures in Undrained strata are reported in Total stress terms.

### 6.5.3 Critical conditions for Drained and Undrained analysis

Soft and very soft clays tend to be weakest under undrained (short term) loading and gain strength with time. Stiff and very stiff clays tend to be strong under undrained (short term) loading and lose strength as suctions dissipate with time. It is important to check behaviour under all relevant conditions. The following table gives some indication of the likely critical conditions for soft and stiff clays.

	Undrained analysis (Short term)	Drained analysis (Long term)
Soft / very soft clay	Critical	---
Stiff / very stiff clay	---	Critical

### 6.5.4 Drained and undrained cohesion

For drained cohesive soils the drained cohesion,  $c'$  must be specified. For undrained cohesive soils the undrained cohesion,  $c_u$  must be specified. See Section 6.8 for discussion of Drained and Undrained cohesion

## 6.6 COEFFICIENT OF EARTH PRESSURE AT REST - $K_o$

### 6.6.1 Definition of $K_o$

$K_o$  defines the initial soil pressure on the wall at the start of the Bending moment and Displacement analysis i.e. after the wall has been installed before the first construction stage.  $K_o$  is defined as the ratio of horizontal to vertical effective stress:-

$$K_o = p_h' / p_v' \quad 6.1$$

$K_o$  values are only used in the Bending moment and Displacement analysis (Section 15.3) and have no effect at all on the Factor of Safety calculations (Sections 15.1 and 15.2).

### 6.6.2 Typical values of $K_o$

For normally consolidated soils the value of  $K_o$  is given approximately by Jaky's formula:

$$K_o = 1 - \sin \phi \quad 6.2$$

where  $\phi$  is the drained angle of friction.

For over consolidated soils the value of  $K_o$  can be much higher and in the case of very stiff clays can be in excess of 2. Values can be obtained from pressure meter tests or from published papers such as Burland, J.B., B.Simpson and H.D.St John (1979).

In the case of OC clays,  $K_o$  may vary with depth. The program allows a linear variation of  $K_o$  with depth. The datum elevation is the same as for a varying  $c_u$  and a varying Young's modulus.

### 6.6.3 Use of $K_o$ in the analysis

Values of  $K_o$  are used at various points in the calculation:-

#### Initial conditions

The program uses  $K_o$  values firstly to calculate the initial earth pressures on the wall immediately after wall installation and before the construction sequence begins. The initial horizontal total pressure is calculated according to the equation:-

$$p_h = p_v' \cdot K_o + u \quad 6.3$$

This calculation is carried out in **effective stress** terms for both drained **and** undrained soil types. The reason for this is that the  $K_o$  state is a **state** i.e. the **starting point** for a series of stress changes. The terms "drained" and "undrained" are used only in relation to the subsequent stress changes.

#### Changing soil properties

The value of  $K_o$  is also used in the construction activity "Change soil properties" if  $K_o$  values are reset (Section 12.1.7). This facility is useful for modelling the build up of  $K_o$  pressures after the end of construction in a stiff overconsolidated clay with a high initial  $K_o$  value.

#### Fill materials

$K_o$  values are used to calculate the initial earth pressures on the wall due to soil placed during a Filling construction stage. The initial horizontal total pressure should be calculated according to the equation:-

$$p_h = p_v' \cdot K_o + u \quad 6.4$$

### 6.6.4 Rate of change of $K_o$ with depth - $dK_o/dy$

$K_o$  is allowed to vary with depth within a soil type. A positive value of  $dK_o/dy$  indicates  $K_o$  increasing with depth. The datum elevation for  $K_o$  is the same as for the cohesion and modulus.

## 6.7 ACTIVE AND PASSIVE EARTH PRESSURE COEFFICIENTS

These are the earth pressure coefficients which determine the **limiting** values of active and passive pressures which the soil can exert on the wall.

### 6.7.1 Values of $K_a$ , $K_{ac}$ , $K_p$ , $K_{pc}$

$K_a$ ,  $K_{ac}$  and  $K_p$ ,  $K_{pc}$  are calculated as functions of:

$\phi$	Soil friction angle
$\beta$	Backfill slope angle
$\tan\delta/\tan\phi$	Wall friction coefficient

See Appendix A for a definition of the sign conventions for  $\beta$  and  $\delta$ . For interactive help on  $K_a$ ,  $K_{ac}$ ,  $K_p$  or  $K_{pc}$  press **F1** at the **Soil properties** menu when editing one of these parameters. The values of  $K_a$ ,  $K_{ac}$ ,  $K_p$  and  $K_{pc}$  calculated by the WALLAP help facility are values of the horizontal components, as required:

Soil properties .... Soil type 1 .... Help for Ka, Kac values	
Soil friction angle, $\phi$ (degrees)	30.00
Backfill slope angle, $\beta$ , rising +ve (degrees)	5.00
Wall friction(adhesion) coefficient ( $\tan\delta/\tan\phi$ or a/c)	0.500
Horizontal earthquake acceleration factor	0
Vertical earthquake accel. Factor (+ve Downwards)	0
Formula for calculating Ka, Kac values	Eurocode 7
Suggested value of Ka	0.309
Suggested value of Kac	1.193
Type "A" to accept suggested value or Click here >	Accept

For cohesionless soils,  $K_{ac}$  and  $K_{pc}$  are assumed to be zero. For undrained cohesive soils,  $K_a$  and  $K_p$  are assumed to be unity. For additional help, on values of  $K_a$  etc.. from other sources, press **F1** while above menu is displayed.

See "Sloping backfill" (Section 5.5) and "Berms" (Section 5.6) for help on modelling complex ground profiles.

See Sections 6.7.2 and 12.1.9 for discussion of Earthquake conditions.

See Appendix A for the calculation of limiting earth pressures from  $K_a$ ,  $K_{ac}$ ,  $K_p$  and  $K_{pc}$ .

### Choice of formulae for calculating $K_a$ , $K_{ac}$ , $K_p$ , $K_{pc}$

The Help facility offers a choice of formulae for calculating  $K_a$  etc... The recommended (default) formula is the one presented in Eurocode 7 Part 1, Annex G. An alternative formula (by Coulomb) may be used for calculating  $K_a$  and  $K_p$  but it has two disadvantages (a) It is inaccurate at high angles of wall friction and slope angle, especially for  $K_p$ ; (b) It only gives values of  $K_a$  and  $K_p$ , **not**  $K_{ac}$  and  $K_{pc}$ .

### Alternative values of $K_p$ and $K_{pc}$

Values of  $K_p$  based on the calculations of Caquot and Kerisel (1949) are given in Appendix A and are also available in the Help Index (type **Alt+H** and enter topic " $K_p$ "). Note that the tabulated values are the horizontal components of passive earth pressure and can therefore be entered directly into the program. Values of  $K_{pc}$  as published in CP2 are also given in Appendix A.

### 6.7.2 $K_a$ and $K_p$ values for seismic loading

A special construction stage "Seismic loading" (Section 12.1.9) should be used to model earthquake conditions. The values of  $K_a$  and  $K_p$  in the soil properties data should **not** be adjusted for seismic acceleration. All necessary adjustments are made automatically by the program using the seismic coefficients defined in the seismic loading data.

### Old Calculation procedure

Many engineers are used to calculating values of  $K_a$ ,  $K_p$  for earthquakes in cohesionless soil according to the formula proposed by Mononobe and Okabe. However these values can **not** be entered directly into WALLAP as they only give the **total** active and passive **forces**, but not the correct pressure **distribution**.

Mononobe and Okabe's formula is still available in the Help facility (press **F1** while editing  $K_a$ ) for those who wish to perform a manual check on WALLAP's automated calculation for seismic loading. The additional active limit force,  $P_{eq}$  due to the earthquake is given by:

$$P_{eq} = 0.5 \gamma h^2 (K_{a_{eq}} - K_a) \quad 6.5$$

According to many codes of practice this force  $P_{eq}$  is applied as an inverted triangular distribution in addition to the usual static pressures i.e. its line of action is 1/3 of the way from the top of the wall. The Seismic Loading stage in WALLAP performs this calculation automatically.

## 6.8 DRAINED AND UNDRAINED COHESION

### 6.8.1 Drained cohesion

For drained cohesive soils the drained cohesion,  $c'$  must be specified. The drained cohesion may be derived from drained triaxial tests or (more usually) undrained triaxial tests with pore pressure measurement. The latter are susceptible to error if the rate of testing is not sufficiently slow (Bishop and Henkel, 1962). High values of drained cohesion should be regarded with suspicion.

### 6.8.2 Undrained cohesion

For undrained cohesive soils the undrained cohesion,  $c_u$  must be specified. Undrained cohesion values may be obtained from undrained triaxial tests or estimated from correlations with SPT values. For over-consolidated clay the following correlation may be used:-

$$c_u \text{ (kN/m}^2\text{)} \cong 4.5 \times N \quad 6.6$$

where  $N$  is the SPT value. The following table gives an approximate indication of cohesion values in terms of the usual borehole log descriptions:-

	Consistency		
	Soft	medium	stiff
Undrained shear Strength, $\text{kN/m}^2$	20-40	40 – 75	75 - 150

Table 6.1 Approximate values of Undrained Cohesion

### 6.8.3 Cohesion varying with depth - $dc/dy$

For cohesive soil (both drained and undrained) the cohesion may be specified to vary linearly with depth according to the equation:-

$$c = c_0 + (y_0 - y).dc/dy \quad 6.7$$

where  $c_0$  is the cohesion at a datum elevation  $y_0$  and  $dc/dy$  is the rate of increase of cohesion with depth (see Figure 3).

$dc/dy$  may take any value, positive or negative. A positive value represents cohesion increasing with depth. For constant cohesion within the stratum enter zero. If a non-zero value is entered for  $dc/dy$  the program requests a value for the datum elevation  $y_0$  in equation 6.7.

## 6.9 YOUNG'S MODULUS

The program requires the value of Young's Modulus in order to calculate changes in wall pressure as the wall moves (see Appendix B).

### 6.9.1 Young's Modulus of Cohesionless soil

#### Normally Consolidated Cohesionless soil

The Young's modulus of normally consolidated (uncompacted) cohesionless soil increases linearly from zero at ground level and is related to its density.

For retaining walls the following values are suggested by Terzaghi (1954):-

	Relative density		
	Loose	medium	dense
	Modulus values, $kN/m^2/m$ depth		
Dry or moist sand	880	2800	7100
Submerged sand	560	1800	4600

Table 6.2 Approximate values of Young's Modulus for cohesionless soil

### Over-consolidated cohesionless soil

The Young's modulus of over-consolidated (compacted) cohesionless soil is approximately proportional to its SPT N value according to the equation:

$$\text{Young's modulus (kN/m}^2\text{)} = F \times \text{SPT N value}$$

where F is in the range 2000 to 6000 for retaining walls in sands and gravels.

### 6.9.2 Young's Modulus of Cohesive soil

#### Modulus of undrained cohesive soil

The following table may be used as a preliminary guide to values of Young's Modulus for cohesive soil:-

	Consistency		
	Soft	Firm	Stiff
Undrained shear strength, kN/m <sup>2</sup>	20 - 40	40 - 75	75 - 150
Young's Modulus kN/m <sup>2</sup>	1600 - 6000	6000 - 20000	20000 - 75000

Table 6.3 Approximate values of Young's Modulus for cohesive soil

The stress-strain behaviour of clays is non-linear and so the value of  $E_u$  itself depends on the strain level at which the modulus is measured. The value of  $E_u$  entered in the data should therefore relate to the magnitude of the strains which occur during excavation. In the absence of direct measurements,  $E_u$  may be derived from published correlations between  $E_u$  and undrained shear strength,  $c_u$ . The relationship is of the form:-

$$E_u = M \cdot c_u \quad 6.8$$

where M depends on the strain at which  $E_u$  is measured. The following table is based on data from Burland et al. 1979:-

Strain level	$E_u/c_u$ (=M)
2.0%	150
1.0%	250
0.4%	400
0.2%	600
0.1%	800

Table 6.4 Approximate relationship between Young's Modulus and undrained cohesion

### Modulus of drained cohesive soil

The drained modulus,  $E'$  (at any particular strain level) will differ from the undrained modulus,  $E_u$ . Wroth (1972) has shown that they are related by the equation:-

$$E' = \frac{2}{3} (1+\nu) E_u \quad 6.9$$

but for drained clay:-

$$\nu = 0.15 \text{ (approx.)}$$

therefore substituting in Eq.6.9 gives:

$$E' = 0.77 E_u \quad 6.10$$

### Anisotropic modulus of drained modulus

Henkel (1972) has shown that for heavily overconsolidated clays the effects of anisotropy can be significant, with the drained horizontal Young's modulus,  $E'_h$  being greater than the drained vertical modulus  $E'_v$ . For example in London Clay:-

$$E'_h = 1.6 E'_v = 1.23 E_u \quad 6.11$$

Since we are dealing with the **horizontal** response to horizontal changes of wall pressure we should use values of  $E'_h$ . However on account of the uncertainties inherent in measuring or estimating soil modulus, and the insensitivity of designs to modulus values the values given in Tables 6.3 and 6.4 may be used for both drained and undrained modulus.

### 6.9.3 Modulus varying with depth

For cohesive and OC cohesionless soil the modulus may be specified to vary linearly with depth according to the equation:-

$$E = E_o + (y_o - y).dE/dy \quad 6.12$$

where  $E_o$  is the modulus at a datum elevation  $y_o$  and  $dE/dy$  is the rate of increase of modulus with depth.  $dE/dy$  may take any value, positive or negative. A positive value represents Modulus increasing with depth (see Figure 3). For constant cohesion within the stratum enter zero. If a non-zero value is entered for  $dE/dy$  the program requests a value for the datum elevation  $y_o$  in equation 6.12.

## 6.10 POISSON'S RATIO

Poisson's Ratio is used in the Bending moment and Displacement analysis. It is used in two different parts of the calculation:-

### 6.10.1 Changes in wall pressure due to vertical stress changes

Several types of construction stage (e.g. Filling, Excavation, Water pressure change, Surcharge application) cause a change in vertical (effective) stress in the soil. The corresponding "immediate" (elastic) change in wall pressure is calculated according to the equation:

$$\Delta p_h' = 2\Delta p_v' \cdot \nu/(1-\nu) \quad 6.13$$

### 6.10.2 Soil spring values

Poisson's Ratio is used in conjunction with Young's Modulus in the calculation of the Soil spring values which represent the elastic response of the soil to wall displacements.

### 6.10.3 Typical values of Poisson's ratio

For granular (cohesionless) soils Poisson's ratio is usually in the range 0.2 to 0.3. For drained over-consolidated clays (and unloading of normally consolidated clays) Poisson's ratio is usually in the range 0.1 to 0.2.

For undrained clays Poisson's ratio is fixed at a value of 0.49 ; the theoretical value of 0.5 would lead to numerical problems in the Finite Element solution.

## 6.11 DATA ENTRY and EDITING

### 6.11.1 Define a new Soil Type

Soil Properties							
--- Soil type --- No. Description (Datum elev.)	Bulk density kN/m <sup>3</sup>	Young's Modulus Eh,kN/m <sup>2</sup> (dEh/dy)	At rest coeff. Ko (dKo/dy)	Consol state. NC/OC ( Nu )	Active limit Ka ( Kac )	Passive limit Kp ( Kpc )	Cohes -ion kN/m <sup>2</sup> ( dc/dy)
1 Sand	17.90	3500	0.450 (0.303)	NC (0.000)	0.277 ( 0.000)	5.000	
2 Soft clay	20.00	12000	0.600 (0.490)	OC (2.000)	1.000 ( 2.000)	1.000	40.00u
3 Stiff clay	21.00	40000	1.800 (0.490)	OC (2.000)	1.000 ( 2.000)	1.000	150.0u
4 Not defined							

At the Soil Properties edit menu select an undefined soil type and:-

- Type **Ctrl+N**, or
- Click **EditNew** on the main menu, or
- Right click and select **Insert at cursor** from the popup menu

When defining a new soil type, you will be prompted for each of the soil properties in turn.

#### Copy soil properties

You can copy all the properties of one soil type to another soil type; see Section 3.9.3 for use of the WALLAP clipboard for copying and pasting data. If the destination soil type was already defined, its properties will be over-written.

### 6.11.2 Edit a Soil Type

Double click or press **Enter** to select the soil type to be edited. Select the property to be edited and enter a new value:-

Soil properties – Soil type 6	
Soil description (20 characters max)	Clay
Bulk Unit Weight – Above the water table	17.90 kN/m <sup>3</sup>
Bulk Unit Weight – Below the water table	17.90 kN/m <sup>3</sup>
Soil type	Cohesive
Consolidation state	OC
Drained / Undrained	Drained
Coefficient of Earth Pressure at Rest, $K_0$	0.450
Rate of increase of $K_0$ with depth	0.000
Active ( $\delta = 25.00 \tan\delta/\tan\phi = 0.500$ ) $K_a$	0.361
$K_{ac}$	1.370
Passive ( $\delta = 25.00 \tan\delta/\tan\phi = 0.333$ ) $K_p$	3.022
$K_{pc}$	4.336
Drained Cohesion (kN/m <sup>2</sup> )	5.000
Rate of Increase of Cohesion with depth (kN/m <sup>2</sup> per m)	0.000
Young's modulus (kN/m <sup>2</sup> )	30000
Rate of increase of Modulus with depth (kN/m <sup>2</sup> /m)	0
Poisson's Ratio	0.150

Press **F1** while editing  $K_a$ ,  $K_p$  etc... to get additional help as described in Section 6.7.1

### 6.11.3 Factor all soil moduli

You can factor the moduli of all soil types or a selected range of soil types; type **Ctrl+F** or select **Edit\Factor all soil moduli** on the main menu. All modulus values of the selected range are divided by the same factor.

### 6.11.4 Factor all soil strengths

You can factor the strengths of all soil types or a selected range of soil types; type **Ctrl+E** or select **Edit\Factor all soil strengths** on the main menu. All values of cohesion and  $\tan\phi$  of the selected range are divided by the same factor.

## 7.0 GROUND WATER CONDITIONS

### Initial ground water condition

This is the water pressure distribution on either side of the wall at the start of construction. It can be either hydrostatic or non-hydrostatic.

Initial water pressures are used in the calculation of initial vertical and horizontal effective soil stresses. For example in heavily over-consolidated clays with high  $K_o$  values it is important that the  $K_o$  values are appropriate to the initial Water Pressure Profile.

Bulk Unit Weight of water is included in this section.

### Water Pressure Profiles

These represent water pressures due to excavation, dewatering, tidal conditions etc.. at various stages of construction.

At any stage in the construction sequence you can change the water pressures on the wall by implementing one of the Water Pressure Profiles defined in this section.

### Submerged ground

Submerged ground is modelled by simply defining a water level above ground level.

## 7.1 INITIAL GROUND WATER CONDITIONS

Initial Ground Water Conditions	
Bulk unit weight of water (kN/m <sup>3</sup> )	10.00
Initial Ground Water Conditions	Hydrostatic
Initial Water Table Elevation - Active side	10.00
Initial Water Table Elevation - Passive side	10.00
Automatic water pressure balancing at toe of wall?	No

### Bulk unit weight of water

The units of bulk unit weight of water must be the same as those used for bulk unit weight of soil (see Section 6.2).

### Initial Ground Water Levels

The program requires the initial elevation of the water table on either side of the wall. Submerged ground is modelled by simply defining a water table above ground level. By default the program assumes hydrostatic pressure distributions on either side of the wall.

### Non-hydrostatic initial conditions

If the initial ground water conditions are not hydrostatic, the initial water pressures should be entered in a Water Pressure Profile (profile No.1 say). Select **Non-hydrostatic** at the initial conditions menu and give the number of the Water Pressure Profile:-

Initial Ground Water Conditions	
Bulk unit weight of water (kN/m <sup>3</sup> )	10.00
Initial Ground Water Conditions	Non-Hydrostatic
Initial Water Pressure Profile Number	1
Automatic water pressure balancing at toe of wall?	Yes

### Initial $K_0$ stresses

Initial water pressures are used in conjunction with  $K_0$  values to calculate initial stresses in effective stress terms.

### Automatic Water Pressure Balancing at toe of wall

This offers a convenient way of balancing water pressures in permeable at the toe of the wall by assuming a linear variation of piezometric head between the water levels either side of the wall.

Without the Automatic Balancing option, the water pressures on either side of the wall are determined hydrostatically by the GWL (or last piezometric point) on each side of the wall separately i.e. the dashed lines in Figure 4.

With the Automatic Balancing option the piezometric head at the toe is determined by linear interpolation between the GWL's (or last piezometric points) on either side of the wall i.e. the dotted lines in Figure 4. Selecting this option has the advantage that the water pressure distribution is adjusted automatically for changes in toe level of the wall.

## 7.2 WATER PRESSURE PROFILES

Changes of water pressure during construction are modelled by defining new water pressure profiles on either side of the wall.

In the case of a simple hydrostatic distribution a single data point is specified whose elevation is the water table e.g. Profile 2, passive side:-

Water pressure profiles								
Water Press. Profile no.	Active side				Passive side			
	Point no.	Elevation m	Piezometric elevation m	Water pressure. kN/m <sup>2</sup>	Point no.	Elevation m	Piezometric elevation m	Water pressure. kN/m <sup>2</sup>
1	1	7.00	7.00	0.0	1	6.00	6.00	0.0
	2	-2.00	6.50	85.0	2	-2.00	6.50	85.0
2	1	7.00	7.00	0.0	1	1.60	1.60	0.0
	2	6.00	7.00	10.0				
	3	-2.00	4.50	65.0				

A water pressure profile does not take effect until it is implemented in one of the Construction Stages (Section 12.1.3).

A maximum of 20 water pressure profiles may be defined, representing 20 stages of dewatering. Each profile may be defined by up to 20 points either side of the wall.

### 7.2.1 Non-hydrostatic water pressure profiles

Where non-hydrostatic conditions are to be modelled the profiles may consist of up to 20 data points representing any desired distribution of water pressure on either side of the wall. The lines A-B-C-D-E and F-G-H in Figure 5 represent non-hydrostatic pressure distributions on the active and passive sides.

The first (topmost) point of each profile is the ground water level. Water pressures at subsequent points are defined in terms of the piezometric **elevation** (not pressure) at each data point on the profile, defined as:-

$$\text{Piezometric elevation} = y + u/\gamma_w$$

where y is the elevation of a point and u is the water pressure at that point.

Successive points in the profile are allowed to have the same elevation so that step changes in water pressure can be modelled e.g. points B and C in Figure 5.

The program assumes a linear distribution of water pressure between successive points on the water pressure profile.

### **Water pressures below the last profile data point**

Water pressures below the last data point, depend on the setting of the "Automatic Water Pressure Balancing" option. Without the Automatic Balancing option, the water pressures are determined hydrostatically by the last piezometric point on each side of the wall independently

With the Automatic Balancing option the piezometric head at the toe is determined by linear interpolation between the last piezometric points on either side of the wall.

### **Negative effective stresses**

If water pressure exceeds total vertical stress at any point, there would be negative vertical effective stresses. The program prints a warning during the analysis and terminates the calculation if this situation arises.

## **7.3 WATER PRESSURES UNDER FOUNDATIONS**

When modelling uplift pressures on the underside of a deep basement, it is essential to provide a suitable reaction at excavation level to balance the uplift pressure. This reaction may consist of a combination of fill (representing the basement slab) and a surcharge representing the additional building weight.

Obviously if the uplift pressure is greater than the dead weight of the basement slab, the additional reaction will be transmitted to the ground surface by tying the slab in to the walls or holding it down with tension piles. However the reaction is provided in practice, a numerical surcharge of suitable magnitude must be provided at excavation level on the passive side of the wall.

The construction sequence is important:-

1. Place fill representing the weight of the basement slab (if any).
2. Apply the surcharge representing the additional reaction of the building to balance the uplift pressures but **do not analyse at this stage** (see Section 12.1.5).
3. Implement the water pressure profile representing the uplift water pressures.

## 7.4 DATA ENTRY and EDITING

### 7.4.1 Define a new Water Pressure Profile

Water pressure profiles									
Water press. profile no.	Active side				Passive side				
	Point no.	Elevation m	Piezometric elevation m	Water pressure. kN/m <sup>2</sup>	Point no.	Elevation m	Piezometric elevation m	Water pressure. kN/m <sup>2</sup>	
1	1	7.00	7.00	0.0	1	6.00	6.00	0.0	
	2	-2.00	6.50	85.0	2	-2.00	6.50	85.0	
2	1	7.00	7.00	0.0	1	1.60	1.60	0.0	
	2	6.00	7.00	10.0	2	-2.00	4.50	65.0	
	3	-2.00	4.50	65.0					
3	Not defined								
4	Not defined								

At the Water Pressure Profile edit menu select an undefined profile and:-

- Type **Ctrl+N**, or
- Click **EditNew** on the main menu, or
- Right click and select **Insert at cursor** from the popup menu

When defining a new profile you are first requested to enter the Ground Water Levels on either side of the wall. Additional data points may then added in any order you choose.

To copy data from an existing profile use the WALLAP clipboard as described in Section 3.9.3.

### 7.4.2 Edit a Water Pressure Profile

Double click or press <Enter> to select the profile to be edited. To change existing values, select the Elevation or Piezometric elevation of any point and enter a new value:

Water pressure profiles ..... Profile No.1									
Water Press.	Active side				Passive side				
profile no.	Point no.	Elevation m	Piezometric elevation m	Water pressure. kN/m <sup>2</sup>	Point no.	Elevation m	Piezometric elevation m	Water pressure. kN/m <sup>2</sup>	
1	1	7.00	7.00	0.0	1	6.00	6.00	0.0	
	2	-2.00	6.50	85.0	2	-2.00	6.50	85.0	

The elevation of a point cannot be changed to a value beyond its upper and lower neighbours. If you do need to do this, then delete the point and insert a new one where needed.

To add a data point, move the cursor to the position in the profile where the point is to be added and:-

- Type **Ctrl+N**, or
- Click **Edit|New** on the main menu, or
- Right click and select **Insert at cursor** from the popup menu

Enter the Elevation and Piezometric elevation of the new point. The Water pressure is calculated from the Elevation and Piezometric elevation and is given for information only.

To delete a data point, move the cursor to the point to be deleted and:-

- Type **Ctrl+X**, or
- Click **Edit|Delete** on the main menu, or
- Right click and select **Delete at cursor** from the popup menu

## **8.0 WALL / SINGLE PILE PROPERTIES**

This data block defines the type of structure (wall or single pile) the toe elevation and the properties of the wall/single pile.

### **8.1 TYPE OF STRUCTURE - RETAINING WALL or SINGLE PILE**

WALLAP is applicable to both walls and single piles.

#### **Retaining Walls**

Retaining Wall Analysis includes:

- Sheet pile walls
- Diaphragm walls
- Contiguous pile walls
- Soldier (or King) pile walls

#### **Single Piles**

Single Pile Analysis is appropriate for isolated piles subjected to horizontal and moment loads at one or more elevations.

### **8.2 TOE ELEVATION**

The Toe Elevation which you enter here is used by the program when calculating the factor of safety (Case A, Sections 13.3.2, 15.1 and 15.2) and also for the Bending moment and Displacement analysis.

If you are starting a new design, you should make an initial estimate of the required toe elevation. The Factor of Safety calculation (for cantilever and single prop walls) will indicate the actual toe depth required to achieve the Factor of Safety given in the Analysis Options.

#### **8.2.1 Determination of optimum wall depth**

For cantilever walls and walls with a single level of props, the depth of a wall is usually determined by considerations of overall stability. It will therefore save time to carry out preliminary runs with the Bending moment and Displacement analysis **switched off** ("Not Required", see Section 13.4.1) in order to find the minimum wall depth required for stability.

The finite element analysis should then be used to calculate strut forces, bending moments and displacements. It may of course prove necessary to increase the depth of the wall to reduce displacements or increase fixity. It is better to overestimate the depth of the wall initially and adjust it later to ensure that the final design fulfils all safety and performance requirements.

### 8.3 MAXIMUM FINITE ELEMENT LENGTH

The program automatically selects a suitable Finite Element Length. You may override the suggested value. If you specify too small an element length there will be too many elements (80 maximum) and the program will automatically use a larger value.

The wall is divided into beam elements for the finite element analysis. The subdivision is carried out in a way such that no element is longer than the value entered here.

### 8.4 WALL SECTION PROPERTIES

You should enter the values of Young's modulus,  $E_w$ , and Moment of Inertia,  $I_w$  of the wall, from which the program calculates the bending stiffness of the wall,  $E_w I_w$ . Care must be taken to enter values in the correct units as prompted by the program. If the values entered correspond to one of the pile sections mentioned in the help file then the section name is displayed in the data listing on screen and also in the printed output.

#### Changing the wall stiffness

There is a facility for changing the wall stiffness ( $E_w I_w$ ) at any stage in the calculation (see Section 12.1.8).

Change of wall stiffness may be used to model:

- a) Change of wall stiffness with time after the end of construction i.e. creep and relaxation effects
- b) Modelling of surcharges which were in place before the wall was installed.
- c) Walls made of more than one material e.g. Concrete piles with a steel H-section embedded in the top of the pile.

#### Composite walls

The wall is initially assumed to be of constant stiffness throughout its height. To model a composite wall, enter a single value for the whole wall under "wall properties" and use the above facility to modify the EI value of parts of the wall as necessary.

## Help with section properties

Press **F1** while editing **Moment of Inertia of wall**. The Help facility offers values of  $I_w$  and moment capacity of standard steel sections:

Moments of Inertia of pile sections from the BSC Piling Handbook.					
Moments capacities based on Grade 50B steel					
Working stresses : Temporary, 215N/mm <sup>2</sup> Permanent, 170N/mm <sup>2</sup>					
Section	Combined Moment of Inertia		Section Modulus	Moment capacity	
	m <sup>4</sup> /m	cm <sup>4</sup> /m		cm <sup>3</sup> /m	Temp. Works kN.m/m
Larssen LX32	0.00072028	72028	3201	688	544
Frodingham 1BXN	0.00004919	4919	688	148	117
Frodingham 1N	0.00006048	6048	713	153	121
Frodingham 2N	0.00013513	13513	1150	247	195
Frodingham 3N	0.00023885	23885	1688	363	287
Frodingham 3NA	0.00025687	25687	1690	363	287
Frodingham 4N	0.00039831	39831	2414	519	410
Frodingham 5	0.00049262	49262	3168	681	538
Frodingham FX13	0.00019693	19693	1313	282	223

After a preliminary analysis, you can check the maximum computed moment against moment capacity in the above table and adjust the section if necessary.

## 8.5 PILE DIAMETER

For a single pile analysis you must specify the diameter of the pile.

## 9.0 STRUTS and ANCHORS

Rows of struts or anchors can be installed at any elevation. Struts, once installed, may subsequently be removed. Only one row of struts or anchors may be specified at any one elevation. The following data is required to define a row of struts or anchors:-

- Elevation at which the wall is supported
- Strut or anchor spacing d
- Cross-sectional area A
- Young's modulus E
- Free length L
- Inclination to the horizontal  $\theta$
- Pre-stressing force
- Tension option Yes or No

Struts and anchors are treated as mathematically equivalent. In the following discussion the term "strut" is used to refer to either a strut or an anchor.

Struts do not take effect until they are actually installed in one of the construction stages.

### 9.1 STRUT STIFFNESS

The program assumes that struts provide an elastic support with a spring constant per unit length of wall given by the expression:-

$$S_{st} = \frac{A.E.\cos^2\theta}{L.d}$$

#### **Allowance for the effect of waler stiffness.**

The strut/anchor model in WALLAP allows only for the stiffness of the struts/anchors without any allowance for waler flexibility. The assumption of infinite waler stiffness will produce reasonable results in most cases because of the tendency of the soil to redistribute load to the points of support (the struts or anchors). However the following approximate calculation can be used to make an estimate of the reduction in stiffness of the support system due to the flexibility of walers.

We define:

Strut stiffness,  $S_{st}$  as above

Waler stiffness,  $S_{wal} = 384 E_{wal} \cdot I_{wal} / (d^2)$

where  $E_{wal}$  = Young's modulus of waler

$I_{wal}$  = 2nd moment of area of waler

Combined stiffness of Struts and Walers =  $S_{st} / (1 + f_{red} \cdot S_{st} / S_{wal})$

From this formula you see that if the waler stiffness is infinite then the overall stiffness reduces simply to the strut stiffness. The factor  $f_{red}$  is an allowance for the redistribution of load from the walers to the strut positions. A factor of 0.5 or less is recommended.

To apply this result to your data you should calculate the bracketed quantity

$$(1 + f_{red} \cdot S_{st} / S_{wal})$$

and apply this as a correction to your strut/anchor data by dividing the area of the strut/anchor by the bracketed value.

### **Free length**

The "free length" of a strut is the distance from the wall to the point at which the strut is rigidly supported. Where the other end of a strut supports a symmetrically placed wall, the "free length" is half the length of the strut. For a continuous floor slab the strut spacing should be entered as unit length, and the area is then the thickness  $\times$  spacing.

## **9.2 PRE-STRESSED STRUTS and ANCHORS**

Specify a value of Pre-stressing force in order to model a strut or anchor which is installed with an initial stress. A positive value represents compression in struts or tension in anchors.

A preliminary analysis should always be carried out with zero pre-stress in the struts or anchors. This will give minimum possible values for strut forces and an upper estimate of displacements. If it is then decided to pre-stress the struts it will be clear to what extent the pre-stress has succeeded in reducing displacements and at what cost in terms of increased strut forces. Pre-stressing the struts is often a rather inefficient way of limiting wall displacements and simply leads to excessively high strut loads.

### 9.3 TENSION IN STRUTS

The Tension option allows the user to specify whether or not struts **can** take tension. Struts can only act in tension if they are fixed to the wall, e.g. floor slabs would normally be allowed to act in tension because they are tied into the wall. If a strut is specified as not being able to act in tension then it will go slack if the wall moves away from the strut.

This option is not applicable to anchors; for anchors select "No".

## 9.4 DATA ENTRY and EDITING

### 9.4.1 Define a new Strut or Anchor

Struts and anchors								
Strut No.	Strut Elevation	Strut spacing m	X-section area of strut sq.m	Youngs modulus kN/m <sup>2</sup>	Free length m	Strut inclination (degs)	Pre-stress per strut kN	Tension allowed?
1	10.00	3.00	0.000650	2.000E+08	10.00	0.00	0.0	Yes
2	6.50	3.00	0.001300	2.000E+08	10.00	0.00	0.0	No
3	Not defined							

At the Strut or Anchor Properties edit menu select an undefined strut profile and

- Type **Ctrl+N**, or
- Click **EditNew** on the main menu, or
- Right click and select **Insert at cursor** from the popup menu

To copy data from an existing strut or anchor use the WALLAP clipboard as described in Section 3.9.3.

### 9.4.2 Edit Strut or Anchor Properties

Select the item to be edited and enter a new value.

## 10.0 SURCHARGE LOADS APPLIED TO THE GROUND

### 10.1 DEFINITION OF SURCHARGES

Surcharges can be applied at or below ground level on the active or passive side of the wall.

Surcharges may take any value positive or negative. A positive surcharge acts downwards; a negative surcharge acts upwards.

All surcharges are defined as rectangular loaded areas; see Figure 6. Ramp surcharges can be defined i.e. Surcharge magnitude may vary linearly with distance from the wall (see Figure 7).

The following parameters define a surcharge:

- Elevation at which the surcharge acts
- Length,  $L$ , parallel to the wall
- Width,  $B$ , perpendicular to the wall
- Distance,  $A$ , of its nearer edge to the wall
- Magnitude,  $Q_1$  per unit area at edge nearest to the wall
- Magnitude,  $Q_2$  per unit area at edge farthest from the wall
- Equivalent soil type (wedge analysis only)

Because the analysis is essentially two dimensional, the program calculates the effect of a surcharge at a point on the wall closest to the mid-length of the surcharge.

Surcharges do not take effect until they are actually applied in one of the construction stages. Surcharges may be applied and subsequently removed. Multiple applications and removals of surcharges are permitted but the number of removals must not exceed the number of applications at any stage.

#### 10.1.1 Surcharge elevation

Surcharges can be applied at or below ground level on the active or passive side of the wall. An error will be reported if a surcharge is applied above ground level or if an Excavation stage undermines a surcharge (i.e. reduces ground level below the surcharge elevation).

### 10.1.2 Surcharge Distance from Wall

A surcharge is applied over a rectangular area. "Distance from the wall" is the distance from the wall to the nearer edge of the surcharge (Figure 6a). A positive value defines a surcharge on the active side, a negative value on the passive side. For surcharges which are next to the wall, enter a zero value. The program will then ask a further question:

Is surcharge no.1 at elevation 12.34, on the Active or Passive side?	
<input type="button" value="Active"/>	<input type="button" value="Passive"/>

The data listing shows (A) or (P) next to the distance to indicate which side of the wall the surcharge is on.

### 10.1.3 Surcharge Length Parallel to Wall

A surcharge is applied over a rectangular area. "Surcharge Length Parallel to the Wall" is the length perpendicular to the plane of the analysis (Figure 6b).

Because the analysis is essentially two dimensional the program calculates the effect of a distributed surcharge at a point on the wall closest to the mid-length of the surcharge.

### 10.1.4 Surcharge Width

"Surcharge Width" is the width perpendicular to the wall (Figure 6c).

Avoid specifying very narrow surcharges close to the wall i.e. width less than the element length. Widths less than 0.1 unit will cause a warning message.

### 10.1.5 Surcharge Magnitude

Surcharges							
Surcharge no.	Elev.	Distance from wall	Length parallel to wall	Width perpend. to wall	Surcharge		Equivalent soil type
					----- kN/m2 ----- Near edge	----- Far edge	
1	11.00	0.00(A)	100.00	6.00	0.00	50.00	1
2	11.00	6.00(A)	100.00	30.00	50.00	=	1
					Q <sub>1</sub>	Q <sub>2</sub>	

Surcharge Magnitude is specified in pressure units e.g. kN/m<sup>2</sup>. Surcharges may take any value positive or negative. A positive surcharge acts downwards; a negative surcharge acts upwards.

Ramp surcharges can be defined i.e. Surcharge magnitude varying linearly with distance from the wall (Figure 7). For a ramp surcharge specify two values, Q<sub>1</sub> and Q<sub>2</sub> representing the load per unit area at the near and far edges of the surcharge respectively.

### 10.1.6 Equivalent Soil Type

This is an optional parameter for surcharges (at ground level) which represent soil masses. This parameter is only meaningful if you select the option to calculate limiting active or passive soil pressures by the Wedge Stability method (Section 13.3.6). Surcharges which represent structural loads should be give the Equivalent Soil Type = 0

The Equivalent Soil Type associates the surcharge with the appropriate soil properties (density, cohesion, friction) so that the wedge analysis takes full account of the properties of the sloping ground.

For buried surcharges this option has no effect. If the Wedge Stability option is not selected then this option is not applicable and is marked "N/A".

## 10.2 DATA ENTRY and EDITING

### 10.2.1 Define a new Surcharge

Surcharges							
Surcharge No.	Elev.	Distance from Wall	Length parallel to wall	Width perpend. to wall	Surcharge ----- kN/m2 -----		Equivalent soil type
					Near edge	Far edge	
1	11.00	0.00(A)	135.00	50.00	20.00	40.00	1
2	9.50	1.00(A)	10.00	2.00	50.00	=	0
3	Not defined						
4	Not defined						
5	Not defined						

At the Surcharge edit menu select an undefined Surcharge and

- Type **Ctrl+N**, or
- Click **EditNew** on the main menu, or
- Right click and select **Insert at cursor** from the popup menu

To copy data from an existing surcharge use the WALLAP clipboard as described in Section 3.9.3.

### 10.2.2 Edit Surcharges

Move to the item to be edited and enter a new value.

## **11.0 HORIZONTAL AND MOMENT LOADS / RESTRAINTS APPLIED TO THE WALL**

### **11.1 DEFINITION OF LOADS / RESTRAINTS**

Loads and Rotational Restraints can be applied to the wall at any elevation. A Load may be any combination of horizontal and moment loads. A Rotational Restraint may be applied on its own or in conjunction with loads.

The following parameters define a Load/Restraint:

- Elevation at which the Load/Restraint acts
- Horizontal Load component per unit length of wall
- Moment Load component per unit length of wall
- Rotational restraint per unit length of wall

Loads / Restraints do not take effect until they are actually applied in one of the construction stages. Multiple applications of Loads are permitted.

More than one Load can be applied at the same elevation. A Load or Rotational Restraint can be applied at the same elevation as a strut.

Only **one** value of Rotational Restraint can be applied at each elevation. A Rotational Restraint cannot be removed once it has been applied.

#### **11.1.1 Load/Restraint elevation**

Loads/Restraints can be applied to the wall at any elevation above or below ground level. An error will be reported if a Load/Restraint is applied below the toe of the wall.

#### **11.1.2 Horizontal load**

A horizontal load is defined by its magnitude,  $P$  per unit length of wall. The sign convention for applied loads is shown in Figure 8. i.e. a positive load acts from the active side towards the passive side.

Horizontal loads may be used to model the effects of structural loads not accounted for by the strut, soil or water pressures defined elsewhere in the data.

### 11.1.3 Moment load

A moment load is defined by its magnitude,  $M$  per unit length of wall. The sign convention for applied moments is shown in Figure 8. i.e. with the active side on the left a clockwise moment is positive.

Moment loads may be used to model the effects of structural loads transmitted to the top of the wall or through floor slabs.

### 11.1.4 Rotational restraint

A Rotational restraint (moment spring) is defined by its rotational stiffness  $K_m$ . The magnitude of the restraint must (of course) be positive and its units are typically:-

kN.m per m run per radian	for a wall
kN.m per radian	for a single pile

This facility may be used to model the effect of floor slabs which are built into the wall. To model complete rotational fixity, enter a very large value e.g.  $10^{30}$  units. A restraint cannot be removed once it has been applied.

### 11.1.5 Moment load applied in combination with a rotational restraint

A special rule is imposed by the program when applying a moment load at a node where a rotational restraint is already acting. The effect of the rotational restraint is suspended during the stage in which the moment is applied but operates again as usual in subsequent stages.

The logic of this rule is as follows:

1. When a moment load is applied at the same elevation as an existing rotational restraint it is assumed that the moment load is applied via the structural member which exerts the rotational restraint. A typical construction sequence would be as follows:

Construction activity	WALLAP stage
Construction of a slab at elevation $y_1$ which provides rotational restraint.	Application of rotational restraint at elevation $y_1$ .
Excavation below the slab.	Excavation with resulting bending moment induced in the wall at $y_1$ due to the restraint of the slab.
Imposition of a vertical load on the slab which causes a bending moment at its connection with the wall.	Application of bending moment at $y_1$ .

2. Since the applied bending moment originates in the slab, the rotational fixity at the connection between slab and wall is not to be taken into account in *this* stage. If it were, most of the applied bending moment would end up in the slab and not the wall and this would be quite inappropriate.

## 11.2 DATA ENTRY and EDITING

### 11.2.1 Define a new Load/Restraint

Applied loads and moment restraints				
Load no.	Elevation	Horizontal load kN/m run	Moment load kN.m/m run	Moment restraint kN.m/m/rad
1	12.00	30.0	0.0	0
2	2.00	0.0	20.0	0
3	7.50	0.0	0.0	1.750E+10
4	Not defined			

At the Load/Restraint edit menu select an undefined Load/Restraint and

- Type **Ctrl+N**, or
- Click **EditNew** on the main menu, or
- Right click and select **Insert at cursor** from the popup menu

To copy data from an existing load/restraint, use the WALLAP clipboard as described in Section 3.9.3.

### 11.2.2 Edit Loads/Restraints

Move to the item to be edited and enter a new value.

## **12.0 CONSTRUCTION STAGES**

### **12.1 DEFINITION OF CONSTRUCTION STAGES**

WALLAP models the stage by stage construction of a wall. Calculations are carried out at each stage (unless otherwise requested). Bending moments and displacements are accumulated from stage to stage.

The following types of construction activities may be specified and combined in any order so as to model the actual construction of the wall:-

- Excavation.
- Filling.
- Change water pressures.
- Installation / removal of struts or anchors.
- Application / removal of surcharges to the ground.
- Application of loads or rotational restraints to the wall.
- Change soil properties.
- Change wall stiffness.
- Seismic loading

A maximum of 80 stages may be defined.

The program normally carries out a full analysis (recalculation of bending moments and displacements) at each stage (regardless of whether output has been requested) in order to ensure that the final result reflects the exact construction sequence. In certain cases two or more activities can be combined by omitting the calculation of bending moments and displacements at a particular stage e.g.

- simultaneous excavation and dewatering
- simultaneous application of several surcharges
- simultaneous change of several soil types

Your attention is drawn to these possibilities in the following sections.

#### **12.1.1 Excavation and Berm formation**

Excavation can be carried out on either the active or the passive side of the wall. An excavation stage is defined by the elevation to which the ground is to be excavated.

## **Berms**

Berms are formed in a special type of Excavation Stage. Optional additional parameters define the dimensions of the berm as shown in Figure 11.

Berms may be created on the active and/or passive sides. Passive pressure limits are automatically adjusted to take account of the reduced passive resistance of the berm compared with a level excavation.

Once formed, a berm is removed either by filling or excavation. A subsequent Fill stage immediately removes the berm i.e. it is assumed that the berm is filled in.

A subsequent Excavation stage will either partially or totally remove the berm depending on the new excavation level.

See Data File DEMO6 for a worked example.

### **12.1.2 Filling**

Fill can be placed on either the active or the passive side of the wall. A filling stage is defined by the elevation to which the ground is to be filled and the soil type to be used as fill.

### **12.1.3 Change water pressures**

Any of the previously defined water pressure profiles (Section 7.2) can be implemented. A Water Pressure stage is defined by the number of the Water Pressure Profile to be implemented.

It can happen that the change of water pressure occurs simultaneously with another activity such as excavation. In such a case the analysis should be postponed until the second activity is complete. The program offers this possibility by displaying the request:-

Analyse at this stage?

For most situations you should answer Y (yes). You should answer N (no) if the water pressure change will occur as a result of excavation rather than as a separate physical activity. The construction sequence is as follows:-

1. Implement the water pressure profile representing dewatering but **do not analyse at this stage.**
2. Excavate

#### **12.1.4 Installation / removal of struts or anchors**

Any of the previously defined rows of struts or anchors (Section 9.0) can be installed or removed. A strut or anchor installation stage is defined by the number of the row of struts or anchors to be installed. The previously defined struts or anchors do not take effect until they are installed as part of the construction sequence.

#### **12.1.5 Application / removal of surcharges**

Any of the previously defined surcharges (Section 10.0) can be applied or removed. A surcharge application stage is defined by the number of the surcharge to be applied. The previously defined surcharges do not take effect until they are applied as part of the construction sequence.

Multiple applications and removals of a surcharge are permitted, but the number of removals may not exceed the number of applications.

It can happen that several surcharges are applied/removed simultaneously or form part of a more complex activity e.g. uplift pressure under a foundation. In such a case the analysis should be postponed until the final activity is complete. The program offers this possibility by displaying the request:

Analyse at this stage?

Answer "Yes" except in the special cases described above.

#### **12.1.6 Application of horizontal and moment loads or rotational restraints to the wall**

Any of the previously defined horizontal or moment loads (Section 11.0) can be applied to the wall. A load application stage is defined by the number of the load to be applied. The previously defined loads do not take effect until they are applied as part of the construction sequence.

Multiple applications of a Load are permitted.

Rotational Restraints may only be applied **once** at each elevation and cannot be removed. The value of a rotational restraint should not be changed once it has been applied.

### 12.1.7 Change soil properties

The properties of a stratum (or strata) can be changed by allocating a new soil type to replace the original soil type. All strata of the original soil type will be changed simultaneously.

The program displays the menu:-

Construction Stage 2	
Construction stage type	Change soil properties
Change strata of Soil Type	2
to Soil Type	3
Analyse at this stage?	Yes
Ko pressures in new Soil Type to be reset?	Yes

This type of construction stage can be used to model various situations.

- a) Softening of ground following excavation; change the passive earth pressure coefficients (and soil stiffness on the passive side); do not reset Ko pressures.
- b) Change from Undrained to Drained conditions; do not reset Ko pressures.
- c) Build up of Ko pressures back to their original value in heavily over-consolidated clay over many years after the end of construction; change soil type A to soil type A(!) and reset Ko pressures.

The Ko pressures should not normally be reset except for case(c) above.

### 12.1.8 Change wall stiffness

Change of wall stiffness may be used to model:

- a) Change of wall stiffness with time after the end of construction i.e. creep and relaxation effects
- b) Modelling of surcharges which were in place before the wall was installed.
- c) Walls made of more than one material e.g. Concrete piles with a steel H-section embedded in the top of the pile.
- d) Excavation below the toe of the wall.

The parameters defined for this stage are:

1. The new EI value of the wall
2. Does the new EI value apply to
  - a) the whole wall?    or    b) part of the wall?

3. The upper and lower limits of the section of the wall to which the new EI value applies (if option 2b was selected).
4. What adjustments are to be made to wall displacements as a result of applying the new EI value?
  - a) Allow the wall to relax with new modulus values.  
Choose this option to model Change of wall stiffness with time.
  - b) Reset displacements to zero at this stage.  
Choose this option to model surcharges which were in place before the wall was installed.
  - c) No adjustments to wall displacements.  
Choose this option to model Walls made of more than one material.

### **12.1.8a Change of wall stiffness with time**

CIRIA Publication C580 recommends that the flexural stiffness of reinforced concrete walls should be calculated using the appropriate Young's Modulus at each stage. Suggested values are:

0.7 x short term uncracked modulus during construction

0.5 x short term uncracked modulus for long term behaviour.

Short term uncracked modulus is typically 28 MPa

To comply with this recommendation you should set the Young's modulus initially to 19.6MPa and define a Change of wall stiffness stage at the end of construction in which EI is redefined based on Young's modulus is 14MPa. The I value is unchanged.

The stiffness change should be applied to the whole wall (unless part of it was already defined as being of a different material) and the Wall displacement option should be selected as *Allow wall to relax with new modulus values*.

### **12.1.8b Modelling of surcharges which were in place before the wall was installed.**

1. Specify the actual wall stiffness in the Wall Properties (see Section 8.3).
2. Define Construction Stage 1 as:-  
Change wall stiffness (EI) to a small value e.g.  $10^{-5}$  kN.m<sup>2</sup>/mrun (or whatever units you are working in).
3. Define Construction Stage 2, 3 etc as surcharge stages to model pre-construction surcharges.

#### 4. Define Construction Stage 4 as:-

Change wall stiffness (EI) back to its value given in the Wall Properties - the program will prompt you with the value previously entered.

Select "Reset displacements to zero" at this stage.

The surcharges imposed in stages 2, 3 etc.. will cause some displacements but negligible moments in the wall because the wall had negligible stiffness. If "Reset displacements to zero" is selected, as suggested above, the initial displacements up to this stage will be ignored and the final result will represent the nett displacements due to subsequent excavation etc...

#### **12.1.8c Walls made of more than one material**

If your wall is composed of more than one material you model it as follows:

- 1) Under Wall properties enter the E and I values of the major part of the wall.
- 2) At stage 1 define a Change wall stiffness stage for that part of the wall which has different properties.
- 3) The Wall displacement option should be selected as *No adjustments to wall displacements.*

In the results for each stage the table of shear forces and bending moments contains an extra column showing the EI value at each elevation

#### **12.1.8d Excavation below the toe of the wall**

It is not normally permitted to excavate below the toe of the wall. However you can overcome this restriction by specifying a toe level deeper than the true toe elevation and then changing the EI value of that extra bit of wall to a negligible value. The toe level used for calculating factors of safety will be adjusted automatically by the program to reflect the real behaviour of the wall. The adjusted value is shown in the printed output with a note of explanation.

### **12.1.9 Seismic loading**

Use this construction stage to model earthquake accelerations, vertical and/or horizontal. Data files DEMO8.DAT and DEMO9.DAT illustrate the use of the seismic loading facility.

The Wedge Stability option (Section 13.3.6) must be selected for both active and passive pressures when modelling earthquake accelerations.

#### **Parameters associated with a seismic loading stage**

##### **1. Horizontal earthquake factor**

This is the Horizontal ground acceleration expressed as a proportion of 'g', the acceleration due to gravity. It is dimensionless. A positive value of Horizontal acceleration increases active limit pressures and decreases passive limit pressures. Values in the range 0.02 to 0.15 are typical.

The values entered in the data must take account of the following factors:

- Regional seismicity
- Return period of the design earthquake
- Local soil conditions
- Category of structure
- Serviceability and Ultimate limit state criteria

##### **2. Vertical earthquake factor**

This is the Vertical ground acceleration expressed as a proportion of 'g', the acceleration due to gravity. It is dimensionless.

A positive value of Vertical acceleration increases both active and passive limit pressures. Values in the range 0.02 to 0.15 are typical.

##### **3. Line of action of quasi-static seismic component of limiting active earth pressure**

The line of action of the additional active seismic force due to the retained soil may act higher than the 1/3 point usually associated with static Coulomb pressures. This parameter allows you specify the elevation of the line of action as a proportion of the retained height. A maximum value of 0.66 is possible but values of 0.60 are typical in practice.

#### 4. Seismic loading model

Two alternative models are available:

##### Quasi-static loading

Active and passive limit pressures are modified according to the specified acceleration. This model is suitable for flexible cantilever walls where it is possible to mobilise the fully active condition. The values of limiting earth pressure are calculated using the Wedge Stability option and not by a modified Coulomb formula.

##### Quasi-static and Pseudo-dynamic loading

In addition to the adjustment of active and passive limit pressures, Seismic loads are applied directly to the wall. This pseudo-dynamic loading is important when modelling medium and stiff walls and walls with stiff props.

#### 5. Dynamic thrust factor

The pseudo-dynamic thrust due to the retained soil is calculated as

$$\gamma H^2 \cdot a_h \cdot F_p \quad \text{where } F_p \text{ is the Dynamic thrust factor}$$

A value of about 1.0 is typical.

#### 6. Line of action of pseudo-dynamic thrust

The line of action of the pseudo-dynamic thrust may act higher than the 1/3 point usually associated with static Coulomb pressures. This parameter allows you specify the elevation of the line of action as a proportion of the retained height. A maximum value of 0.66 is possible but a value of 0.55 is typical in practice.

This information is taken from Geotechnical Earthquake Engineering by Steven L.Kramer (1996) who quotes the work of J.Wood (1973). For more details of this work please refer to the WALLAP Help system.

#### Water pressure

The above parameters relate to dry or impermeable soil where any water present does not move relative to the soil. For additional advice on the modelling of dynamic pore pressures and the dynamic effects of free water please refer to the WALLAP Help system.

### **Cyclic loading**

WALLAP may be used to examine the effects of cyclic loading. You can specify successive seismic loading stages with positive and negative horizontal accelerations. In most cases there will be little further movement or increase in wall pressure after 2 cycles of loading.

### **The effect of seismic loading in subsequent construction stages.**

Unlike other forces (surcharges etc..) applied in the construction sequence, earthquake accelerations do not persist in the subsequent construction stages. However, wall pressures generated during a seismic loading stage will not necessarily return to their pre-quake values. A certain amount of strut force may also get "locked in".

#### **12.1.10 "Analyse at this stage?" option**

Each construction stage is normally regarded as a discrete activity which is completed before the next stage begins. Therefore the program re-establishes equilibrium after each stage. Certain activities such as Water pressure change, Surcharge application and Soil type changes may form part of a group of events or activities which are to be regarded as occurring simultaneously.

The "Analyse at this stage?" option permits the suppression of analysis at certain stages until the group of events is complete. The use of this option is described under the particular construction stages.

There are certain points in the construction sequence where this option is inappropriate, namely:-

- The first and last stages - these are always analysed.
- The stage before the installation of an unstressed strut (unless this stage is itself the installation of an unstressed strut) - this is always analysed.

## 12.2 DATA ENTRY and EDITING

### 12.2.1 Define a new Construction Stage

Construction Stages	
Construction stage no.	Stage description
1	Apply surcharge no.1 at elevation 11.00
2	Apply surcharge no.2 at elevation 9.50
3	Install strut or anchor no.1 at elevation 10.00
4	Apply water pressure profile no.1
5	Excavate to elevation 6.00 on PASSIVE side

At the Construction Stage edit menu move the cursor to the position of the new Construction Stage and

Type **Ctrl+N**, or

Click **Edit|New** on the main menu, or

Right Click and select **Insert at cursor** from the popup menu

You are requested to confirm the position of the new stage in the construction sequence:

Insert before Stage No.n ?

Now select the type of construction stage from the dropdown menu:-

- Fill on Active side of wall
- Excavate on Active side of wall
- Fill on Passive side of wall
- Excavate on Passive side of wall
- Change the Water Pressures
- Install or remove a Strut
- Apply or remove a Surcharge
- Apply a Load / Restraint to the wall
- Change Soil Properties
- Change Wall Stiffness
- Seismic loading

The information required for each type of stage is different:

Stage type	Information required
Excavation	Excavation level Berm dimensions (optional)
Filling	Fill level Soil type of fill material
Change water pressures	Water pressure profile number Analyse at this stage (Yes or No)
Struts	Strut number Install or Remove
Surcharges	Surcharge number Apply or remove Analyse at this stage (Yes or No)
Loads / Restraints	Load/Restraint number
Change soil properties	Old and New soil types $K_0$ pressures to be reset (Yes or No) Analyse at this stage (Yes or No)
Change wall stiffness	New wall stiffness, EI Whole or part of the wall to be changed? Elevations of the changed part Action on displacements
Seismic loading	Horizontal and vertical accelerations Line of action of seismic force Seismic model (quasi-static / pseudo-dynamic) Pseudo-dynamic load parameters (optional)

To copy data from an existing construction stage, use the WALLAP clipboard as described in Section 3.9.3.

### 12.2.2 Edit Construction Stages

Double click or press **Enter** to select the stage to be edited. The Construction Stage edit menu varies according to the type of stage. A typical menu is:

Construction Stage 2	
Construction stage type	Apply or remove a Surcharge
Surcharge No	2
Surcharge to be Applied or Removed	Applied
Analyse at this stage?	Yes

Select an item and enter a new value.

## 13.0 FACTORS OF SAFETY and ANALYSIS OPTIONS

### 13.1 TYPE OF STRUCTURE - RETAINING WALL or SINGLE PILE

WALLAP is applicable to both walls and single piles. See Section 8.1 for details.

### 13.2 TYPES OF ANALYSIS - FOS and BENDING MOMENT ANALYSIS

WALLAP carries out two quite separate types of analysis within the one program:-

- **Factor of Safety** calculation for determining overall stability of a wall with one prop or no prop (cantilever). There is a choice of methods of calculation. The FoS calculation is a Limit Equilibrium Analysis
- **Bending Moment, Displacement and Strut Force** calculation. This is an elastic-plastic analysis using Subgrade Reaction or Finite Element methods to examine soil-structure interaction.

### 13.3 STABILITY ANALYSIS

The stability analysis considers potential failure mechanisms.

For a cantilever wall the potential mechanism is forward rotation of the top of the wall. For walls with a single strut or anchor the potential mechanism is forward rotation of the toe of the wall about the prop.

The result of a stability analysis is a "factor of safety"; this is the factor by which disturbing forces exceed restoring forces. The stability analysis considers only the limiting values of wall pressures i.e. active and passive limits.

#### **Toe Elevation and Factor of Safety**

The main purpose of the Factor of Safety calculation is to establish that the Toe Elevation is sufficiently deep to achieve an adequate factor of safety. To assist you in the design process, the program does two calculations

- a) Calculation of Factor of Safety for the given Toe Elevation (as specified in the Wall Properties)
- b) Calculation of required Toe Elevation for a given Factor of Safety,  $F_p$  (as specified in Section 13.3.2).

## **Limitations**

The stability analysis is not carried out when the tendency to failure is from "right" to "left". If you want to calculate the Factor of Safety under these conditions you would have to reverse the data (see Section 13.3.7). The bending moment and displacement analysis is not affected unless you have struts which go slack.

There is no stability analysis at stages where there is more than one prop. There is no simple method of calculating Factors of Safety for multi-propped walls without making arbitrary assumptions about the distribution of prop forces. The Bending Moment and Displacement analysis provides all necessary results for multi-propped walls.

Initial stresses and elastic parameters (i.e.  $K_o$  pressures, soil modulus, Poisson's ratio, strut stiffness and strut pre-stress) do not enter into the factor of safety calculation.

The stability analysis takes no account of the construction sequence i.e. dewatering followed by excavation will give the same final Factor of Safety as excavation followed by dewatering. Only the current condition is analysed.

### **13.3.1 Factor of Safety - Method of Calculation**

There is a choice of methods for calculating the Factor of Safety:-

- Civil Engineering Code of Practice No.2 (1951)
- BSC Piling Handbook
- Burland-Potts method
- Strength Factor method

Method (c) is described by Burland et al. (1981) and also in CIRIA Report No.104 (1984).

Method (d) is the method prescribed by CIRIA Publication C580 and Eurocode7 and is the most rational and consistent method available.

All the methods are based on an assumed failure mechanism in which the wall rotates, causing the fully active condition to be mobilised on the active side of the wall and the fully passive condition on the passive side.

In methods (a) (b) and (c) the "Factor of Safety" is the factor by which the "Nett Available" passive pressures must be reduced in order to bring about this failure mechanism. The definition of "Nett Available" passive pressures is different for each method.

In method (d) the "Factor of Safety" is the factor by which the soil strengths ( $c$  and  $\tan\phi$ ) must be reduced in order to bring about failure.

The resulting pressure distributions are hypothetical and it is for this reason that these methods are only to be used for calculating Factors of Safety and not for bending moments or displacements.

The methods are compared and discussed briefly in BS8002(1994) Annex B.

### **CP2 method of calculating Factor of Safety**

Details of the calculation and recommended factors of safety for design to be used with this method are given in:

Civil Engineering Code of Practice No.2 (1951)  
Earth Retaining Structures.  
Institution of Structural Engineers.

### **BSC Piling Handbook method of calculating Factor of Safety**

Details of the calculation and recommended factors of safety for design to be used with this method are given in:

BSC Piling Handbook. 4th edition.  
British Steel Corporation (1984)

### **Burland-Potts method of calculating Factor of Safety**

Details of the calculation and recommended factors of safety for design to be used with this method are given in:

Burland, J.B., D.M.Potts and N.M.Walsh (1981)  
The overall stability of free and propped embedded  
cantilever retaining walls. Ground Engineering, July 1981

### **Strength Factor method for calculating Factor of Safety**

This method differs from all the above methods in that it does not rely on arbitrary definitions of nett active and nett passive pressures. The FoS is defined directly in terms of soil strength i.e. the factor by which all values of cohesion and  $\tan\phi$  must be reduced to bring about a state of limiting equilibrium (failure).

The Strength Factor method gives consistent results for all types of soil strata including soft clays.

### **Wall friction and adhesion**

When using the Strength Factor method make sure that the Soil Friction angle and the Wall Friction (Adhesion) factor are consistent with the values of  $K_a$ ,  $K_{ac}$ ,  $K_p$ ,  $K_{pc}$  for each soil type.

Press **F1** when editing  $K_a$  (or  $K_p$ ) to use the online help facility for deriving earth pressure coefficients in terms of Soil Friction angle and Wall Friction (Adhesion) factor for each soil type.

Recommended factors of safety for design to be used with this method are given in CIRIA Publication C580 and Eurocode 7.

### **13.3.2 Factor of Safety for calculating Toe Elevation**

The program assesses stability from two points of view:

- a) Calculate a Factor of Safety for the given Toe Elevation.
- b) Calculate the Toe Elevation for a required Factor of Safety,  $F_p$ , specified by the user.

For calculation (b) you should specify a value of  $F_p$  which is appropriate to the circumstances (SLS or ULS) and method of calculation as recommended in relevant codes of practice.

From the results of calculation (b) you can obtain the Toe Elevation which will provide the required minimum Factor of Safety at all stages of construction.

### **13.3.3 Factor of Safety for calculation of tie force**

For single propped walls the program does an additional calculation:

Calculate the Prop Force for a given Factor of Safety,  $F_t$ , specified by the user (usually 1)

A Factor of Safety,  $F_t = 1$ , for calculating the prop force is suggested (in accordance with standard practice) because this usually gives a higher prop force than using  $F_p$ .

The prop force given by this analysis will not necessarily agree with that obtained from the Bending Moment and Displacement calculation. Good agreement may be obtained when wall displacements are sufficient to mobilise the fully active condition. The Bending Moment

and Displacement calculation will produce a higher prop force in the case of a stiff wall with a rigid support. This higher value should be used for design.

#### 13.3.4 Minimum Equivalent Fluid Density

When the theoretical active earth pressure in **undrained** cohesive soil is small or negative, the program will impose a minimum earth pressure calculated from the minimum equivalent fluid density.

This option allows designs to be carried out in accordance with codes of practice (e.g. CIRIA Publication C580, Section 5.5.1) which require retaining walls to be designed for a minimum equivalent fluid density of  $5\text{kN/m}^3$  in undrained conditions.

The specified minimum equivalent fluid density is applied by the program to all undrained strata. If a zero value is given no minimum pressure will be assumed.

The printed results are annotated to show which values of active limit pressure have been determined by the minimum equivalent fluid density rule.

#### 13.3.5 Maximum Depth of Water-filled Tension Crack

In some design codes it is assumed that where the theoretical active pressure in **undrained** cohesive soil is less than zero, that the wall will be subjected to full water pressure down to a depth of  $2c_u/\gamma'$ . In practice this may be a rather severe assumption where the theoretical depth of tension crack is very great.

The program allows a flexible approach in permitting the user to specify the maximum depth,  $Z_t$ , below (current) ground level to which full water pressure will be taken. The actual depth to which tension cracks develop in practice is rarely greater than 3m or 4m. The action of struts at lower levels limits the possible movement of the wall away from the soil.

A large value of  $Z_t$  will ensure that full water pressure is taken to the full depth of any **theoretical** tension crack (but this may be excessively conservative). A zero value of  $Z_t$  will result in zero water pressure in tension cracks, which may be excessively optimistic.

The water pressure in a tension crack is calculated with respect to a water table which is the higher of

- a) the specified ground water level,
- or b) the top of the undrained stratum.

This rule is based on the reasonable assumption that the water table defined in a drained stratum overlying an undrained stratum is the highest water level which will occur i.e. it is not automatically assumed that the water table is at ground level. It is up to the user to specify an appropriate water level in any such overlying drained strata.

The specified maximum depth of water filled tension crack is applied by the program to all undrained strata.

### **13.3.6 Calculate active and passive limit pressures by Wedge Stability**

This option causes the program to calculate Active (and/or Passive) Limit Pressures in a more rigorous way than the conventional use of earth pressure coefficients,  $K_a$  and  $K_{ac}$ . (or  $K_p$ ,  $K_{pc}$ ). This option is appropriate for certain cases where the usual assumptions of earth pressure theory are not strictly applicable, such as:

- Sloping backfill with cohesion (for which the usual earth pressure coefficients are not applicable)
- A berm or uneven ground on the active (or passive) side
- Intense surcharges over a limited width
- Ramp surcharges
- Weak soil layers at depth
- Non hydrostatic water pressures
- Seismic loading (earthquakes)

The following points should be noted:

#### **Berms**

The existing berm excavation option is perfectly adequate for simple berms on the passive side. The new facility becomes relevant when there are additional passive surcharges or other complicating factors.

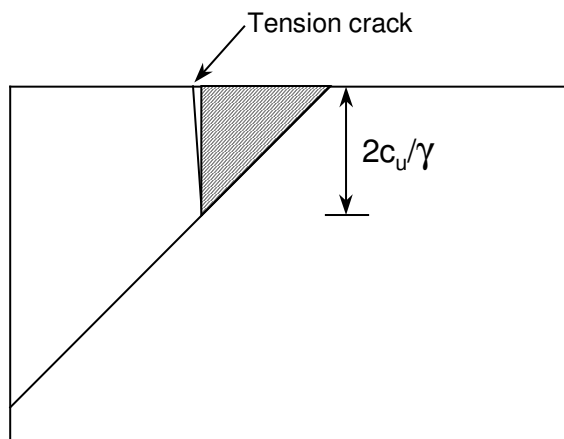
#### **Soil strength parameters**

The wedge stability analysis makes use of the phi and wall friction parameters defined for each soil type. The values of phi and delta defined in the data (see help screens for  $K_a$  etc...) must be appropriate and "compatible" with the earth pressure coefficients.

The limiting earth pressures calculated by wedge stability include the effects of wall friction (if defined). However please note that the effects of **wall friction** on **passive pressures** is somewhat underestimated and leads to slightly conservative results. Unless there are special circumstances (unusual surcharges or sloping ground) on the **passive side** you are advised to use the wedge stability option mainly for active pressures. This will also save time as the calculation of passive pressures by wedge stability takes longer than active pressures.

### Tension cracks

The wedge analysis of cohesive soils ignores any part of the wedge (shaded area below) which lies up hill of a potential tension crack (as estimated from the cohesion of the soil).



Nevertheless the results of wedge analyses cannot be expected to give identical results to the traditional methods of calculating earth pressures for cohesive soils. Limited tests done so far indicate that wedge analyses give slightly (but not significantly) lower earth pressures which can be used with confidence.

### Sloping ground

Do not introduce values of  $\beta$  (backfill angle) into the calculation of  $K_a$  or  $K_p$  for sloping ground. Sloping ground is modelled by the use of surcharges or berms. All  $\beta$  angles must be zero.

### Surcharges

Surcharges (at ground level) which represent soil masses have an additional parameter - the Equivalent Soil Type (see Section 10.1.6) - which associates the surcharge with the appropriate soil properties (density, cohesion, friction) so that the wedge analysis takes full account of the properties of the sloping ground. Surcharges which represent structural loads should be given the Equivalent Soil Type = 0

The Wedge Stability Analysis is strictly 2-dimensional and takes no account of the length of the surcharge (parallel the wall). The effect of very short surcharges may be over-estimated. A warning message is issued if the error is likely to be significant.

### Factor of Safety calculations

All the usual methods of calculating Factors of Safety can be used in conjunction with this Wedge Stability option but please note that the Strength Factor method will take significantly longer because of the repeated calculation of limiting earth pressures each time the strengths are factored by a different value.

### Efficiency of the Wedge Analysis

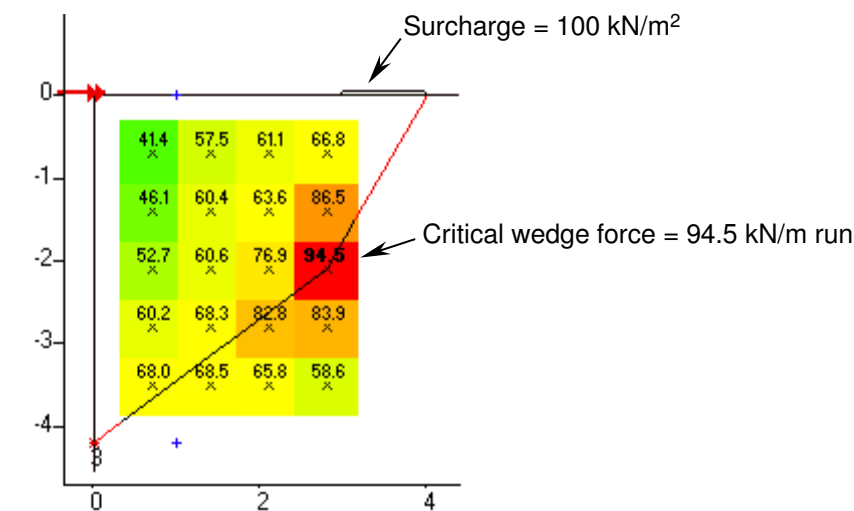
Certain data choices will significantly increase the time taken for the wedge analysis. They are :

- Use of the Strength Factor method for FoS calculations,
- Wall friction
- Passive limits by wedge analysis.

### Checking

You are advised to carry out some parallel calculations, with and without the wedge stability option as a check on the wedge analysis. Dramatic differences between results should be regarded with suspicion.

The wedge analysis is carried internally within Wallap using a module of the Geosolve Slope program. Here follows a typical result for one wedge, showing how the presence of an intense surcharge results in a critical active wedge which is not the simple wedge assumed by Coulomb. A tabulated summary of the wedge calculations is given in the "Messages" panel on the Results page. You do not normally have access to the temporary slope stability analysis files generated by WALLAP.



### 13.3.7 Reverse the data for walls tending to move from right to left

WALLAP only calculates factors of safety for conditions where the active side is on the left and the passive side on the right. Where the direction of movement of the wall alternates during construction you will have to do separate analyses to obtain factors of safety for all stages.

When the wall is tending to move from right to left, the program may print the message:-

Conditions not suitable for factor of safety calculation  
or Wall tending to move from right to left

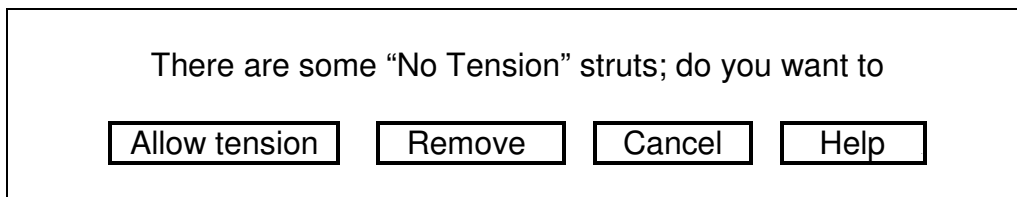
You will also see the message

Note: To obtain a Factor of Safety for the case of wall failing from right to left you should reverse the data (Ctrl+K) and re-analyse.

You should save your current data before making the reversal. Then from the Main menu select Edit | Reverse Coordinates or type **Ctrl+K**. The data set will be renamed, adding "**\_Rev**" to the filename. Full symmetrical reversal of the data can only be made if either

- a) there are no struts
- or
- b) all struts are defined as able to take tension.

If this is not the case you will be prompted with the question



The options are explained as follows:

**Allow tension** All "No Tension" struts are converted to struts which can take tension.

**Remove** All stages in which a "No Tension" strut is installed or removed are modified to a neutral activity (changing soil type 1 to soil type 1). The strut definitions are left unchanged but the struts do not get installed. There will be warnings that certain struts are defined but not used.

**Cancel** The Data Reversal is abandoned.

**Help** Displays this help screen

### **13.4 BENDING MOMENT and DISPLACEMENT CALCULATION**

The bending moment and displacement analysis models the actual behaviour of the wall during construction as closely as possible. A factor of safety is not calculated, but collapse of the wall will be detected if the factor of safety is less than unity.

The wall and soil are modelled as a beam and springs. Wall displacements, bending moments and strut forces are calculated at each stage of the construction sequence. Active and passive soil pressures are checked to ensure that limiting values are not exceeded.

#### **Prop strength**

The stability of multi-propped walls (for which there is no stability analysis) depends on the strength of the props. The props in WALLAP are assumed to be elastic but infinitely strong. It is up to you to ensure that props are designed to take the calculated loads.

#### **Symmetry**

The program behaves symmetrically with respect to the left ("active") and right ("passive") sides of the wall except in respect of struts which have been defined as Non-tension struts (see Section 9.2).

The bending moment and displacement analysis produces an economical design which automatically takes account of any moment reduction due to fixed earth support.

### 13.4.1 Subgrade Reaction or 2-D Finite Element model

WALLAP offers two soil models for the bending moment calculation. Alternatively the bending moment calculation can be switched off altogether ("NOT required"). The following menu is displayed:

B.M. and displacement calculation method
Subgrade reaction model
2-D Finite element model
Not required

#### Subgrade Reaction model

The soil springs are non-interactive. The Subgrade Reaction model is suitable for all routine work. The main limitation compared with the 2-D F.E. model is that it does not model Soil Arching.

#### 2 Dimensional Finite Element model

The soil springs are interactive and are derived from a 2-D finite element mesh representing the actual soil layers on either side of the wall.

The 2-D F.E. model provides a more rigorous approach which offers the possibility of modelling soil arching and the effect of soil layers below the toe of the wall.

The 2-D Finite Element model should only be used for more detailed investigation where the quality of site investigation and knowledge of the ground conditions justify the additional analytical complexity.

#### 'NOT required'

The bending moment calculation is omitted altogether so that the program simply calculates factors of safety (for those stages where there is one strut or no strut).

This option is useful in order to establish the depth of the wall required to satisfy factor of safety criteria, before going on to calculate bending moments and strut forces.

### 13.4.2 Open Tension Crack analysis

The development of tension cracks and their possible closure during reverse wall movements is traced rigorously throughout the construction sequence. After a crack has opened, positive soil pressure can only develop again if there is sufficient reverse wall movement.

If this option is switched **off**, then soil is deemed to remain in contact with the wall when it reaches zero active pressure. Positive soil pressure develops again immediately there is any reverse wall movement.

### **Water Pressure in Tension Crack**

At present it is not permitted to specify "Maximum depth of water filled tension crack" (for undrained soils) in conjunction with the Open Tension Crack analysis. There is no fundamental reason why these options should not be combined, it is just that the program can't cope with them.

### **Minimum Equivalent Fluid Pressure**

It is not permitted to specify "Minimum Equivalent Fluid Pressure" (for undrained soils) in conjunction with the Open Tension Crack analysis. The two concepts are clearly incompatible i.e. there cannot be a minimum soil pressure if a crack has formed. If the Minimum Equivalent Fluid Pressure is required for factor of safety calculations then switch off the Open Tension Crack analysis and do a separate run to calculate factors of safety.

### **13.4.3 Soil Arching option (2-D F.E. analysis only)**

Arching is the ability of soil to find support where it is available and relieve pressures at points of lesser support. Arching behaviour can be modelled when using the 2-D F.E. analysis. It is not available during subgrade reaction analysis.

### **Definition of arching**

The arching rule allows active **pressures** to fall to values below the Coulomb active limiting pressure, provided the total active **force** on each potential active wedge mechanism is not less than the Coulomb active limiting force.

A full description of the active arching calculation method is given by Pappin, Simpson, Felton and Raison (1986).

### **Effect of arching**

With arching, the program can predict the sort of trapezoidal pressure distribution which Peck (1943) observed in strutted excavations in sand. Instead of the usual triangular pressure diagram based on Coulomb active limit pressures, soil pressures near ground level were well in excess of the active limit while active pressures near excavation level were significantly below Coulomb active limiting pressure.

The inclusion of arching tends to increase strut forces and decrease bending moments. A cautious approach would be to carry out analyses with and without arching to obtain reasonably conservative estimates of both strut forces and bending moments.

You may wish to consider whether arching action might be reduced under long term conditions due to vibration or other cyclic loading such as varying ground water level.

#### **13.4.4 Non-linear soil modulus parameter**

This is the parameter L in the approximate non-linear elastic soil model illustrated in Figure 10 and discussed in Appendices B.2.2. and C.2.2. The increase of soil stiffness with distance from the wall is assumed to be exponential:-

$$E = E_o \cdot 2^{(x/L)}$$

where  $E_o$  = Modulus adjacent to the wall,  
 $E$  = Modulus at distance  $x$  from the wall  
 $L$  = Distance from the wall where the modulus is double its given value,  $E_o$ .

The same value of L is applied to all soil layers.

Enter a zero for L to model constant modulus with distance from the wall.

In reality the zone of maximum strain is probably confined to the soil mass within a horizontal distance equal to the total wall depth. A reasonably conservative approach would therefore be to use a value of L equal to the total wall depth.

A more precise value for L could be obtained by calibrating the program against a full finite element analyses with a strain hardening soil model.

#### **Warning**

If the "rigid boundaries" are very far from the wall and L is set to 0 (no increase of stiffness with distance) the analysis will produce unrealistically large wall displacements.

### **13.4.5 Wall length perpendicular to the plane of analysis**

Specify the actual wall length (perpendicular to the plane of analysis). The influence of this parameter is not significant except for very short walls.

The length of the wall is taken into account in making a plane strain approximation to what is actually a three dimensional problem. Soil stiffness coefficients are increased compared with theoretical values for an infinitely long wall.

### **13.4.6 Excavation (Fill) width**

This parameter defines the width of the excavated (filled) area in Excavation and Filling construction stages - see Figure 9a. WALLAP models the actual width of excavation and does **not** assume an infinitely wide excavation.

**Excavation and Fill** - The same parameter defines the widths of the Excavation **and** Fill.

**Active and passive sides** - Different widths of excavation/fill can be defined for the two sides of the wall.

### **Symmetrical excavation**

In the case of a symmetrical excavation you should still enter the full excavation width, even when the rigid boundary on the passive side is set at half the excavation width because of symmetry as shown in Figure 9b.

**Graphical output** - The actual width of excavation is shown on the graphical output.

### **13.4.7 Distance from wall to rigid vertical boundaries**

This parameter defines the lateral limit of the soil block which is included in the analysis - see Figure 9a. All strains and displacements beyond this distance will be ignored.

On the active (non-excavation) side this distance should be between one and three times the wall depth.

On the passive (excavation) side, there are two situations which commonly exist:

1. Very wide or asymmetrical excavation - see Figure 9a.  
As for the active side this distance should be between one and three times the wall depth.
2. Symmetrical excavation - see Figure 9b.  
Set the rigid vertical boundary at a distance equal to half the excavation width, on the assumption that the excavation behaves symmetrically and the centre line is a line of zero horizontal displacement.

### **13.4.8 Elevation of rigid lower (horizontal) boundary**

(2-D F.E. analysis only)

This is the elevation of the rigid lower boundary of the finite element mesh in the 2-D F.E. analysis. All strains and displacements below this elevation will be ignored.

A reasonable depth in many problems would be half the wall depth below the toe of the wall.

### **13.4.9 Boundary conditions at rigid lower boundary**

(2-D F.E. analysis only)

The rigid lower boundary can be defined as Smooth (i.e. frictionless) or Rough. It should normally be taken as Rough. The displaced soil shape will indicate if the lower boundary is influencing the analysis unduly.

### **13.4.10 Boundary conditions at rigid vertical boundaries**

(2-D F.E. analysis only)

The vertical rigid boundaries can be defined as Smooth (i.e. frictionless) or Rough.

#### **Active side**

On the active side, the rigid vertical boundary should normally be taken as Rough.

#### **Passive side**

On the passive (excavation) side, there are two situations which commonly exist:

1. Very wide or asymmetrical excavation. The boundary should be taken as Rough (Figure 9a).

2. Symmetrical excavation. The rigid vertical boundary is usually on the centre line of a symmetrical excavation and should therefore be taken as Smooth (Figure 9b).

### **13.4.11 Boundary conditions between soil and wall**

(2-D F.E. analysis only)

You may specify rough (full adhesion) or smooth (no adhesion) between soil and wall.

This condition is applied to the formulation of the elastic Finite Element mesh, independently of the value of  $d$  used in the derivation of  $K_a$  and  $K_p$  given in the soil properties.

The values of  $K_a$  and  $K_p$  given in the soil properties must include their own allowance for wall friction (if required).

### **13.4.12 Iteration limits**

The calculation of bending moments and displacements is iterative due to the need to satisfy active and passive limits as well as the elastic properties of wall and soil. The number of iterations allowed per construction stage is normally fixed by the program at 200 iterations for the Subgrade Reaction method and 2000 iterations for the 2D FE method.

Convergence failure, if it occurs, is most likely due to one of the reasons mentioned in Section 15.8.2. and not because of the program allowing too few iterations. However you can, if necessary, adjust the iteration limit by inserting an instruction in the form of a special text anywhere in the Sub-title (see Section 4.1). The text is of the form

[IL=nnnn]

where 'IL' stands for 'iteration limit' and nnnn is the number iterations required.

## **13.5 SINGLE PILE ANALYSIS**

WALLAP may be used to calculate deflections, bending moments and shear forces in a single pile subject to horizontal and moment loads and rotational restraints.

The pile may be subjected to horizontal and moment loads or rotational restraints at one or more elevations. Piles in submerged ground (e.g. mooring dolphins) can be analysed.

### 13.5.1 Limitations of single pile analysis

The following differences in operation should be noted:-

- Only the bending moment analysis is carried out. A factor of safety is not calculated explicitly but a low factor of safety would be indicated by excessive displacements.
- The only permitted construction activities are:
  - Application of horizontal and moment loads to the pile.
  - Application of rotational restraints to the pile.
  - Equal changes of water level on active and passive sides of the wall.
- Excavation, filling and the application of surcharges to the ground are not permitted.

### 13.5.2 Earth pressure coefficients for single piles

#### Active pressure coefficients

The program always assumes the limiting active pressure to be zero due to arching. Non-zero values of  $K_a$  and  $K_{ac}$  specified by the user will be ignored.

#### Passive pressure coefficients

You should enter the usual values of  $K_p$  and  $K_{pc}$  for retaining walls. The program uses these values to calculate the limiting passive pressure in accordance with Equation 6.10 and then multiplies the result by a factor of 3 to allow for the three dimensional nature of the single pile problem compared with a wall.

### 13.5.3 Analysis method for single piles

WALLAP uses the subgrade reaction method for single pile analysis. Soil moduli are the same as for a wall analysis. The finite element model is not available for single piles.

## 14.0 OUTPUT OPTIONS

During an analysis the program creates output files, xxxxx.OUT and xxxxx.BIN, containing all the information required to generate reports (RTF files).

The generation of reports is carried out as a post-processing operation after you have had a chance to view the results of an analysis on the screen. There is considerable freedom to select the amount of output actually included in a report. Section 3.11 gives full details.

Some of the report options are selected during the generation of the report, other options are included in the input data. This section deals with **Custom stage selection** i.e. the stage output selections which can be made as part of the input data. If you do not make specific choices here you can still generate reports using the **Automatic stage selection** option (Section 3.11.1)

### 14.1 CUSTOM STAGE SELECTION

The basic output for a construction stage consists of:

- Factor of Safety (if applicable)
- Displacements,
- Shear forces,
- Bending moments
- Strut forces.

Additional output for any stage is available:

- Active and passive pressures (optional)
- Graphical output. (optional)

The following menu allows you to select more or less detailed output for each stage:-

Stage output options				
Stage no.	-----Stage description -----	----- Output options -----		
		Displacement Bending mom. Shear force	Active, Passive pressures	Graphical output
1	Apply surcharge no.1 at elev. 11.00	No	No	No
2	Apply surcharge no.2 at elev. 9.50	No	No	No
3	Install strut no.1 at elev. 10.00	No	No	No
4	Apply water pressure profile no.1	No	No	No
5	Excav. to elev. 6.00 on PASSIVE side	Yes	No	No
6	Install strut no.2 at elev. 6.50	No	No	No
7	Apply water pressure profile no.2	No	No	No
8	Excav. to elev. 3.00 on PASSIVE side	Yes	Yes	Yes

Select an item for editing and press **Y** or **N** or <Space bar> to toggle a setting.

### **14.1.1 Displacements and bending moments**

This is the basic output giving shear forces, bending moments, wall displacements, and strut forces at each node elevation, in addition to the factor of safety (if calculated). If this option is not selected then the resulting report will not contain any output for the relevant stage.

### **14.1.2 Active and passive pressures**

This optional extra output includes the following information at each node elevation for both sides of the wall:-

- Water pressure
- Vertical pressure
- Active limit pressure
- Passive limit pressure
- Actual soil pressure

### **14.1.3 Graphical output**

The report will include diagrams of displacements, shear forces bending moments and wall pressures. Graphical output on the screen include some colour. Graphics in report files are in monochrome.

## **14.2 SUMMARY OUTPUT**

All reports include Summary output (text). The optional inclusion of Summary graphical output is decided during report creation - see Section 3.11.

See Chapter 15 for a full description of the tables and graphs.

## 15.0 INTERPRETATION OF RESULTS

Reports include output for all stages for which output was requested. If more than one strut has been installed at a particular stage, there will be no stability analysis and therefore a Factor of Safety will not be output for that stage.

The output for each stage begins on a new page with the title block and the stage description (Fill, excavate etc..). The results of the stability analysis are output first followed by the bending moment and displacement results.

### 15.1 STABILITY ANALYSIS OF CANTILEVER WALLS

Typical results for a cantilever wall:-

Stage No. 3    Excav. to elev. 6.00 on PASSIVE side								
STABILITY ANALYSIS according to Strength Factor method								
Factor of safety on soil strength								
			FoS for toe elev. = -2.00		Toe elev. for FoS = 2.000		Strut force for F=1.000	
Stage No.	--- G.L. Act.	--- Pass.	Strut Elev.	Factor of Safety	Moment equilib. at elev.	Toe elev.	Wall Penetr- -ation	Strut force kN/m run
2	11.00	6.00	Cant.	2.553	-0.90	0.20	5.80	-----
3	11.00	6.00	10.00	3.104	n/a	1.30	4.70	90.12
			Case A		Case B		Case C	

The depth of the wall, either assumed (case A) or calculated (case B), is taken in all cases to include the extra depth required to generate reverse passive resistance at the toe of the wall. Thus no additional penetration should be added to these depths to achieve the corresponding factor of safety.

In WALLAP, the extra depth required to generate reverse passive resistance is actually *calculated* (using the same factor of safety) rather than estimated as a fixed percentage of the wall penetration.

#### Case A

The program may print the message:-

```
Conditions unsuitable for FoS calc.
```

This may be because:-

- There is no nett overturning moment; the active pressures are small or zero, possibly due to the presence of cohesive soil.
- The wall is tending to move from right ("passive") to left ("active"). If you want to calculate the **factor of safety** under these conditions you would have to reverse the data (see Section 13.3.7).

## Case B

This result is useful at the preliminary stages of design when you are selecting the toe elevation of the wall. WALLAP only calculates the required toe elevation for Case B if it is **above** the specified toe elevation given in the wall properties (Section 8.2). To ensure that a result is calculated for Case B you should specify a suitably low toe elevation under wall properties. The toe elevation calculated in Case B is not used anywhere else in the calculations. The toe elevation used in the Bending Moment analysis is always the value which you entered under wall properties.

### Stability analysis; cantiliver wall – description of results

Heading	Interpretation
G.L. Act.	Ground level, active side, at this stage.
G.L. Pass.	Ground level, passive side, at this stage.
Strut Elev.	Not applicable. "Cant" indicates a cantilever wall (i.e. no strut).
FoS for toe elev. = xxxx	<b>Case A</b> Calculated Factor of Safety for the toe elevation given in the data under "Wall Properties". If the FoS is not adequate at any stage, the wall should be made deeper.
Moment equilb. at elev.	The elevation at which overturning moments balance restoring moments for a cantilever`wall.
Toe elev. For Fos = yyyyy	<b>Case B</b> Toe elevation required to achieve the Factor of Safety given in the data under "Analysis Options".
Wall penetration	Wall penetration below GL on the passive side (corresponding to the above toe elevation).
Strut force For F = zzzzz	<b>Case C</b> Not applicable to cantilever walls.

## 15.2 STABILITY ANALYSIS OF PROPPED/ANCHORED WALLS

Typical results for a propped / anchored wall:-

Stage No. 3    Excav. to elev. 6.00 on PASSIVE side									
STABILITY ANALYSIS according to Strength Factor method									
Factor of safety on soil strength									
			FoS for toe elev. = -2.00		Toe elev. for FoS = 2.000		Strut force for F=1.000		
-----									
Stage No.	--- Act.	--- Pass.	Strut Elev.	Factor of Safety	Moment equilib. at elev.	Toe elev.	Wall Penetr- ation	Strut force kN/m run	
2	11.00	6.00	Cant.	2.553	-0.90	0.20	5.80	-----	
3	11.00	6.00	10.00	3.104	n/a	1.30	4.70	90.12	
				Case A		Case B		Case C	

### Stability analysis; propped wall – description of results

Heading	Interpretation
G.L. Act.	Ground level, active side, at this stage.
G.L. Pass.	Ground level, passive side, at this stage.
Strut Elev.	Strut or anchor elevation.
FoS for toe Elev. = xxxx	<b>Case A</b> Calculated Factor of Safety for the toe elevation given in the data under "Wall Properties". If the FoS is not adequate at any stage, the wall should be made deeper.
Moment Equilib. At elev.	Not applicable to propped walls.
Toe elev. For Fos = yyyyy	<b>Case B</b> Toe elevation required to achieve the Factor of Safety given in the data under "Analysis Options".
Wall penetration	Wall penetration below GL on the passive side (corresponding to the above toe elevation).
Strut force For F = zzzzz	<b>Case C</b> The strut force corresponding to an assumed Factor of Safety (usually 1) as given under "Analysis Options".

**Case A**

The program may print the message:-

```
Conditions not suitable for factor of safety calculation
```

This may be because:-

- a) The prop force is negative i.e. the resultant of the active pressures acts at a lower elevation than the resultant of the passive pressures!
- b) The prop is so low that there is no nett overturning moment.
- c) There is no nett overturning moment; the active pressures are small or zero, possibly due to the presence of cohesive soil.
- d) The wall is trying to fail from right ("passive") to left ("active"). If you want to calculate the **factor of safety** under these conditions you would have to reverse the data (see Section 13.3.7).

**Case B** - See comments for Case B in Section 15.1.

**Case C** - See comments in Section 15.5.

**15.3 BENDING MOMENT and DISPLACEMENT CALCULATION**

Details of the bending moment and displacement calculation are described in:

	Topic
Section 13.4	Analysis options
Appendix B	Subgrade reaction model
Appendix C	2D finite element model
Appendix D	Matrix solution

**Subdivision into elements**

The program creates a node at every elevation at which data has been defined e.g. strata, strut, surcharge, excavation, fill and water table (but not every point on the water pressure profiles).

The larger element lengths are automatically subdivided by the program.

For the Subgrade Reaction option the bottom node is at the toe of the wall. For the Finite Element option the bottom node is at the lower rigid boundary. Node spacings below the toe of the wall are generally larger than above the toe. Results are output for all node levels.

The bending moment and displacement results are presented in three tables described in Sections 15.3.1/2/3

### 15.3.1 Table 1 - Displacements, bending moments and strut forces

Node no.	Y coord	Nett pressure kN/m <sup>2</sup>	Wall disp. m	Wall Rotation rad.	Shear force kN/m	Bending moment kN.m/m	Strut forces kN/m	Applied moments kN.m/m
1	11.00	5.54	0.031	-2.34E-03	0.0	0.0		
2	10.00	10.49	0.033	-2.41E-03	8.0	5.6	82.61	
		10.49			-74.6	5.6		
3	9.50	12.97	0.034	-2.26E-03	-68.7	-29.9		
4	8.25	39.92	0.036	-3.78E-04	-35.7	-90.5		
5	7.00	45.62	0.035	2.537E-03	17.8	-96.1	-0.00	
6	6.50	31.26	0.033	3.648E-03	37.0	-81.7		
7	6.00	37.16	0.031	4.525E-03	54.1	-58.6		
8	4.50	-17.05	0.023	5.671E-03	29.2	-2.5		
9	3.00	-2.91	0.015	5.280E-03	14.3	23.4		
10	1.60	15.00	0.008	4.251E-03	22.7	35.4		
11	1.00	18.08	0.006	3.600E-03	32.6	51.3		
		-47.35			32.6	51.3		
12	-0.50	-16.09	0.002	1.866E-03	-14.9	41.2		
13	-2.00	35.99	-0.000	1.095E-03	0.0	0.0		
Strut force at elev. 10.00 = 82.6 kN/m						run = 247.8 kN per strut (horiz.)		
						= 251.6 kN per strut (incl.)		
The strut at elev.			7.00 is slack					

Heading	Interpretation
Y coord	Elevation at which results are given. Where there is a step change in shear force or bending moment, one y coordinate refers to two lines of results.
Nett pressure	Nett total pressure, including water pressure; (active - passive)
Wall disp.	Total horizontal wall displacement. A "g" next to the wall displacement indicates a gap has formed between soil and wall. See additional note below
Wall rotation	Total rotation of the wall (radians)
Shear force	Shear force in the wall (per unit length of wall) Note: Step changes at strut levels and at applied horizontal forces
Bending moment	Bending moment in the wall (per unit length of wall) Note: Step changes at applied moments and rotational restraints.
Strut forces	Strut force / Applied horizontal load (per unit length of wall). For an inclined strut the value given here is the horizontal component. If a strut and an applied load exist at the same elevation (as when modelling temperature stresses in struts) then the printed value is the sum of the strut load and the applied load
Applied moments	Applied moment load (per unit length of wall). This can be a moment applied as a fixed value or the reaction due to a rotational restraint.

## Equilibrium check

The shear force and bending moment at the toe of the wall should be zero. If Convergence failure occurs there may be an out of balance shear force and/or bending moment at the toe of the wall (see Section 15.8.2).

### 15.3.2 Soil - wall gaps; Open tension crack option

Node no.	Y coord	Nett pressure kN/m <sup>2</sup>	Wall disp. m	Wall rotation rad.	Shear force kN/m	Bending moment kN.m/m	Strut forces kN/m	Applied moments kN.m/m
1	0.00	-80.00	g 0.022	6.66E-03	200.0	0.0	-200.00	
2	-0.75	-89.00	g 0.017	6.41E-03	136.6	134.3		
3	-1.50	-74.94	g 0.013	5.77E-03	75.1	211.0		
4	-2.25	-63.59	g 0.009	4.91E-03	23.2	245.6		
5	-3.00	-50.82	0.005	3.98E-03	-19.7	247.2		
6	-3.75	-25.86	0.003	3.11E-03	-48.5	218.2		
7	-4.50	-6.61	0.001	2.38E-03	-60.6	174.5		
8	-5.25	5.95	-0.001	1.81E-03	-60.9	127.2		
9	-6.00	14.30	-0.002	1.42E-03	-53.3	83.2		
10	-6.75	20.98	-0.003	1.17E-03	-40.1	47.3		
11	-7.50	18.35	-0.004	1.04E-03	-25.3	23.6		
12	-8.25	13.47	-0.005	9.77E-04	-13.4	9.1		
13	-9.00	8.48	-0.005	9.55E-04	-5.1	2.2		
14	-9.50	5.14	-0.006	9.52E-04	-1.7	0.4		
15	-10.00	1.80	-0.006	9.52E-04	-0.0	0.0		

Note: g-1.00 soil/wall gap on active side  
-1.00g soil/wall gap on passive side

A gap can develop between soil and wall where the active limit is equal to zero in cohesive soil i.e. the soil is strong enough to be self supporting. The Gap may close in subsequent stages if the direction of wall movement is reversed.

A "g" before the displacement value indicates a gap on the left (active side of the wall; a "g" after the displacement indicates a gap on the right (passive) side of the wall. Further details of the gap size are given in the Active pressure tables (Section 15.3.5).

Gaps are only computed if the Open Tension Crack option is selected (Section 13.4.2). If the Open Tension Crack option is **not** selected then cohesive soil is assumed to stay in contact with the wall even when the active pressure has fallen to zero.

### 15.3.3 Strut force summary

Strut force at elev. 10.00 = 82.6 kN/m run = 247.8 kN per strut (horiz.)  
= 251.6 kN per strut (incl.)  
The strut at elev. 7.00 is slack

At the end of Table 1 (Section 15.3.1) the strut loads are summarised in terms of load per unit length of wall **and** load per strut. In the case of inclined struts, the total strut load (inclined) and the horizontal component are given.

The "slack" message indicates that the strut at this elevation has no load in it. This can only happen if the "No tension" option has been selected in the strut properties.

### 15.3.4 Derivation of incremental displacements

Total wall displacements are output in Table 1. Incremental displacements can be found manually as the difference between displacements in two successive stages.

### 15.3.5 Table 2 - Earth pressures on the Active side of the wall

Node no.	Y coord	----- ACTIVE side -----							
		Water press. kN/m2	----- Effective stresses -----				Earth pressure kN/m2	Total earth pressure kN/m2	Soil stiffness coeff. kN/m3
			Vertic -al kN/m2	Active limit kN/m2	Passive limit kN/m2	Earth pressure kN/m2			
1	11.00	0.00	20.00	5.54	100.00	20.31	20.31	1154.2	
2	10.00	0.00	37.87	10.49	189.37	15.19	15.19	6925.1	
3	9.50	0.00	46.83	16.28	234.16	12.97	12.97A	942.2	
4	8.25	0.00	144.12	45.81	720.58	39.92	39.92A	1727.4	
5	7.00	0.00	164.68	45.62	823.38	45.62	45.62a	2512.6	
6	6.50	5.00	95.54	26.47	477.72	26.47	31.47a	2826.7	
7	6.00	10.00	99.49	27.56	497.47	27.56	37.56a	3140.8	
		Total>	109.49	29.49	189.49	29.49	29.49a	2153.7	
8	4.50	Total>	139.50	59.50	219.50	59.50	59.50a	2153.7	
9	3.00	Total>	169.50	89.50	249.50	89.50	89.50a	2153.7	
10	1.60	Total>	197.50	117.50	277.50	119.64	119.64	2153.7	
11	1.00	Total>	209.50	129.50	289.50	136.62	136.62	2153.7	
		Total>	209.50	50.00m	306.81	154.14	154.14	7178.9	
12	-0.50	Total>	241.00	57.50m	329.43	238.69	238.69	7178.9	
13	-2.00	Total>	272.50	65.00m	354.76	354.76	354.76p	141643.1	

Note: 45.62a Soil pressure at active limit  
154.12p Soil pressure at passive limit  
12.97A Arching - soil pressure below active limit

#### Active pressures with soil arching

Node no.	Y coord	----- ACTIVE side -----							
		Water press. kN/m2	----- Effective stresses -----				Earth pressure kN/m2	Total earth pressure kN/m2	Soil stiffness coeff. kN/m3
			Vertic -al kN/m2	Active limit kN/m2	Passive limit kN/m2	Earth pressure kN/m2			
1	0.00	Total>	0.00	0.00				Soil/wall gap = 0.022 m	4701
2	-0.75	Total>	15.00	0.00				Soil/wall gap = 0.016 m	4701
3	-1.50	Total>	30.00	0.00				Soil/wall gap = 0.010 m	4701
4	-2.25	Total>	45.00	0.00				Soil/wall gap = 0.004 m	4701
5	-3.00	Total>	60.00	0.00	140.00	4.59	4.59		4701
6	-3.75	Total>	75.00	0.00	155.00	24.57	24.57		4701
7	-4.50	Total>	90.00	10.00	170.00	41.70	41.70		4701
8	-5.25	Total>	105.00	25.00	185.00	55.48	55.48		3478
9	-6.00	Total>	120.00	40.00	200.00	67.15	67.15		3478
10	-6.75	Total>	135.00	55.00	215.00	77.99	77.99		3478
11	-7.50	Total>	150.00	70.00	230.00	88.35	88.35		3478
12	-8.25	Total>	165.00	85.00	245.00	98.47	98.47		3478
13	-9.00	Total>	180.00	100.00	260.00	108.48	108.48		3478
14	-9.50	Total>	190.00	110.00	270.00	115.14	115.14		3478
15	-10.00	Total>	200.00	120.00	280.00	121.80	121.80		3478

#### Active pressures with soil-wall gap

Note: The active and passive limits both refer to the left ("active") side of the wall. The actual earth pressure will always lie between the active and passive limits, except in the case of arching active pressures - see below.

<b>Heading</b>	<b>Interpretation</b>
Y coord	Elevation at which results are given. Where there is a step change any of the pressures, one y coordinate refers to two lines of results.
Water press.	In drained strata the water pressure is given. In undrained strata the message "TOTAL>" is printed to indicate that soil pressures at this elevation are given as total stresses.
Vertical	Vertical stress (effective stress in drained soil) (total stress in undrained soil)
Active limit	Limiting active pressure (effective stress in drained soil) (total stress in undrained soil) 'm' indicates Minimum Equivalent Fluid Pressure. 'w' indicates water pressure in tension crack
Passive limit	Limiting passive pressure (effective stress in drained soil) (total stress in undrained soil)
Earth pressure	Actual wall pressure (effective stress in drained soil) (total stress in undrained soil)
Soil/wall gap	The soil is self supporting and a gap has formed between soil and wall. See Section 15.3.2 for details.
Total earth pressure	Actual wall pressure (total stress) 'a' indicates soil at active limit 'A' indicates sub-active soil pressure due to arching (only if Arching option selected with 2D F.E. model) 'p' indicates soil at passive limit
Soil stiffness Coefficient	Soil spring value (Subgrade reaction model) or Diagonal component of soil stiffness matrix (2D-FE model)

### **15.3.6 Table 3 - Earth pressures on the Passive side of the wall**

The headings are as for Table 2 but all results refer to the right ("passive") side of the wall.

## 15.4 SUMMARY OUTPUT

### 15.4.1 Bending moment, shear force and displacement envelopes

Bending moment, shear force and displacement envelopes							
Node no.	Y coord	Displacement		Bending moment		Shear force	
		maximum m	minimum m	maximum kN.m/m	minimum kN.m/m	maximum kN/m	minimum kN/m
1	11.00	0.031	0.000	0.0	0.0	0.0	0.0
2	10.00	0.033	0.000	8.0	0.0	11.2	-74.6
3	9.50	0.036	0.000	6.1	-29.9	4.1	-68.7
4	8.25	0.043	0.000	10.1	-90.5	1.3	-35.7
5	7.00	0.048	0.000	9.2	-96.1	23.3	-10.1
6	6.50	0.049	0.000	7.3	-81.7	42.6	-90.8
7	6.00	0.049	0.000	4.4	-100.6	54.1	-73.5
8	4.50	0.047	0.000	0.0	-168.5	29.2	-6.8
9	3.00	0.036	0.000	23.4	-102.9	105.0	0.0
10	1.60	0.021	0.000	48.0	-2.1	119.7	0.0
11	1.00	0.015	0.000	121.1	0.0	128.2	0.0
12	-0.50	0.005	0.000	122.4	0.0	0.0	-44.0
13	-2.00	0.000	-0.000	0.0	0.0	0.0	-0.0

Heading	Interpretation
Y coord	Elevation at which results are given
Displacements	Maximum and minimum Displacements at this Elevation during the whole construction sequence
Bending moment	Maximum and minimum Bending Moment at this elevation during the whole construction sequence
Shear force	Maximum and minimum Shear Force at this elevation during the whole construction sequence

### 15.4.2 Maximum and minimum bending moment, shear force and displacement at each stage

Maximum and minimum bending moment and shear force at each stage								
Stage no.	Bending moment				Shear force			
	maximum kN.m/m	elev.	Minimum kN.m/m	elev.	maximum kN/m	elev.	minimum kN/m	elev.
1	10.1	8.25	-5.7	3.00	11.2	1.00	-7.2	6.00
2	24.4	-0.50	-18.5	4.50	31.3	1.00	-13.6	6.00
3	No calculation at this stage							
4	41.4	-0.50	-48.1	4.50	50.1	1.00	-19.7	6.00
5	51.3	1.00	-96.1	7.00	54.1	6.00	-74.6	10.00
6	No calculation at this stage							
7	45.5	-0.50	-84.8	7.00	64.2	1.00	-71.9	10.00
8	122.4	-0.50	-168.5	4.50	128.2	1.00	-90.8	6.50

Maximum and minimum displacement at each stage					
Stage no.	Displacement				Stage description
	maximum m	elev.	minimum m	elev.	
1	0.003	11.00	-0.000	-2.00	Apply surcharge no.1 at elev. 11.00
2	0.015	11.00	-0.000	-2.00	Apply surcharge no.2 at elev. 9.50
3	No calculation at this stage				Install strut no.1 at elev. 10.00
4	0.020	6.50	-0.000	-2.00	Apply water pressure profile no.1
5	0.036	8.25	-0.000	-2.00	Excav. to elev. 6.00 on PASSIVE side
6	No calculation at this stage				Install strut no.2 at elev. 6.50
7	0.037	8.25	0.000	11.00	Apply water pressure profile no.2
8	0.049	6.00	-0.000	-2.00	Excav. to elev. 3.00 on PASSIVE side

### 'No calculation at this stage'

The bending moments, shear forces and displacements are the same as at the end of the previous stage.

No calculation is carried at the installation of a strut which is **not pre-stressed**. The introduction of such a strut does not cause any immediate change in soil or wall stresses.

No calculation is carried for water pressure or surcharge stages where calculation was not requested.

### 15.4.3 Strut forces at each stage

Strut forces at each stage (horizontal components)				
Stage no.	--- Strut no. 1 --- at elev. 10.00		--- Strut no. 2 --- at elev. 6.50	
	kN/m run	kN/strut	kN/m run	kN/strut
4	10.5	31.5	---	---
5	82.6	247.8	---	---
7	80.9	242.7	16.7	50.1
8	80.7	242.2	133.4	400.2

Blanks indicate that the strut was not installed at that stage.

## 15.5 STRUT FORCES

Both the stability and the finite element analyses will give a value of the prop force for singly propped walls. The results of the analyses will not necessarily agree and may in some instances diverge widely.

The reason for the disagreement is that the stability analysis assumes that all soil pressures on the active side of the wall are at the active limit and takes no account of the sequence of construction operations or pre-stressing of the struts. The finite element analysis will generally yield a higher strut force which should be used as the basis for design.

## 15.6 GRAPHICAL OUTPUT

**Shear force and bending moment** are plotted on one diagram with shear force shown in dashed lines. There is no legend on this diagram as everyone knows that zero shear force corresponds to maximum bending moment.

**Active pressures** (left) and **passive pressures** (right) are plotted on one diagram. Total pressure (soil + water) is shown in solid lines and water pressure in dashed lines.

**Displacements** and **Nett wall pressures** are plotted on separate diagrams.

## **15.7 DESIGN CRITERIA**

### **15.7.1 Factor of safety**

Each method of Factor of Safety calculation must be used in conjunction with the design factors of safety recommended for that method and the relevant design conditions e.g. permanent or temporary works; SLS or ULS; level of risk etc.

The Strength Factor method is the method prescribed by CIRIA Publication C580 and Eurocode 7, and is the most rational and consistent method available. It has the advantage that factors of safety are specified directly in terms of soil strength ( $c$  and  $\phi$ ) and fit into the overall structural design philosophy.

The Burland-Potts method is also rational and consistent but the relevant design factors are not embodied in a code of practice.

The CP2 and BSC Piling handbook method should only be used in circumstances familiar to the user and one should on no account extrapolate to unfamiliar soil types or structural geometries. These methods should not be used for undrained analysis of propped walls in soft clay.

### **15.7.2 Multi-propped walls**

Multi-propped walls (for which there is no stability analysis) depend on the strength of the props for overall stability. The props in WALLAP are assumed to be elastic but infinitely strong. It is up to the user to ensure that props are designed to take the calculated loads and that the wall is capable of sustaining the calculated bending moments.

### **15.7.3 Bending moments**

In selecting a design bending moment profile it should be remembered that the maximum bending moment may be rather sensitive to the degree of fixity at the toe of the wall. If fixity has been obtained by toeing into a very stiff stratum it would be prudent to consider the minimum likely penetration, bearing in mind the difficulty of achieving the design penetration in dense strata.

### **15.7.4 Displacements**

The number and position of temporary struts may have a significant effect on wall displacements. Small amounts of over excavation can have a large effect on displacements. Calculations should be carried out for worst possible cases as well as for the anticipated construction sequence.

Anchors are normally pre-stressed to a high proportion of their working load. The **strut force summary** should be examined to see to ensure that anchors are not overstressed at any stage and the pre-stress should be adjusted accordingly. On the other hand you should avoid putting too little pre-stress in the anchors as this may lead to excessive wall movements.

## **15.8 ERROR MESSAGES**

### **15.8.1 \*\*\* Conditions unsuitable for factor of safety calculation**

See Section 15.1

### **15.8.2 \*\*\* Convergence failure; Out of balance forces.**

The equilibrium bending moment and displacement solution at each stage is obtained using an iterative procedure. Some ill-conditioned problems fail to converge and the result is a non-equilibrium force distribution.

"Convergence failure" is easily identified by an out of balance shear force at the toe of the wall. The degree of non-convergence and the extent to which the results may be in error can be gauged directly from the value of shear force at the toe of the wall.

An out of balance force in one construction stage will show up in all subsequent construction stages, even if the calculations in all subsequent stages are convergent. This is because the forces are calculated cumulatively.

In rare cases the iterative procedure may diverge wildly. The analysis is interrupted with the message "ill-conditioned problem".

Convergence failure is most likely to occur in one of the following circumstances:

- An extreme ratio of soil to wall stiffness.
- An extreme ratio of strut to wall stiffness  
(Realistic values of strut stiffness should always be used).
- A very great contrast between one soil stiffness and another.
- 2D F.E. analysis with Open Tension Crack analysis switched **on**.

The following messages are displayed:

### **Warning message with stage output**

```
*** Convergence failure - Out of balance shear force
      at elevation -12.34 is 5.67% of the maximum
      shear force. see Note.
```

or

```
*** Convergence failure - ill-conditioned problem
```

### **Explanatory Note with summary output**

The following note is printed at the end of the summary output:-

```
Convergence errors have occurred in at least one
Construction Stage. The errors are cumulative, and the
results of all stages must be inspected for significant out
of balance moment or shear at the toe of the wall.
```

```
Failure of the iterative procedure to converge to an
equilibrium solution may be due to a very high ratio of soil
stiffness to wall stiffness. The data should be reviewed to
see if realistic values have been specified.
```

#### **Out of balance shear forces.**

<b>Percentage Error</b>	<b> </b>	<b>Interpretation</b>
< 2%		Generally acceptable
2% to 4%		Use with caution
> 4%		Should not be used

It is unlikely that convergence failure will occur due to the program allowing too few iterations. However you can, if necessary, adjust the iteration limit. For details see Section 13.4.12.

### **15.8.3 \*\*\* Passive failure**

This message indicates that a mechanism has formed and that no further calculation can be carried out. There is no indication about the actual factor of safety except that it is, presumably, less than unity.

Failure cannot usually occur when there is more than one strut since even when all the soil has failed, two struts are enough to prevent a mechanism forming. However a mechanism can form if one or more struts goes "slack". This would suggest that the struts should be repositioned.

### **15.8.4 \*\*\* Data error - Negative vertical effective stresses**

This condition arises due to excessively high water pressures. The water pressure at all elevations must be less than the total vertical pressure i.e. the weight of all soil layers plus any surcharges.

When modelling water pressures under foundations, be sure to follow the construction sequence described in Section 7.3.

### **15.8.5 \*\*\* Weak stratum below toe of wall**

The combination of weak soil and vertical pressure difference (between the two sides of the wall) means that the active limit on one side can exceed the passive limit on the other side of the wall. Where the wall terminates in such a stratum there is a potential failure mechanism in which soil flows under the wall.

This will not show up directly in the Factor of Safety or Bending Moment calculations (unless the 2-D FE method is used). The appearance of the warning message means that the design is inadequate and that the toe of the wall should be deeper.

### 15.8.6 \*\*\* Incompatible values of $K_a$ , $K_p$ or $K_{ac}$ , $K_{pc}$

The program needs values of  $\phi$  (soil friction angle) and  $\delta$  (wall friction angle) for certain types of analysis:

1. Berm analysis
2. Factor of Safety on soil strength
3. Calculation of  $K_a$  and  $K_p$  by Wedge Analysis

You should use the Help facility (**F1**) when editing  $K_a$ ,  $K_p$ ,  $K_{ac}$  and  $K_{pc}$ , to ensure that their values are consistent with each other and correspond to your known values of  $\phi$  and wall friction coefficient which you should enter in the Help menu:-

Soil properties ... Soil type 3 ... Help for $K_a$ , $K_{ac}$ values	
Soil friction angle, $\phi$ (degrees)	35.00
Backfill slope angle, $\beta$ , rising +ve (degrees)	5.00
Wall friction(adhesion) coefficient ( $\tan\delta/\tan\phi$ , or a/c)	0.333
Horizontal earthquake acceleration factor	0
Vertical earthquake acceleration factor (+ve Downwards)	0
Formula for calculating $K_a$ , $K_{ac}$ values	Eurocode 7
Suggested value of $K_a$	0.256
Type "A" to accept suggested value(s) or Click here →	Accept

#### For cohesive soil

The values of  $\phi$  and wall friction/adhesion (needed for the analysis) are backfigured from the  $K_a$ ,  $K_{ac}$  (or  $K_p$ ,  $K_{pc}$ ) values for the active and passive sides respectively.

#### For cohesionless soil

The value of  $\phi$  is backfigured from the  $K_a$  (or  $K_p$ ) and wall friction values.

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## NOTATION and GLOSSARY

$\beta$	Backfill angle
$\gamma$	Unit weight of soil
$\gamma_w$	Unit weight of water
$\delta$	Angle of wall friction
$\phi$	Angle of soil friction
$\nu$	Poisson's Ratio
$\theta$	Inclination of strut or anchor to the horizontal
$c_u$	Undrained shear strength of cohesive soil
$c'$	Drained shear strength of cohesive soil
$D$	Equivalent footing width for calculation of coefficient of horizontal subgrade reaction
$E_u$	Young's modulus of cohesive soil (undrained)
$E'$	Young's modulus of cohesive soil (drained)
$E_w \cdot I_w$	Bending stiffness of retaining wall
$F_p$	Factor of safety on passive for calculating wall depth
$F_t$	Factor of safety on passive for calculating tie force
$K_a, K_{ac}$	Active earth pressure coefficients
$K_p, K_{pc}$	Passive earth pressure coefficients
$K_o$	At rest earth pressure coefficient
$k_h$	Coefficient of horizontal subgrade reaction
$L$	Non-linear modulus parameter
$p_v, p_h$	Vertical and horizontal total stress
$p'_v, p'_h$	Vertical and horizontal effective stress
$\Delta p$	Incremental wall pressure
$P_{eq}$	Additional active force due to earthquake acceleration
$u$	Water pressure
$x$	Wall displacement
$\Delta x$	Incremental wall displacement
$y$	Elevation

### Glossary

SLS	Serviceability Limit State
ULS	Ultimate Limit State

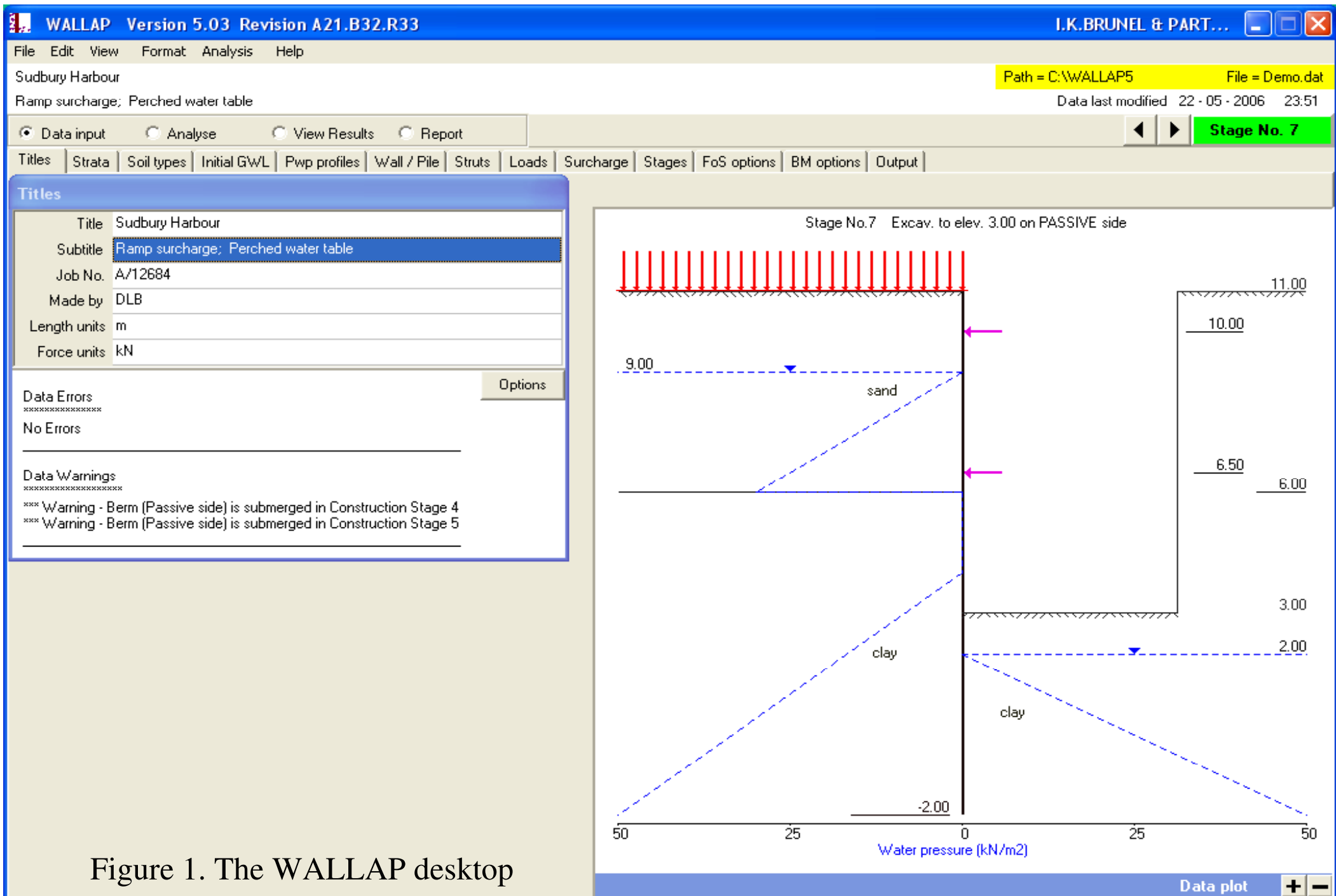


Figure 1. The WALLAP desktop

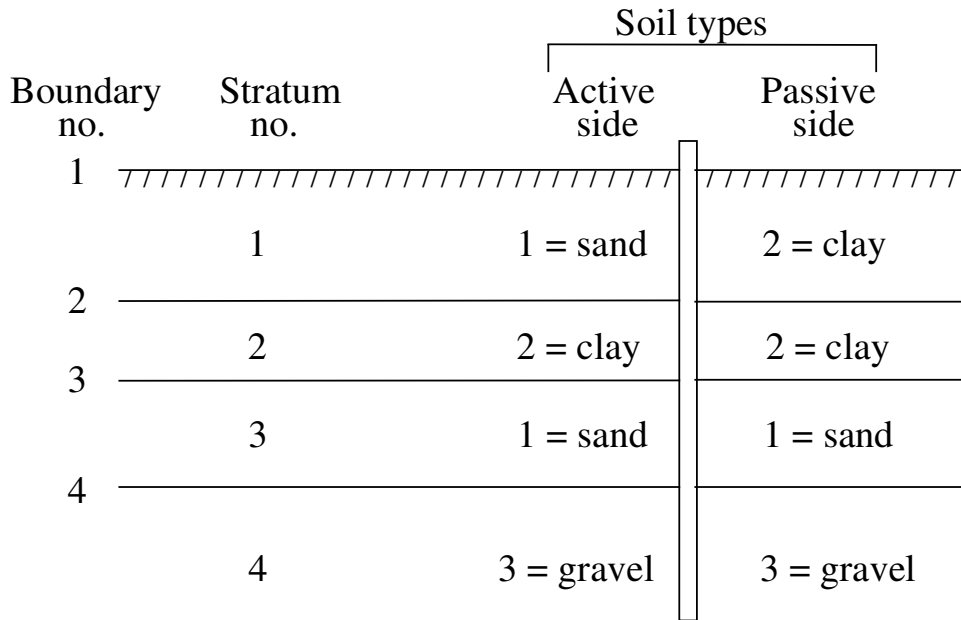


Figure 2. Initial strata profile. Numbering of strata and soil types

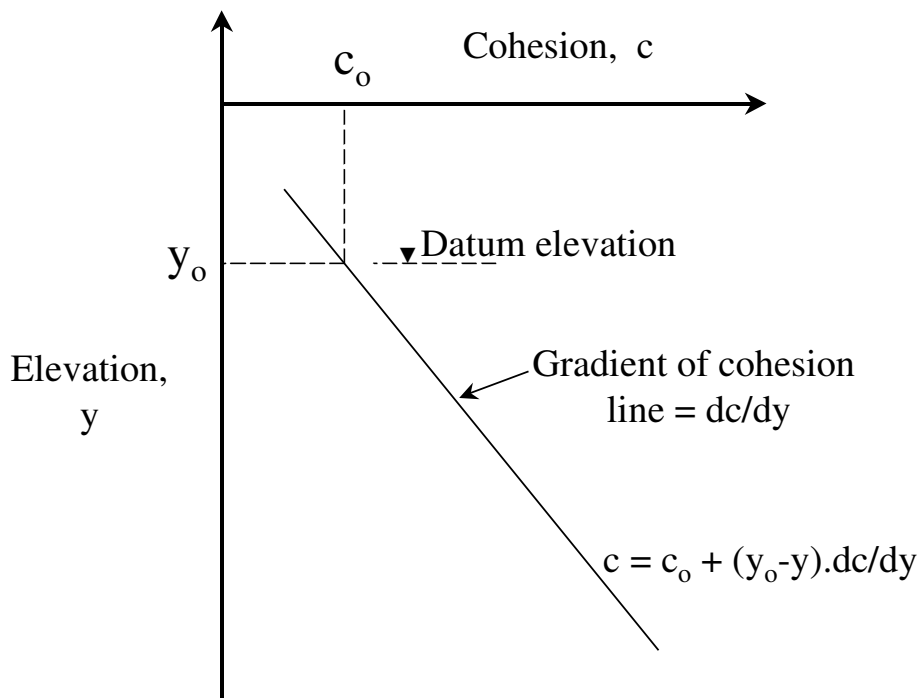


Figure 3. Variation of cohesion with depth

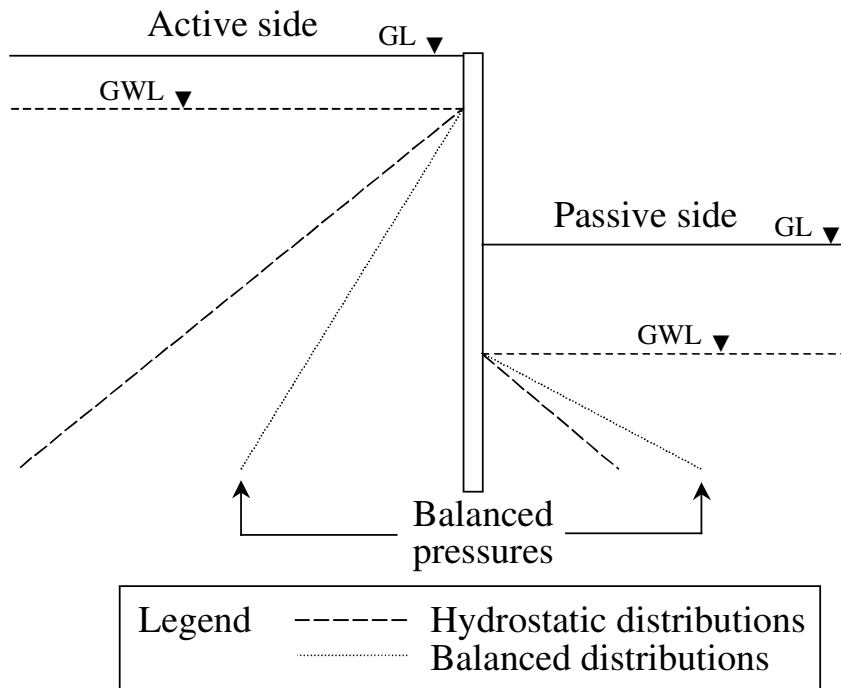


Figure 4. Automatic Water Pressure Balancing at toe of wall

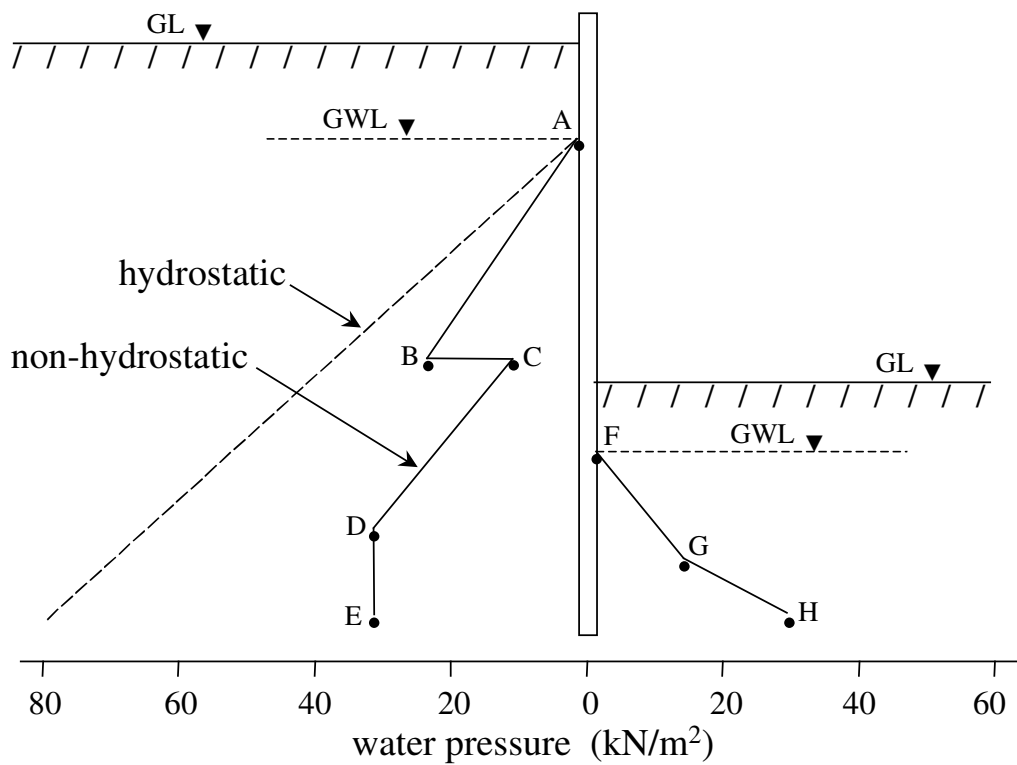


Figure 5. Non-hydrostatic water pressure profiles

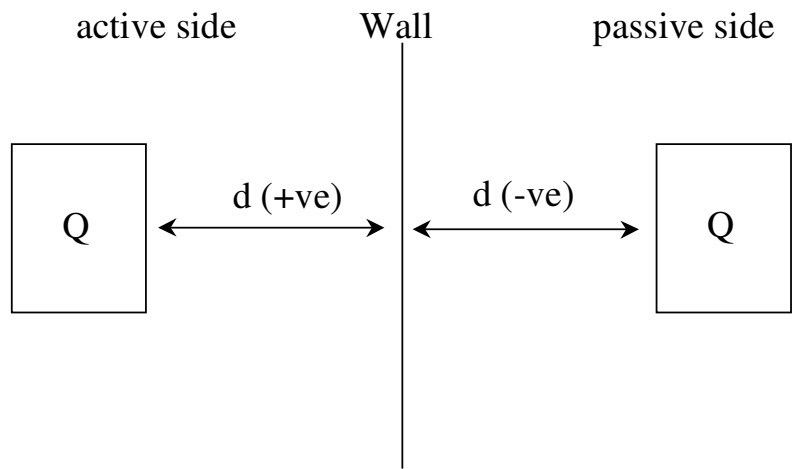


Figure 6a. Distance of surcharge from wall - plan view

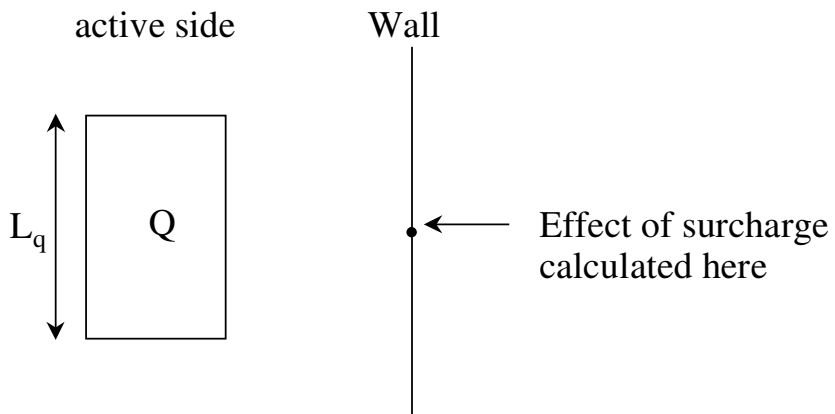


Figure 6b. Surcharge length parallel to wall - plan view

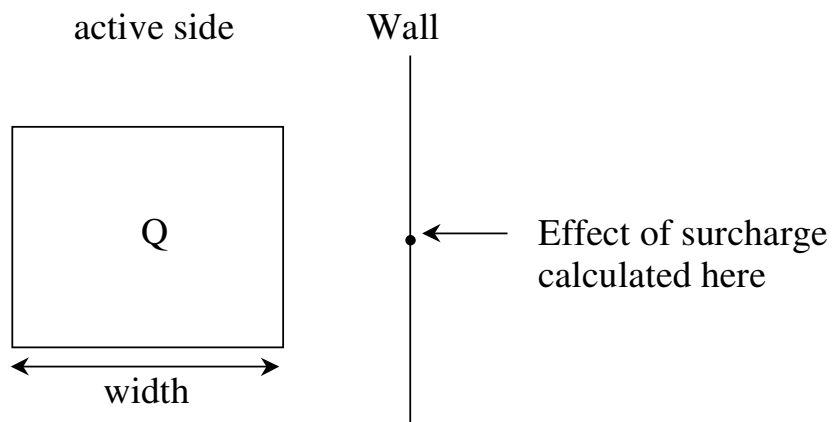


Figure 6c. Surcharge width perpendicular to wall - plan view

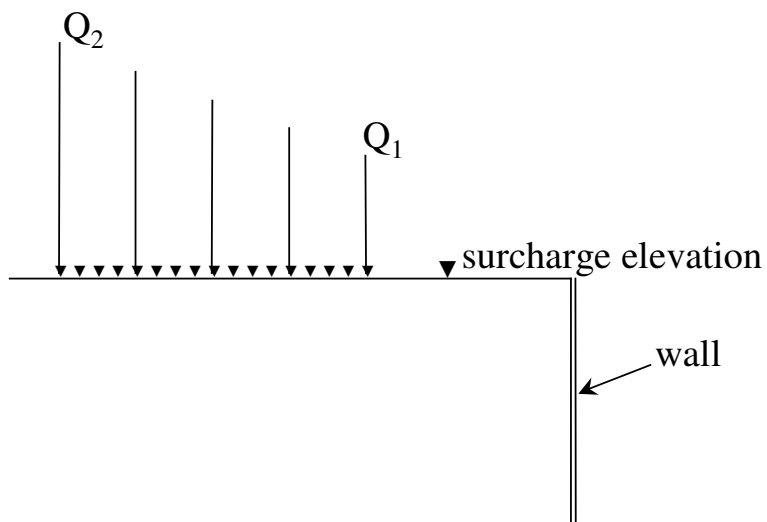


Figure 7. Ramp surcharge - magnitude varying with distance from wall

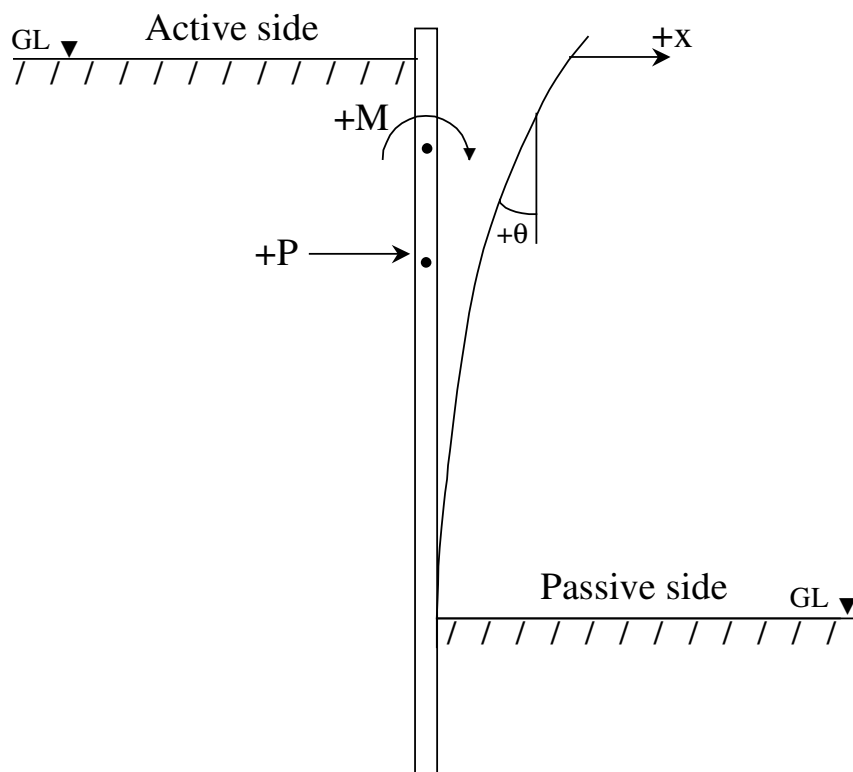


Figure 8. Sign conventions for wall displacements, rotations and loads applied to the wall

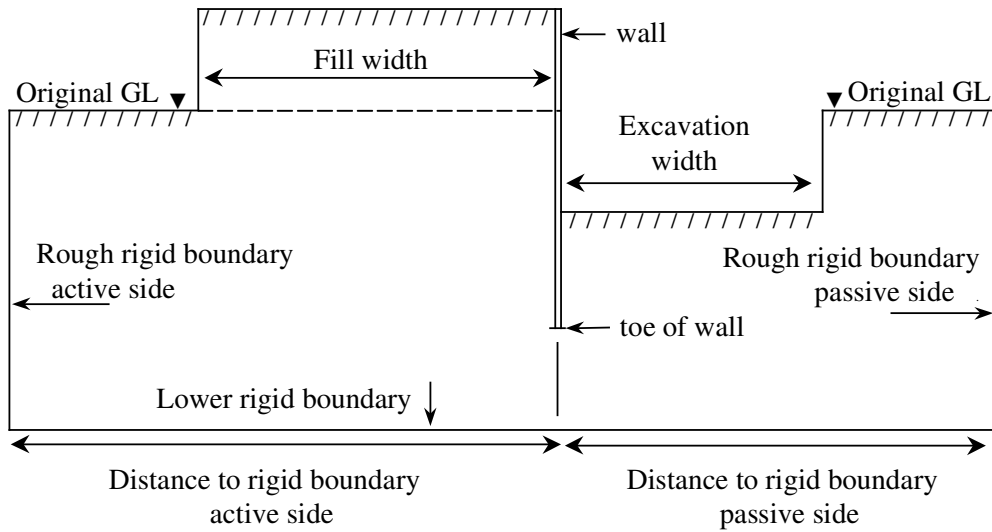


Figure 9a. Boundary conditions for very wide or asymmetrical excavation

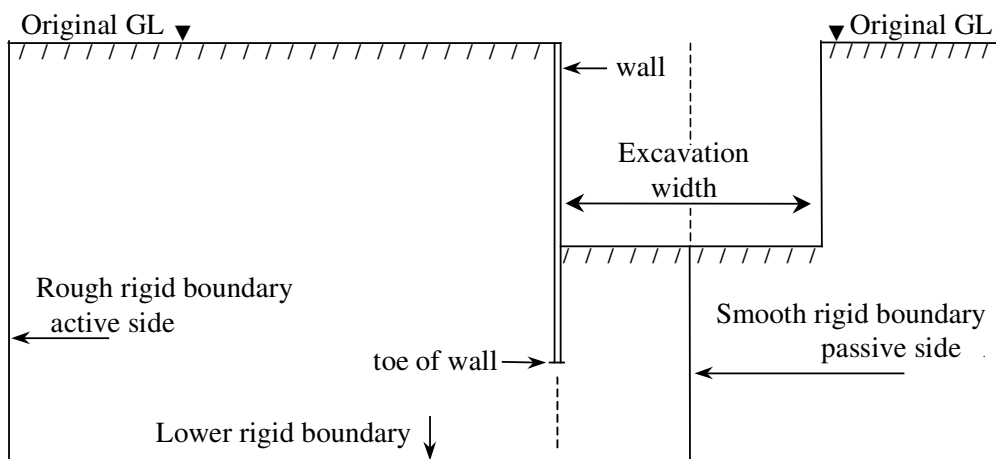


Figure 9b. Boundary conditions for typical symmetrical excavation

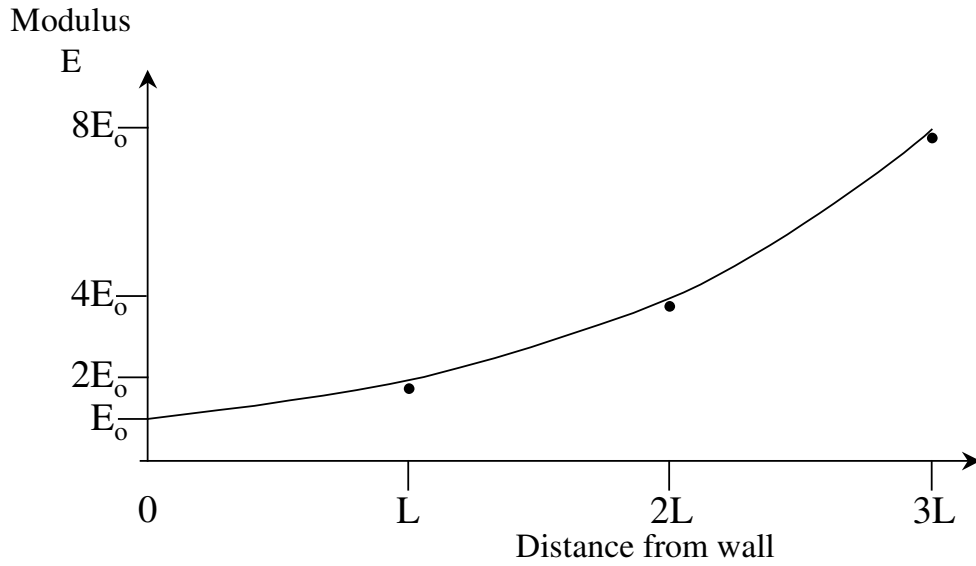


Figure 10. Non-linear modulus parameter, “L”.  
Variation of Young’s Modulus with distance from the wall

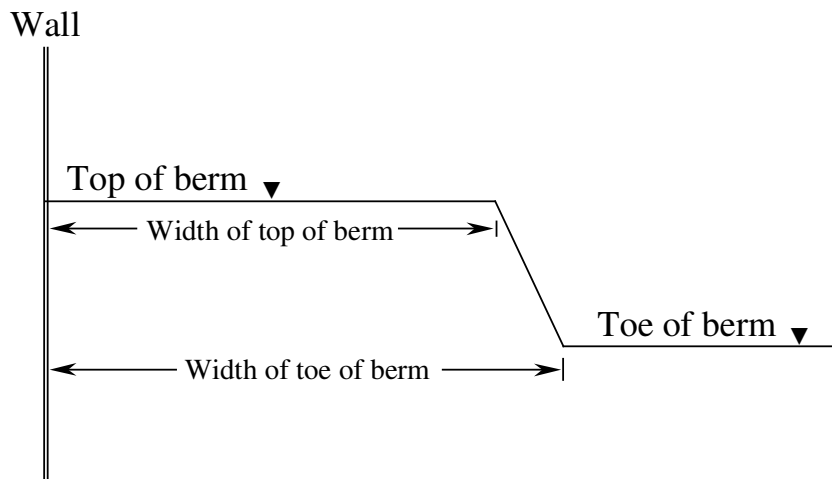
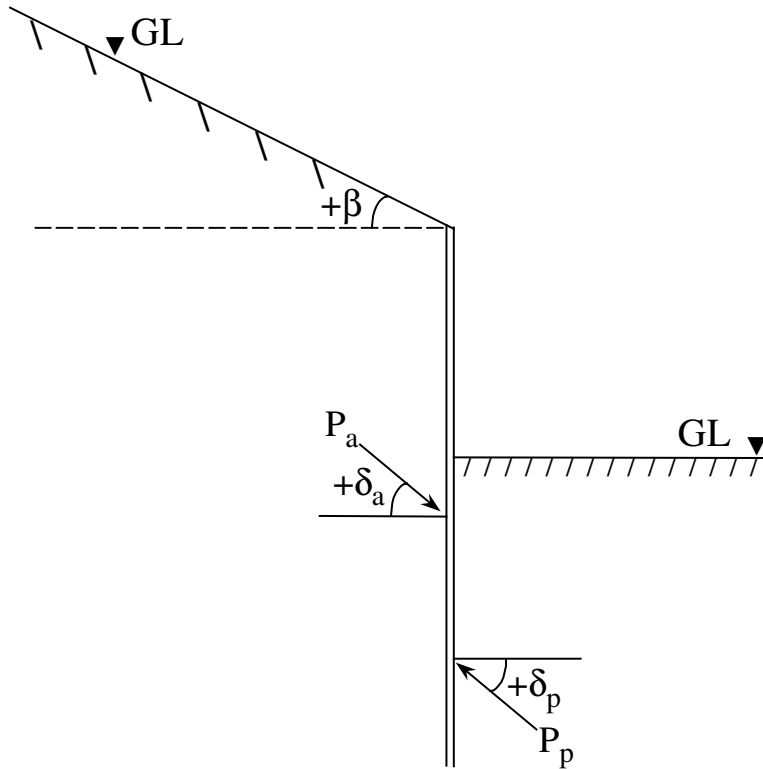


Figure 11. Berm parameters

APPENDIX A  
EARTH PRESSURE COEFFICIENTS

A.1 SIGN CONVENTION FOR ANGLE OF WALL FRICTION  
AND BACKFILL ANGLE



Wall friction angle	$\delta$
Backfill angle	$\beta$

The total active force inclined at an angle  $\delta$  to the normal is given by

$$P_a = \frac{1}{2}\gamma h^2 \cdot K_a$$

The horizontal component of  $P_a$  is given by

$$P_a = \frac{1}{2}\gamma h^2 \cdot K_a \cdot \cos \delta$$

The help facility within WALLAP calculates values of  $K_a \cdot \cos \delta$  so that they can be entered directly into the data

## A.2 CALCULATION OF LIMITING EARTH PRESSURES

### A.2.1 Drained soil - Active pressure

For drained soil the program calculates limiting active (effective) pressures according to the equation:-

$$p_a' = p_v' \cdot K_a - K_{ac} \cdot c' \quad A.1a$$

where  $p_v'$  is the vertical effective stress,  $c'$  is the drained cohesion. The limiting total pressure is:-

$$p_a = p_a' + u \quad A.1b$$

where  $u$  is the water pressure. When the value of  $p_a'$  (in cohesive soil) calculated from equation 6.8a is negative, the program takes  $p_a'$  as zero and the minimum wall pressure is taken as equal to  $u$  in accordance with the recommendations of CP2.

### A.2.2 Drained soil - Passive pressure

The program calculates limiting passive (effective) pressures according to the equation:-

$$p_p' = p_v' \cdot K_p + K_{pc} \cdot c' \quad A.2a$$

where  $p_v'$  is the vertical effective stress,  $c'$  is the drained cohesion. The limiting total pressure is:-

$$p_p = p_p' + u \quad A.2b$$

where  $u$  is the water pressure.

### A.2.3 Undrained soil - Active pressure

For undrained soil the program calculates limiting active total pressures according to the equation:-

$$p_a = p_v \cdot K_a - K_{ac} \cdot c_u \quad A.3$$

where  $p_v$  is the total vertical stress and  $c_u$  is the undrained cohesion.

When the value of  $p_a$  calculated from equation 6.9 is less than the minimum equivalent fluid pressure (Section 13.3.4) the program takes  $p_a$  to be equal to the minimum equivalent fluid pressure, in accordance with the recommendations of CP2.

Within the tension crack zone (Section 13.3.5) the program takes  $p_a$  to be not less than the water pressure, in accordance with the recommendations of CP2.

#### A.2.4 Undrained soil - Passive pressure

The program calculates limiting passive total pressures according to the equation:-

$$p_p = p_v \cdot K_p + K_{pc} \cdot c_u \quad \text{A.4}$$

where  $p_v$  is the total vertical stress and  $c_u$  is the undrained cohesion.

### A.3 Table of values of horizontal component of $K_p$ based on Caquot and Kerisel (1949)

Soil Friction Angle (degrees)	Wall friction angle (degrees)							
	0	+5	+10	+15	+20	+25	+30	+35
10	1.42	1.55	1.62	-	-	-	-	-
15	1.70	1.88	2.05	2.12	-	-	-	-
20	2.04	2.28	2.55	2.77	2.83	-	-	-
25	2.46	2.85	3.21	3.57	3.85	3.89	-	-
30	3.00	3.56	4.07	4.63	5.16	5.53	5.56	-
35	3.69	4.48	5.30	6.14	6.99	7.83	8.41	8.36
40	4.60	5.78	7.03	8.37	9.75	11.3	12.7	13.8
45	5.83	7.58	9.58	11.8	14.3	16.9	19.7	22.5
50	7.55	10.2	13.5	17.4	21.9	26.9	32.6	38.9

#### A.4 Table of values of $K_{ac}$ from CP No.2 (1951)

Wall Friction angle $\delta$	Wall adhesion ratio $C_w/C$	Soil friction angle, $\phi$ (degrees)					
		0	5	10	15	20	25
0	0	2.00	1.83	1.68	1.54	1.40	1.29
0	1	2.83	2.60	2.38	2.16	1.96	1.76
phi	0.5	2.45	2.10	1.82	1.55	1.32	1.15
phi	1	2.83	2.47	2.13	1.85	1.59	1.41

#### A.5 Table of values of $K_{pc}$ from CP No.2 (1951)

Wall Friction angle $\delta$	Wall adhesion ratio $C_w/C$	Soil friction angle, $\phi$ (degrees)					
		0	5	10	15	20	25
0	0	2.0	2.2	2.4	2.6	2.8	3.1
0	0.5	2.4	2.6	2.9	3.2	3.5	3.8
0	1	2.6	2.9	3.2	3.6	4.0	4.4
phi	0.5	2.4	2.8	1.82	3.8	4.5	5.5
phi	1	2.6	2.9	2.13	3.9	4.7	5.7

These tables are presented here mainly for historical interest. More accurate values of  $K_p$  and  $K_{pc}$  should be obtained by using the Help facility within WALLAP

## APPENDIX B

### SUBGRADE REACTION ANALYSIS; FORMULATION OF STIFFNESS MATRIX

#### B.1 INITIAL CONDITIONS

##### B.1.1 Initial geometry

The wall is vertical (see Figure B.1). The left and right soil blocks are rectangular. Initial ground level is the top of Stratum No.1. Boundaries between soil types may be at any elevations as specified in the Strata Profile data. The soil types either side of the wall need not be symmetrical.

##### B.1.2 Initial boundary conditions

The left and right boundaries are rigid. The upper boundary (GL) is a free surface. The pressure between soil and wall is limited (at every stage) by Active and Passive limit pressures. Soil layers below the toe of the wall are not included in the Subgrade Reaction analysis.

#### B.2 ELASTIC BEHAVIOUR

##### B.2.1 Division of the wall into beam elements

The wall is divided into elements as follows:-

Nodes are placed at:	Strata boundaries
	Strut elevations
	Excavation and fill levels

Additional nodes are inserted to comply with the "Maximum element length" ( $l_{\max}$ ) defined in the Wall properties section. All node elevations are given in the output.

### B.2.2 Soil Stiffness

Poisson's ratio,  $\nu$ , is a constant for each soil type, but Young's modulus,  $E$  may vary vertically (parameter  $dE/dy$ ) and with distance from the wall (non-linear modulus parameter,  $L$ ). If  $L$  is defined (i.e. non-zero) then the modulus increases exponentially with distance from the wall (see Figure 10). The value of  $E$  at any distance from the wall is given by:

$$E = E_o \cdot 2^{(x/L)} \quad \text{B.3}$$

Where  $E_o$  = Modulus adjacent to the wall,  
 $E$  = Modulus at distance  $x$  from the wall  
 $L$  = Non-linear modulus parameter (distance from the wall where the modulus is double its given value,  $E_o$ )

### Subgrade Reaction springs

For wall pressures in between the active and passive limits the relationship between wall pressure and wall deflection at any point is calculated by the program according to the equation:-

$$\Delta p / \Delta x = k_h$$

where  $\Delta p$  is the change in wall pressure associated with a wall displacement  $\Delta x$ , and  $k_h$  is the coefficient of horizontal subgrade reaction. Two values of  $k_h$  ( $k_{hL}$  and  $k_{hR}$ ) are defined at each node, for the left and right sides of the wall respectively. The two values are added to give the total soil spring value at that node.

### Evaluation of soil spring values.

The values of  $k_{hL}$  and  $k_{hR}$  at each node elevation are evaluated as if the soil were an elastic stratum of finite depth subjected to a rectangular load. In this case however the load is acting horizontally on a vertical soil face (see Figure B.3). The effect of the free surface at ground level is ignored in respect of its effect on the assumed half-space.

The formula given by Steinbrenner (1934) and quoted by Bowles (1982) gives the surface displacement on a stratum of depth,  $z$ , as a function of the following parameters:-

<b>Steinbrenner's parameter</b>	<b>Corresponding WALLAP parameter</b>
Length of the load	Length of the wall normal to the plane of analysis
Width of the load	Parameter, D, as defined in Section B.2.3 and Figure B.2.
Depth of stratum	Distance from the wall to the rigid boundary.
Young's modulus and Poisson's ratio	Young's modulus and Poisson's ratio at the current node

All parameters are the ones for the relevant side of the wall (right or left). For soils with non-uniform modulus, the displacements are summed in layers, as described by Butler(1975).

### **B.2.3 Definition of the parameter D**

For both cohesive and cohesionless soils, the parameter D is related to the deflected shape of the wall as discussed by Terzaghi (1954, Figure 7). The value of D varies over the depth of the wall according to the direction of movement of each segment, Z, of the wall (Figure B.2). The definition of D given by Terzaghi has been modified slightly by taking D to be the height of wall which is moving at least 50% of the maximum movement in each segment. This avoids undue influence from parts of the wall with negligible displacements.

The same value of  $D_1$  is used throughout the whole depth of segment  $Z_1$  and similarly for each of the other segments. The values of D are recalculated in each construction stage based on the **incremental** displacements in that stage.

Terzaghi only discusses D for **passive** subgrade reaction, on the assumption that the fully active condition will be mobilised on the active side. This assumption is not justified in all cases. Values of D on the active side are calculated in WALLAP on the same basis as for the passive side; however because the height of wall in contact with soil is greater, the values of D on the active and passive sides will not be the same at all levels.

### B.2.4 Global stiffness matrix

We define:

- [a<sub>L</sub>] stiffness matrix for left soil block
- [a<sub>R</sub>] stiffness matrix for right soil block
- [s] stiffness matrix for struts and rotational restraints
- [w] stiffness matrix for the beam elements of the wall

The soil stiffness matrices [a<sub>L</sub>] and [a<sub>R</sub>] represent elastic supports to the wall. The matrices are diagonal i.e. all off diagonal components are zero.

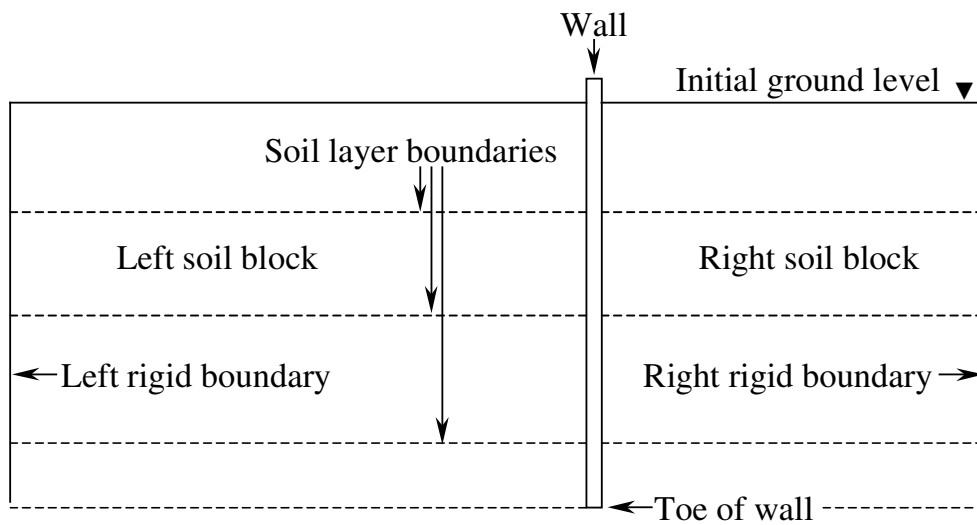
There is no interaction between nodes and thus the subgrade reaction model takes no account of the soil below the wall or the effects of soil arching.

The combined global stiffness for the wall-soil-strut system is:

$$[G] = [a_L] + [a_R] + [s] + [w] \quad \text{B.4}$$

The solution is only derived for horizontal displacements and rotations at node on the wall.

Details of the solution procedure are given in Appendix D.



Note: The wall is actually modelled by beam elements of zero thickness; it is shown above as having finite thickness for illustrative purposes only.

Figure B.1 Subgrade reaction analysis - Initial conditions

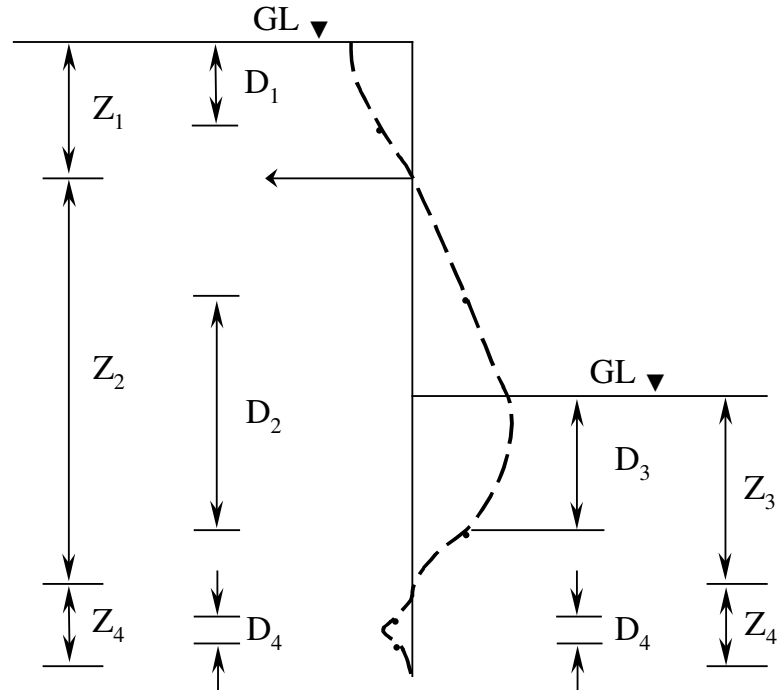


Figure B.2 Parameter D as a function of the deflected shape of the wall

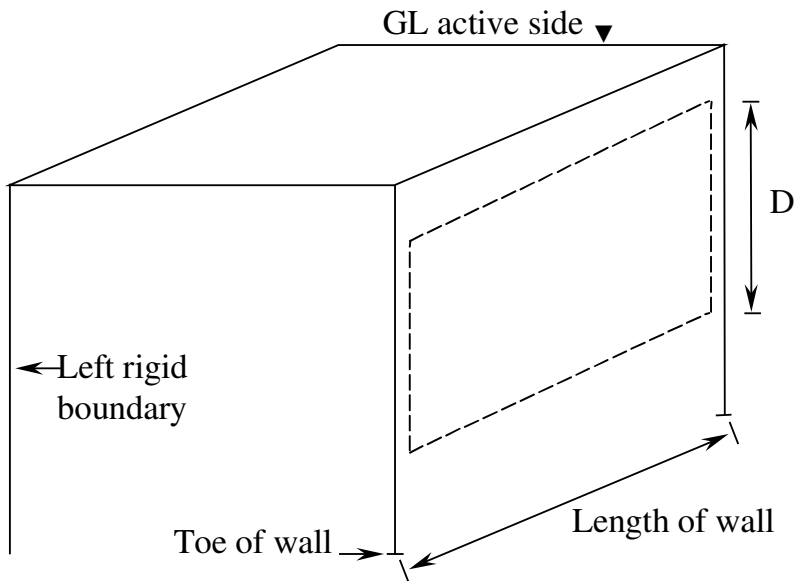
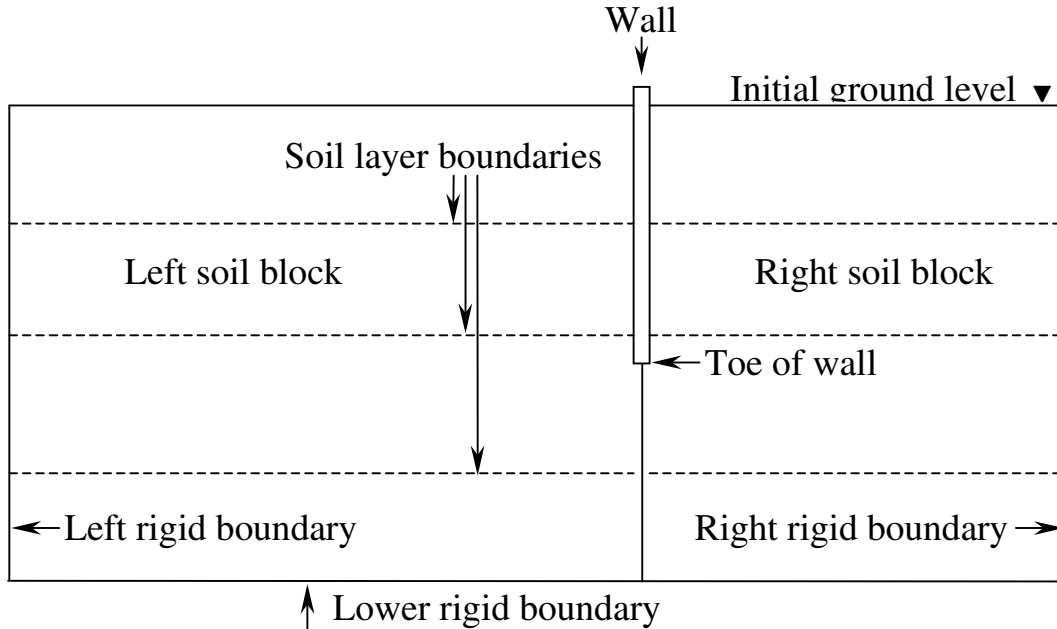


Figure B.3 Typical rectangular loaded area for derivation of soil springs

## APPENDIX C

### FINITE ELEMENT ANALYSIS; FORMULATION OF STIFFNESS MATRIX

#### C.1 INITIAL CONDITIONS



Note: The wall is actually modelled by beam elements of zero thickness; it is shown above as having finite thickness for illustrative purposes only

Figure C.1 2-D Finite element analysis - Initial conditions

##### C.1.1 Initial geometry

The wall is vertical. The left and right soil blocks are rectangular. Initial ground level is the top of Stratum No. 1. Boundaries between soil types may be at any elevations as specified in the Strata Profile data. The soil types either side of the wall need not be symmetrical.

##### C.1.2 Initial boundary conditions

The left, right and lower boundaries are either smooth-rigid or rough-rigid as defined in the data. Contact between soil and wall (for the purposes of calculating the elastic stiffness matrix) is either rough or smooth as defined in the data. The vertical soil-soil boundary between the left and right blocks (below the toe of the wall) is perfectly rough. The upper boundary (GL) is a free surface. The pressure between soil and wall is limited (at every stage) by Active and Passive limit pressures.

## C.2 ELASTIC BEHAVIOUR

### C.2.1 Division into elements

The left and right soil blocks are divided into 4 noded rectangular elements shown schematically:-

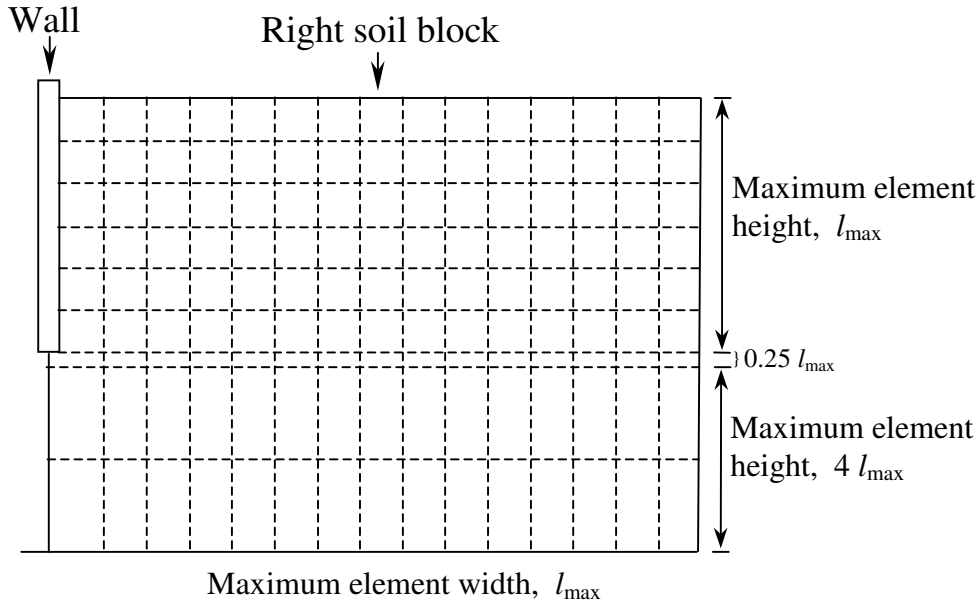


Figure C.2 Division of soil mass into elements

The division in the vertical direction is as follows:-

Nodes are placed at:

- Strata boundaries
- Strut elevations
- Excavation and fill levels

#### Above the toe of the wall

Additional nodes are inserted to comply with the "Maximum element length" ( $l_{max}$ ) defined in the Wall properties section.

#### Below the toe of the wall

One node is placed at a  $\frac{1}{4}$  of the "Maximum element length" below the toe. This node is required in order to model the horizontal stress discontinuity at the toe of the wall.

Additional nodes are inserted at 4 times the "Maximum element length". The wider node spacing is adopted for efficiency and economy of the calculation.

All node elevations are given in the output.

In the horizontal direction the soil block is divided into elements of equal width, less than or equal to  $l_{max}$ .

## C.2.2 Stiffness matrix

### Element stiffness matrix

The plane strain stiffness matrix of each element is calculated from its dimensions and the elastic parameters of its soil type.

Poisson's ratio,  $m$ , is a constant for each soil type, but Young's modulus,  $E$  may vary vertically (parameter  $dE/dy$ ) and with distance from the wall (non-linear modulus parameter,  $L$ ). If  $L$  is defined (i.e. non-zero) then the modulus increases exponentially with distance from the wall (see Figure 10). The value of  $E$  for each element is given by:

$$E = E_0 \cdot 2^{(x/L)} \quad \text{C.3}$$

where  $E_0$  = Modulus adjacent to the wall,  
 $E$  = Modulus at distance  $x$  from the wall  
 $L$  = Non-linear modulus parameter (distance from the wall where the modulus is double its given value,  $E_0$ )

### Approximate 3D correction factor

The stiffness matrix is (as stated above) calculated assuming plane strain conditions i.e. no strain in the direction parallel to the wall. This assumption is reasonable for very long walls.

WALLAP makes an approximate correction to the stiffness matrix to take account of the finite length of the wall. **All** soil moduli are multiplied by a correction factor related to the ratio of the length to the height of the wall. The correction factor is based on elastic displacements beneath a rectangular footing compared with an infinite strip load. The correction factor includes the effect of the distance to the rigid boundaries and the non-linear modulus parameter,  $L$ . The following table gives an indication of the size of the correction factor according to the length-height ratio of the wall.

Ratio of length to Height of the wall.	Approximate maximum 3D correction factor
3	1.02
2	1.08
1	1.30
0.5	1.78
0.25	2.66

### Global stiffness matrix

The global stiffness matrix  $[A]$  for each soil block (left or right) is assembled from the matrices of the individual elements.  $[A]$  is partially eliminated to create matrix  $[a]$  in which the only variables are the horizontal and rotational displacements at the vertical (wall) boundary. We define:

- $[a_L]$  stiffness matrix for left soil block
- $[a_R]$  stiffness matrix for right soil block
- $[s]$  stiffness matrix for struts and rotational restraints
- $[w]$  stiffness matrix for the beam elements of the wall

The soil stiffness matrices  $[a_L]$  and  $[a_R]$  represent elastic supports to the wall. The matrices are fully populated (not banded) i.e. every node interacts with every other node, ensuring that the analysis takes full account of the soil masses either side of and below the wall including the effects of soil arching.

The combined global stiffness for the wall-soil-strut system is:

$$[G] = [a_L] + [a_R] + [s] + [w] \quad C.4$$

The solution is only derived for horizontal displacements and rotations along the line of the wall.

Details of the solution procedure are given in Appendix D.

## APPENDIX D

### BENDING MOMENT AND DISPLACEMENT SOLUTION

#### D.1 INITIAL WALL PRESSURES

These are always calculated in effective stress terms (even for undrained soil types).

$$\text{Vertical total stress, } \sigma_v = \int_0^z \gamma \cdot dz \quad \text{D.1}$$

$$\text{Effective horizontal stress, } \sigma_h' = (\sigma_v - u) \cdot K_0 \quad \text{D.2}$$

#### D.2 INCREMENTAL APPLIED LOADS

The term "incremental" denotes the division of the construction sequence (and similarly the analysis) into stages. Displacements, bending moments and soil pressures are added cumulatively from stage to stage. When the analysis of a stage is suppressed at the users request (e.g. a water pressure or surcharge stage) the applied loads are carried forward to the next stage.

##### D.2.1 Constructions stages

The analysis proceeds according to the Construction sequence defined in the data. The incremental forces depend on the type of construction stage and may include:

- Loads applied to the wall (including strut pre-stress)
- Change of water pressures
- Incremental soil pressures due to excavation or filling
- Incremental soil pressures due to surcharges

We define:

- {P} vector of incremental applied horizontal forces (including incremental soil pressures)
- {M} vector of incremental applied moment loads
- {F} Combined vector of incremental forces {P} and moments {M}

### **D.2.2 Loads applied directly to the wall**

The contributions to {P} and {M} are taken directly from the values defined in the data under "Horizontal and moment loads". Also included here is the strut pre-stress which is applied at the stage when a strut is installed.

### **D.2.3 Excavation, filling and water pressures**

#### **Excavation**

The excavated material is removed. The pressure on the wall from the excavated material at the end of the previous stage is removed.

#### **Filling**

The fill material is placed at its  $K_o$  value.

#### **Water pressure change**

The contributions to {P} are derived from the incremental water pressures as defined in the data.

### **D.2.4 Soil-wall pressures due to changes in vertical stress**

#### **Vertical stress changes**

The following construction stages produce vertical effective stress changes in the soil:-

- Surcharge applications
- Excavation
- Filling

Excavation and filling are mentioned here as well as in the above section on account of their effect on underlying strata. The vertical stress change in the soil (adjacent to the wall) is calculated according to the Boussinesq elastic distribution for a rectangular load on an elastic half space.

In the case of a surcharge the dimensions and magnitude of the surcharge are given in the surcharge data. For excavation and filling stages the width is the "Width of excavation/filling" given in the "Bending moment calculation options".

## Horizontal stress changes

For each node we define:

$\sigma_{ho}'$  Horizontal effective stress at end of previous construction stage

$\Delta\sigma_v'$  Vertical effective stress increment due to surcharge, filling or excavation

$\Delta\sigma_h' = 2\Delta\sigma_v' \cdot \nu/(1-\nu)$  Horizontal effective stress increment due to surcharge, filling or excavation

The **incremental applied horizontal soil pressures** on the wall are calculated assuming **no horizontal movement of the wall**. Boussinesq elastic values of  $\Delta\sigma_v'$  are therefore doubled as suggested by Terzaghi (1954) because of the "zero wall movement" assumption.

The values of  $\Delta\sigma_h'$  contribute to the components of  $\{P\}$ , the vector of incremental applied horizontal forces.

**Note:** The "zero wall movement" assumption and doubling of the horizontal pressures are simply a mathematical device and its validity does not depend on the actual wall stiffness. During the elastic solution (see below) these **incremental soil pressures** (together with the incremental loads and water pressures) are allowed to come into equilibrium with the wall-soil-strut system and the soil pressures are adjusted accordingly.

### D.3 ELASTIC SOLUTION

We define:

$\{\delta\}$  vector of incremental horizontal displacements and rotations

$\{\Delta P_L\}$  vector of horizontal nodal reactions for soil on the left of the wall.

$\{\Delta P_R\}$  vector of horizontal nodal reactions for soil on the right of the wall.

$\Delta\sigma_{he}'$  Horizontal effective stress adjustment as applied loads come into equilibrium.

$\Delta\sigma_{hi}'$  Effective soil pressure at end of stage

Incremental nodal displacements and loads are related by:

$$[G].\{\delta\} = \{F\} \quad D.3$$

Incremental forces at each stage produce incremental displacements. The stiffness matrix  $\{G\}$  is recalculated at each stage according to the current soil geometry and properties. The solution for a construction stage proceeds as follows:

1. Calculate  $\{F\}$  for current stage (see details above)
2. Solve equation D.3 by inverting  $[G]$  to obtain incremental displacements:

$$\{\delta\} = [G]^{-1} [F] \quad D.4$$

3. Derive the left and right soil components of the nodal reactions:

$$\{\Delta P_L\} = [a_L].\{\delta\} \quad D.5a$$

$$\{\Delta P_R\} = [a_R].\{\delta\} \quad D.5b$$

4. Derive the soil pressure adjustments  $\Delta\sigma_{he}'$  corresponding to  $\{\Delta P_L\}$  and  $\{\Delta P_R\}$
5. Calculate the new soil pressure at each node

$$\sigma_{h1}' = \sigma_{ho}' + \Delta\sigma_h' + \Delta\sigma_{he}' \quad D.6$$

6. At each node, check the new soil pressures  $s_{h1}'$  against the active and passive limits. If  $s_{h1}'$  lies outside either limit, apply an initial stress correction which is included in  $\{F\}$  and solve again from step 1. Repeat until convergence is achieved.
7. From the incremental deflections  $\{d\}$  calculate the incremental shear force and bending moments in each element and the incremental forces and moments at struts and rotational restraints.
8. Add incremental deflections, forces and bending moments to the values at the end of the previous stage to obtain new total deflections, forces and bending moments.

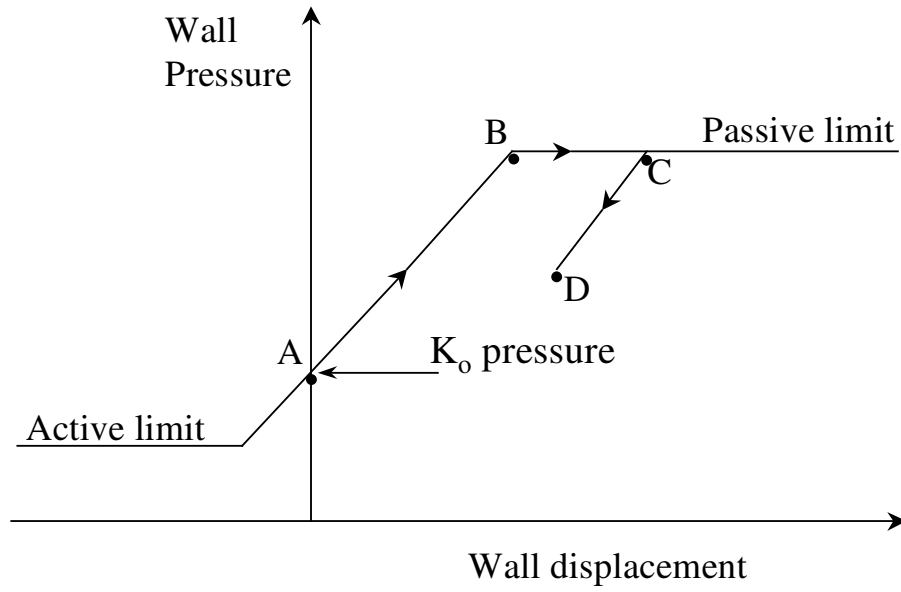


Figure D.1 Wall pressure - displacement relationship

## APPENDIX K

### SOLDIER (or KING) PILE RETAINING WALLS

#### Use of WALLAP to model a Soldier Pile wall with infill panels

##### Symbol definitions

$K_{a \text{ true}}$	Active earth pressure coefficient	}	usual values for
$K_{p \text{ true}}$	Passive earth pressure coefficient	}	soil next to a
$E_{\text{true}}$	Young's modulus of soil	}	solid wall
b	Width of soldier piles		
S	Spacing of soldier piles		

The usual WALLAP two dimensional analysis of a plane wall can be adapted to the case of a Soldier (or King) pile wall although the analysis is approximate.

The following suggested procedure considers stability from the point of view of two potential failure modes:

1. The ability of all the passive soil (both in front of the soldier piles and between the soldier piles) to resist the **combined** effect of forces on the wall due to the active soil pressures **above** excavation level **and** the direct effect of active soil pressures **below** excavation level (i.e. the usual requirement for a solid retaining wall).
2. The ability of the passive soil **in front of the soldier piles** to resist the forces transmitted through the wall due to the active soil pressures **above** excavation level.

##### Mode 1

This is simply a conventional wall analysis treating the soldier pile system as a solid wall. The values of  $K_a$ ,  $K_p$  etc.. are the usual values for the various soil types **without** the adjustments described below.

##### Mode 2

Above excavation level

The infill sections are assumed to behave like a solid wall with the usual values of  $K_a$ ,  $K_p$  and Young's modulus.

### Below excavation level

The soldier piles without infill panels are assumed to behave as individual piles in the following way:-

1. The active limit is zero due to arching
2. The passive limit is equivalent to a short length of wall equal to 3 times the width of a pile. (assuming  $S > 3b$  )

Soil Parameter	Value for soil next to piles with infill panels (above excav. level)	Value for soil next to piles without infill panels (below excav. level)
$K_a$	$K_{a \text{ true}}$	0
$K_p$	$K_{p \text{ true}}$	$K_{p \text{ true}} \cdot 3b/S$ * see Note
E	$E_{\text{true}}$	$E_{\text{true}} \cdot 3b/S$

It is suggested to use the same factor ( $3b/S$ ) for scaling the modulus as for  $K_p$ . If this is felt to be too optimistic then a scale factor of  $2b/S$  could be used for both  $K_p$  and Young's modulus.

Broms (1964<sup>1</sup>) recommends that in cohesive soils, passive resistance should be ignored to a depth of 1.5 pile diameters.

Further reading on the passive resistance of single piles can be found in Tomlinson (1994), Clayton et al. (1993) and Broms(1964<sup>2</sup>),

#### \* Note for undrained soil types

Soil types defined as "undrained" are restricted within the program to having a  $K_p$  value of unity. This is incompatible with the above recommendation to scale  $K_p$  values. In order to define  $K_p$  values not equal to unity, you use the "drained" soil type to model undrained strata (**below excavation level only**), but set the Cohesion, Modulus and Poisson's Ratio to their undrained values.

Undrained strata **above** excavation level **must** be defined as undrained otherwise the program will not implement the Minimum Equivalent Fluid Pressure and Water Filled Tension Crack rules for any undrained soil behind the wall.

The bending stiffness of the wall is assumed to be constant throughout its height since the wall derives its stiffness almost entirely from the soldier piles. Thus:-

$$EI \text{ (per m run)} = \frac{EI \text{ (per pile)}}{\text{pile spacing}}$$

### **Interpretation of results**

It is an essential design requirement that stability is satisfied for both Modes 1 and 2. The design bending moments should be taken from the worse of the two Modes. Two main cases may be distinguished which may help in understanding which Mode is more critical:

**Case (A)** Where the piles are embedded in weak ground and/or the piles are close together, Mode 1 is likely to be more critical. Where piles are closer than 3 times their width this will usually be the critical case.

**Case (B)** Where the piles are embedded in strong ground and/or the piles are far apart, Mode 2 is likely to be more critical.

### **References**

**Broms B. (1964<sup>1</sup>)**

Lateral resistance of piles in cohesive soils.  
ASCE Journal, Vol.90 SM2 March 1964 pp.27-63

**Broms B. (1964<sup>2</sup>)**

Lateral resistance of piles in cohesionless soils.  
ASCE Journal, Vol.90 SM3 May 1964 pp.123-156

**Clayton, C.R.I., J.Milititsky and R.I.Woods (1993)**

Earth Pressure and Earth Retaining Structures.  
2nd edition. Blackie.

**Tomlinson, M.J. (1994)**

Pile Design and Construction Practice.  
4th edition. Spon.

Program: WALLAP Version 5.01 Revision A06.B23.R11 | Run No. KP01A  
 King Pile wall. See file KP01B for reduced Kp values | Made by :  
 Pile width = 0.4m Pile spacing = 3m | Date:20-05-2002  
 Mode 1 | Checked :

SOIL PROFILE Units: kN,m

Stratum no.	Elevation of top of stratum	Active side	Soil types	Passive side
1	0.00	1 Sand		1 Sand
2	-1.00	2 Soft clay		2 Soft clay
3	-4.00	3 Gravel		3 Gravel
4	-8.00	4 Firm clay		4 Firm clay

SOIL PROPERTIES

No. Description (Datum elev.)	Bulk density kN/m3	Young's Modulus Eh, kN/m2 (dEh/dy)	At rest coeff. Ko (dKo/dy)	Consol state. NC/OC (Nu)	Active limit Ka (Kac)	Passive limit Kp (Kpc)	Cohes -ion kN/m2 (dc/dy)
1 Sand	20.00	20000	0.500	OC (0.200)	0.333 (0.000)	4.369 (0.000)	
2 Soft clay ( 0.00 )	18.00 ( 600 )	10000 ( 600 )	0.500	OC (0.490)	1.000 (2.000)	1.000 (2.000)	30.00u (2.0000)
3 Gravel	19.00	30000	0.500	OC (0.200)	0.280 (0.000)	5.800 (0.000)	
4 Firm clay	19.00	30000	0.500	OC (0.490)	1.000 (2.000)	1.000 (2.000)	60.00u

GROUND WATER CONDITIONS  
 Density of water = 10.00 kN/m3  
 Initial water table elevation Active side -10.00 Passive side -10.00

WALL PROPERTIES  
 Elevation of toe of wall = -10.00  
 Youngs modulus of wall E = 2.0000E+08 kN/m2  
 Moment of inertia of wall I = 1.3510E-04 m4/m run  
 E.I = 2.702E+04

CONSTRUCTION STAGES  
 Construction stage no. Stage description  
 1 Excavate to elevation -4.00 on PASSIVE side

FACTORS OF SAFETY and ANALYSIS OPTIONS  
 Type of structure - Retaining wall

Stability analysis:  
 Method of analysis - CP2  
 Factor on passive for calculating wall depth = 2.00  
 Factor on passive for calculating tie force = 1.00

Parameters for undrained strata:  
 Minimum equivalent fluid density = 5.00 kN/m3  
 Maximum depth of water filled tension crack = 2.00 m

Bending moment and displacement calculation:  
 Method - Subgrade reaction model using Influence Coefficients  
 Open Tension Crack analysis? - No  
 Non-linear Modulus Parameter (L) = 10.000 m

Boundary conditions:  
 Length of wall (normal to plane of analysis) = 100.00 m  
 Width of excavation on active side of wall = 20.00 m  
 Width of excavation on passive side of wall = 20.00 m  
 Distance to rigid boundary on active side = 20.00 m

Distance to rigid boundary on passive side = 20.00 m  
 Program: WALLAP Version 5.01 Revision A06.B23.R11 | Run No. KP01B  
 King Pile wall. See also file KP01A | Made by :  
 Pile width = 0.4m Pile spacing = 3m S/b=7.5 | Date:20-05-2002  
 Mode 2 | Checked :

SOIL PROFILE Units: kN,m

Stratum no.	Elevation of top of stratum	Active side	Soil types	Passive side
1	0.00	1 Sand		1 Sand
2	-1.00	2 Soft clay		2 Soft clay
3	-4.00	3 Gravel		3 Gravel
4	-8.00	4 Firm clay		4 Firm clay

SOIL PROPERTIES

No. Description (Datum elev.)	Bulk density kN/m3	Young's Modulus Eh, kN/m2 (dEh/dy)	At rest coeff. Ko (dKo/dy)	Consol state. NC/OC (Nu)	Active limit Ka (Kac)	Passive limit Kp (Kpc)	Cohes -ion kN/m2 (dc/dy)
1 Sand	20.00	20000	0.500	OC (0.200)	0.333 (0.000)	4.369 (0.000)	
2 Soft clay ( 0.00 )	18.00 ( 600 )	10000 ( 600 )	0.500	OC (0.490)	1.000 (2.000)	1.000 (2.000)	30.00u (2.0000)
3 Gravel	19.00	12000	0.500	OC (0.200)	0.000 (0.000)	2.320 (0.000)	
4 Firm clay	19.00	12000	0.500	OC (0.490)	0.000 (0.000)	0.400 (0.800)	60.00d

GROUND WATER CONDITIONS  
 Density of water = 10.00 kN/m3  
 Initial water table elevation Active side -10.00 Passive side -10.00

WALL PROPERTIES  
 Elevation of toe of wall = -10.00  
 Youngs modulus of wall E = 2.0000E+08 kN/m2  
 Moment of inertia of wall I = 1.3510E-04 m4/m run  
 E.I = 2.702E+04

CONSTRUCTION STAGES  
 Construction stage no. Stage description  
 1 Excavate to elevation -4.00 on PASSIVE side

FACTORS OF SAFETY and ANALYSIS OPTIONS  
**As for Run KP01A**

## Notes

Data files KP01A and KP01B represent the two Modes of a Soldier Pile wall to be analysed as described in Appendix K

In KP01B the Ka values for soil types 3 and 4 have been set to zero and the Kp values for soil types 3 and 4 have been reduced in accordance with the expression

$$K_{p\text{King pile}} = K_{p\text{true}} \cdot 3b/S$$